

**ON THE ENERGY EFFICIENCY OF DYNAMIC SPECTRUM
ACCESS IN THE AD-HOC WIRELESS LAN SCENARIO**

A Dissertation by

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The following faculty members have examined the final copy of this dissertation for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Doctor of Philosophy with a major in Electrical Engineering.

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DEDICATION

To My Parents

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ABSTRACT

Wireless data communications, especially to and from portable mobile devices, is one of the fastest growing paradigms in the field of computer communications. This fast paced growth of wireless communication devices is making some communication frequency bands overcrowded. There exists legacy frequency spectrum that remains under utilized. As a result, there are great inefficiencies in how the overall available frequency spectrum is utilized, motivating the need for new technologies to solve this issue. Cognitive Radio (CR) is an emerging technology proposed over the past decade in order to deal with spectrum inefficiency and to help improving wireless communication performance. A CR has the capability to scan across the spectrum to find under utilized channels and use them for communications under some stipulated conditions.

A key aspect of CRs 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 of licensed spectrum. 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. 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. As a result, the focus of this work is on the ad hoc Wireless LAN scenario that works in the highly congested ISM bands.

In this dissertation three important contributions to research on ad-hoc WLAN cognitive radios are presented. First, a comprehensive survey on prior research in cognitive radio networks with a focus on the implications for energy consumption is presented. Second, the energy consumption of a radio that uses the CR technique is modeled and analyzed for a static scenario with fixed channel conditions and node populations. As part of this work four novel spectrum scanning algorithms are proposed and analytically evaluated for their energy consumption. Finally, the energy consumption of a radio that employs the CR technique through one of our four spectrum scanning schemes is studied through simulations for dynamic scenarios that include diverse channel conditions and varying node populations.

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LIST OF ABBREVIATIONS

CDMA	- Code Division Multiple Access
CR	- Cognitive Radio
CRN	- Cognitive Radio Network
CSMA	- Carrier Sense Multiple Access
CTS	- Clear To Send
DCF	- Distributed Coordination Function
DN	- Dominant Node
DSA	- Dynamic Spectrum Allocation
ED	- Energy Detection
FC	- Fusion Center
FCC	- Federal Communications Commission
FFT	- Fast Fourier Transform
HFD	- Hard Fusion Decision
ISM	- Industrial Scientific and Medical
LD	- Load Distribution
MAC	- Medium Access Protocol
MIMO	- Multiple In Multiple Out
PA	- Power Amplifier
PAP	- Primary Access Point
PC	- Power Control
PU	- Primary User

LIST OF ABBREVIATIONS (continued)

QoS	- Quality of Service
RTS	- Request To Send
SAP	- Secondary Access Point
SDR	- Software Defined Radio
SFD	- Soft Fusion Decision
SIFS	- Short Inter-Frame Space
SIR	- Signal to Interference Ratio
SISO	- Single In Single Out
SNR	- Signal to Noise Ratio
SU	- Secondary User
TCP	- Transmission Control Protocol
TPC	- Transmission Power Control
VLSI	- Very Large Scale Integrated circuit
WLAN	- Wireless Local Area Network
	-

CHAPTER 1

INTRODUCTION

Increasing computing power, and new applications and features are fueling the trend of ever greater number of portable wireless communication devices. The number of wireless communication devices is projected to grow from 3 billion to 100 billion by the year 2025 [1]. Frequency spectrum is a limited resource that many wireless electronic devices rely on for their communication needs. The fast growing number of wireless devices are creating a scarcity of spectrum on some common frequency bands. Present radio technology cannot deal with 2-3 orders of magnitude increase from near about 100 devices per square km today to 10,000 devices per square km in 2025 [76]. Thus, there is a need to develop techniques and technologies that can alleviate the spectrum scarcity problem.

Thankfully, the spectrum scarcity problem can be addressed by solving the broader problem of spectrum usage inefficiency. In the U.S., frequency spectrum is allocated by the Federal Communications Commission (FCC). Wireless devices operate on specific allocated bands, with these bands being licensed or unlicensed. The licensed bands are typically auctioned off to the highest bidder who then uses the spectrum for specific applications. The unlicensed bands are open to use by anyone as long as they meet certain guidelines of output power. The Industrial, Scientific, and Medical (ISM) band is one example of an unlicensed band commonly used by many wireless devices such as wireless local area network (LAN) radios, cordless phones, microwave ovens. There are other bands that are allocated for specific legacy applications such as TV broadcasting or maritime applications. However, such specific allocations has resulted in great inefficiencies in spectrum usage; some bands are highly congested, while other lay unutilized most of the time. For example the ISM bands are heavily used, while some TV channel frequencies are not used for large chunks of time.

In Figure 1.1, frequency occupancies in USA show how inefficiently the spectrum is being used. One study showed that only 6% [8] of the available spectrum was occupied at any

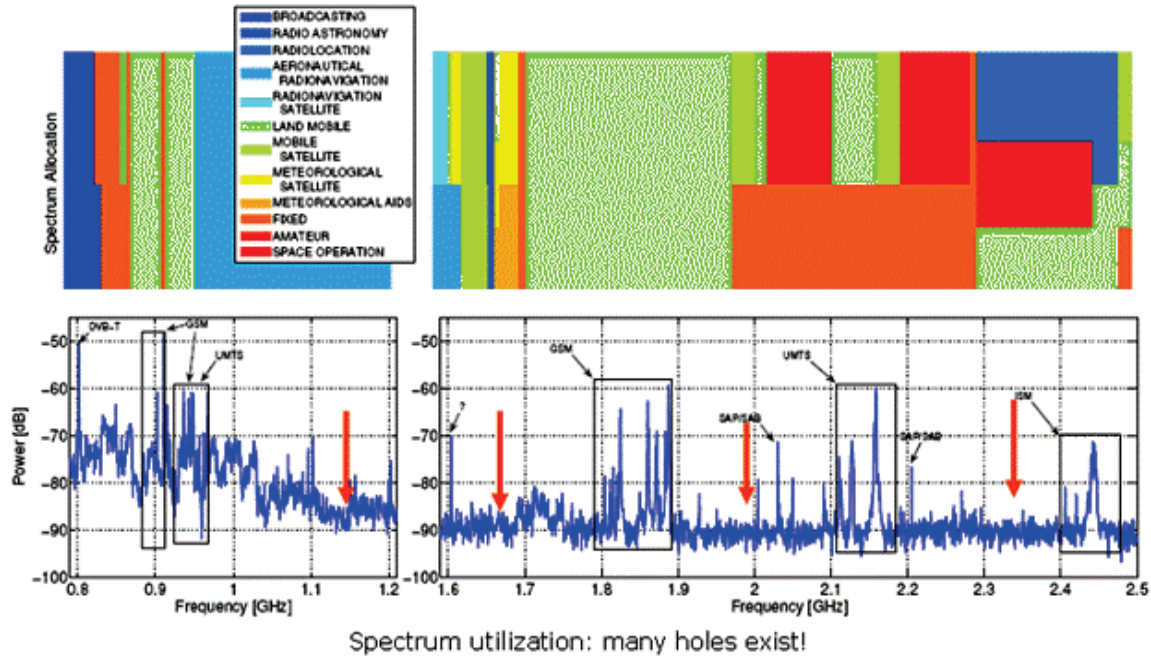


Figure 1.1: Spectrum usage [70]

given time. Thus, by solving the spectrum efficiency problem through increased utilization of the most frequency bands, the spectrum scarcity problem could be solved on the congested bands.

The motivation behind the invention of new radio technology arose from the case of under utilization of the spectrum and the speedy growth of wireless mobile devices. Joseph Mitola [58] proposed the cognitive radio (CR) in 1999, to solve the spectrum inefficiency. According to his proposal, unlicensed Secondary Users (SU) should have the access to the licensed spectrum and share it with the Primary Users (PU) under certain conditions. CR can be used in many areas like: wireless networks, smart grid, and wireless sensor networks, military use etc. Research is ongoing to make CR technology feasible, improve quality of service of wireless communications using CR, and build new applications leveraging CR features.

Working Principles of Cognitive Radios

Cognitive radio is a kind of software defined radio (SDR) where many features of the radio can be controlled by software as opposed to the traditional hardware-based approach. CRs

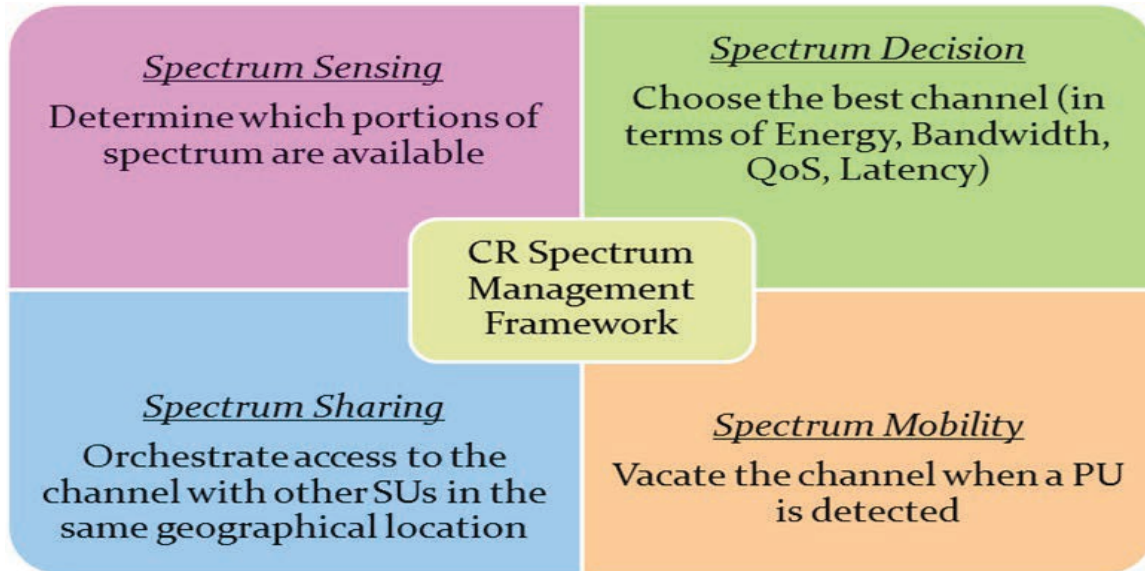


Figure 1.2: Basic operation flow chart [2]

have greater flexibilities as compared to the traditional radios where they can easily switch from one frequency to other. This flexibility comes with certain conditions. Each channel has a PU who is allocated spectrum to; SUs can utilize this spectrum if the PU is not using it. SUs must however either move out of the channel or reduce their transmit power (to reduce interference) as soon a PU begins using it. Thus, each SU must employ what is called the CR-technique to scan periodically for spectrum to move to, and run decision algorithms to decide which new channel may be most appropriate to move to. In addition, each SU must also run PU detection algorithms to vacate channels promptly when a PU decides to use its channel.

The SU follows the basic steps shown in Figure 1.2 to use legacy bands occupied by PUs. They are: i) spectrum sensing ii) spectrum decision iii) spectrum mobility and iv) spectrum sharing. A CR network works differently based on the type of network architecture as shown in Figure 1.3. In an infrastructure network, there is an access point (AP) to co-ordinate communications. Each node scans all or a subset of the channels and updates the AP on the viability of those channels. After getting the scanning result, AP decides which channels are available to use for network operations and assigns channels to specific nodes for use. In an

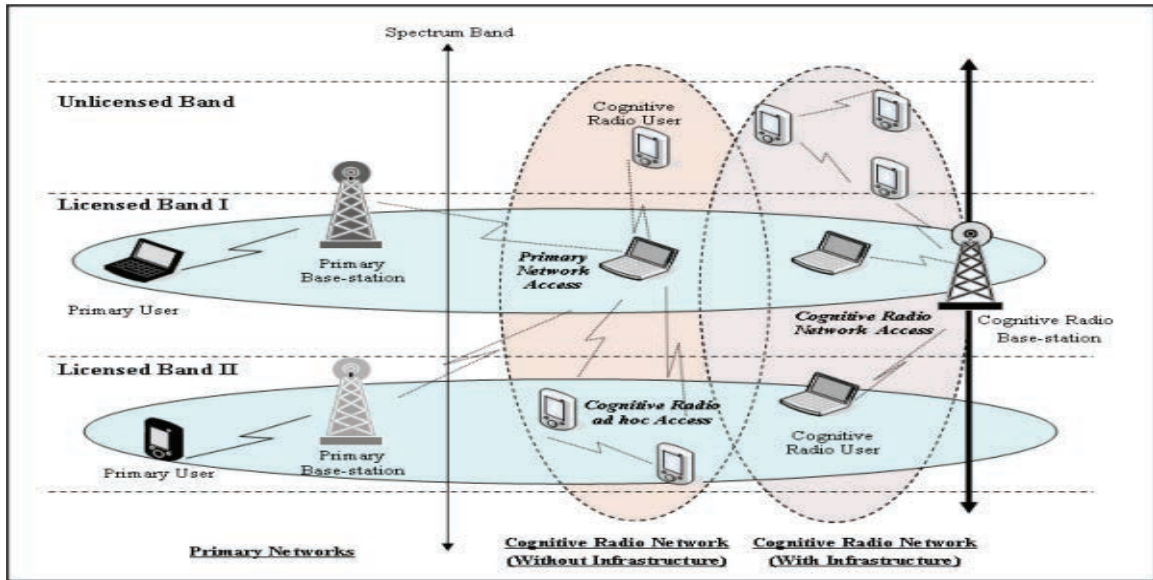


Figure 1.3: CR network, [85]

ad-hoc network, all the nodes have the same responsibilities. When they need to send data they scan the channels to select the best one for their communication. A common channel exists for coordinating operations of the network which every node monitors. A receiver and transmitter pair use this common channel to complete the spectrum selection process. After selection, both the transmitter and receiver can move to that channel and start sending data. They check their current channel periodically to see if any PU shows up or not.

Need for Studying Energy Consumption

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. Energy consumption is one of the most important issues to consider in developing new features and applications in mobile battery operated devices. Battery technology has typically not kept with the increasing rate of energy needs to run applications. The fact

that the success of the CR technique depends on a power-intensive scanning 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 lifetime.

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 carrier sense multiple access (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.

Scope of Contributions

In prior work, Mandayam [54] pointed 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, the focus of this work would specifically be on WLAN devices with a goal of gaining 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 understanding 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 such as cellular data networks and wireless sensor networks.

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. The biggest difference of this work over prior work in the literature is its focus on a general scenario where multiple nodes compete to find and utilize spectrum for communication. Prior research has typically looked at PU related aspects of CRNs (as will be shown in the

later chapters of this dissertation) 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. This work assumes that the energy consumed for control and coordination on the common control channel is negligible compared to the energy consumed for data communications with a receiver. This assumption typically holds for all cases except highly dynamic (and rare) environments where a node changes spectrum at a rate insignificant compared to the number of packets it communicates.

Contributions

Through a survey presented in Chapter 2, we classify prior research done in the area of CRNs with energy consumption implications. This sets a good base to understand the state of the art and to identify what areas need additional research in terms of energy consumption and CRs. Prior research was classified into three broad categories: dynamic spectrum access, hardware, and protocol design. In each category, there has been a great amount of work done to improve the performance, functionality, quality of service, and even legality of the CR paradigm. Many of the proposed approaches were found to have implications to the energy consumption of CRNs, and were thus described in the survey even if exploring energy consumption aspects was not the primary focus. Additional research directions in the area of CRNs with a more explicit focus on energy consumption where more work needs to be done is also identified.

In Chapter 3, we present an analysis of the energy consumed by CR-based radios when competing amongst themselves to find and utilize spectrum for communication. Numerical evaluations compare 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 are proposed for CR-based nodes that result in considerable energy savings for a CR-based node compared to a conventional radio under certain conditions. The results in this chapter are for a static scenario with a constant channel packet error rate and fixed node populations. However, the analytical results in this chapter can serve as a useful guideline for static scenarios with more or less constant channel conditions across the spectrum under consideration.

In Chapter 4, we study the energy consumption of CR nodes under dynamic channel conditions. This work takes into account both the physical layer as well as higher layer aspects and evaluated four channel scanning schemes (first proposed in Chapter 3) under dynamic channel conditions. A CR node employing any of the four proposed scanning schemes was found to save energy even in highly dynamic channel scenarios with high channel load variability. However, in conditions of low channel load variability, only two of the four schemes were found more likely to save energy due to more conservative scanning approaches that don't waste energy, looking for better channels when one may not be available.

Thus, through these contributions, advances are made to model, analyze, and evaluate the energy consumption aspects of CRs, an often overlooked aspect. Additional future work that can be done along the research direction taken in this dissertation is discussed in Chapter 5 along with concluding remarks.

CHAPTER 2

LITERATURE SURVEY IN THE AREA OF CRNS WITH ENERGY CONSUMPTION IMPLICATIONS

2.1 Introduction

Prior work on the Cognitive Radio (CR) technique has mainly dealt with aspects such as spectrum sensing, co-existence of primary and secondary users, and channel access. There has been relatively less emphasis on studying the energy consumption implications of this revolutionary paradigm. The energy consumption of the CR technique is particularly relevant when used in battery-life constrained mobile devices. This article provides a comprehensive survey of research done in cognitive radio networks with implications to energy consumption and what future areas need to be explored in the future. Aspects covered include dynamic spectrum access, CR hardware, and protocol design.

Cognitive radio (CR) is defined as a form of wireless communication in which a transceiver can intelligently detect which communication channels are in use and which are not, and instantly move into vacant channels while avoiding occupied ones [68] or share a used channel at a lower power. This characteristic distinguishes CRs from conventional radios, which do not have spectrum-scanning capability.

The motivation behind the emergence of cognitive radio technology according to [9] and [82] is the under-utilization of the spectrum and the rapid increase in the number of wireless mobile devices. Studies have shown that only 6% of a fully occupied spectrum is actually used [82]. In 1999, Joseph Mitola proposed the CR [57], as a solution to the need for full-spectrum efficiency. This meant that the spectrum could be used or shared by an unlicensed secondary user (SU), to access the licensed spectrum and possibly share it with the licensed primary user (PU) under certain conditions. As a result, the research to evolve the CR has been increasing steadily in all directions. Various applications such as, wireless networks [78], smart grid [92], wireless sensor networks [17], and military use [31], among others,

have since been adopted for the CR applications [27]. To support different applications, CR networks should have the following characteristics: be energy efficient, fulfill quality of service (QoS) requirements, and be capable of overcoming the challenges brought about by the heterogeneous nature of the network environment [81]. The focus on energy consumption is important especially in mobile devices that have limited battery capacity and considering CRs in particular spend a large amount of energy scanning [10]. Saving energy consumed by information and communication technologies aligns itself with broader environmental sustainability goals as well [72].

In this chapter, we survey the literature for prior research done for CRs that may have implications for the energy consumed by these radios. In this work we classify such work into three broad categories: **dynamic spectrum access (DSA), hardware, and protocol design**. DSA is a method of obtaining a communication medium by either sharing or opportunistic scanning for free channels and can be additionally grouped into the two categories of sensing and co-existence. The hardware category covers energy-related work at the hardware level of three main aspects of CR: antennas, power amplifiers (PAs), and software defined radios¹ (SDRs). Finally, the protocol design category covers research done on protocols in the upper and lower layers of the network stack to form and manage a CR network. To the best of our knowledge, this is the first survey that looks at research on cognitive radio networks from a energy consumption perspective. Figure 2.1 shows the complete classification tree that will be discussed in this chapter. Through there can be overlaps among sub-trees in the nature of work done, each work discussed contributes primarily along the lines of its branch in the classification tree. In the next two sections (Sections 2.2 and 2.3) we describe the research work done in each of the three broad categories, with additional details and insights on the direct or indirect implications to energy consumption. Dynamic spectrum access is the area with the most amount of research with implications to energy

¹SDRs are in this category even though they involve software because they serve as hardware-replacements by replacing traditional components built on hardware.

consumption, but the other areas of hardware and protocols are also growing. A summary of this survey along with directions for future research in energy consumption related aspects of CRs is presented in Section 2.4.

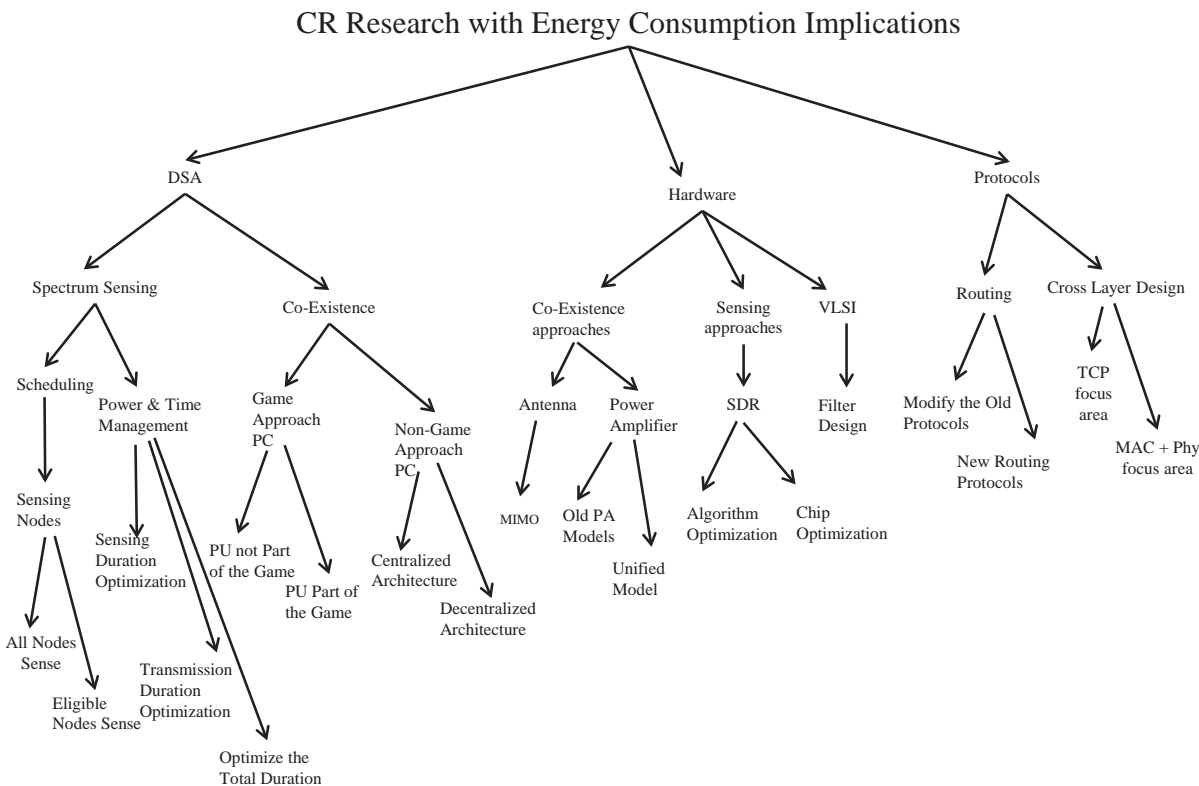


Figure 2.1: Overall classification tree

2.2 Dynamic Spectrum Access

DSA is a broad term covering different types of spectrum access. It can be categorized as a dynamic exclusive-use model, open sharing model, or hierarchal access model [67]. The aim of the first model is to increase spectrum efficiency by allowing the spectrum owner to rent out part of its share when it is not being used. This model is considered to be dynamic spectrum allocation rather than access. It includes no changes on the original basic structure and hence no changes from an energy point of view.

The second model is also known as the spectrum commons [90] and [86]. As it allows spectrum sharing only between the peer users of the unlicensed band, this model has little or nothing to do with energy efficiency. In both models, there is no need to scan the spectrum or to adjust the transmitted power because the users either rent the unutilized spectrum or use the free unlicensed bands.

Under certain constraints, the third model suggests that the secondary user (SU) can benefit from the unutilized spectrum. It can either share the same channel with the primary user (PU) or it can use the unutilized channels of the PU. The first method requires the SU to adjust its power so it does not cause service degradation for the PU. while in the second method, the SU must scan the spectrum to make sure that the PU is not using the channel at that particular time. Both models have a strong relationship with the energy and power consumed by the radios and the network. The hierarchal access model has two approaches, sensing and co-existence. Various authors might have used different names to describe these approaches. Opportunistic spectrum access and non-opportunistic spectrum access, or overlay and underlay spectrum access, are different names for the same approaches [67]. The following two subsections survey the energy-related work in these areas.

2.2.1 Spectrum Sensing

The sensing aspect of CR mainly deals with finding the right spectrum to use for communication, as introduced in the seminal paper [57]. This involves finding a 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 [94, 21, 64, 16, 33, 75, 80, 51]. Further, the detection and avoidance of primary users 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 [7, 43, 44, 45]. Some important considerations include the determination of the duration to sense the channel [82, 25] and

the duration to communicate packets [50]. In [39], authors proposed a new MAC protocol to optimize the scanning time. They used only one radio for both channel scanning and data transmission.

Out of the four main functions of the CR (sensing, management, mobility, and sharing), sensing is considered to be the key function [37]. At this point it is important to distinguish between sensing and scanning. The SU senses one particular channel to check whether it is being used by a PU or not. However, multiple channels are scanned by one or more SUs. As scanning is energy intensive, the energy consumed in scanning is classified as the number one problem that might delay the advance of CRs [79].

There are two types of channel sensing: cooperative (or collaborative) and non-cooperative. Regardless of the sensing method, detection and decision-making methods are almost the same for both types of scanning. One detection criteria is energy detection (ED), where the PU is detected based on the energy it emits while it is active. ED is considered the simplest technique and requires no prior knowledge about the PUs signals, which makes it the most preferred over cyclostationary feature detection and compressed sensing [67].

The two well-known decision-making methods are the hard fusion decision (HFD) and the soft fusion decision (SFD) [67]. In the HFD, the SU makes its own decision and decides whether the PU is active or not. It sends either zero or one to a fusion center (FC) or to a central node, in cooperative sensing, where the final decision is made. In the SFD, the SU collects and sends the collected information to the FC, rather than making the decision itself.

In terms of total network energy and sensing overhead, non-cooperative sensing is more efficient since not all nodes have to do the same job; that is, one node is selected to handle controlling and messaging between the nodes. In addition, non-cooperative sensing requires no synchronization between the SUs, which makes it easier to implement [67]. However, the main idea behind CRs is spectrum efficiency. So, when it comes to accuracy and spectrum

utilization, not to mention its throughput capability, cooperative sensing excels. Cooperative sensing overcomes important problems such as shadowing and fading effects as well.

In cooperative scanning, multiple SUs collaborate to form either a centralized or clustered structure. In the centralized structure, multiple SUs scan the spectrum, individually searching for active PUs. The collected data is sent to the closest FC that makes the final decision. The FC then allocates the available spectrum to one or more SUs. However, in cluster-based cooperation, SUs form clusters based on specific criteria. Each cluster has one dominant node (DN). The nodes in each cluster scan the spectrum and send the collected data to the DN, which in turn communicates with the FC for the final decision and spectrum allocation.

As there many more complexities in distributed operation in cooperative sensing, related work can be further classified based on in two ways: scheduling, and power and time allocation. The following two sections discuss the related work in the literature.

Scheduling

The number of SUs and the way they collaborate define scheduling in cooperative sensing. Multiple nodes are distributed equally to scan multiple channels in the scenarios considered in [97] and [53]. The FC decides the number of SUs that should sense each channel to form a centralized architecture. Based on the maximum immediate reward, a decision is made. The work in [97] shows that the best combination is to distribute the SUs evenly between the channels. It was proven in [53] that all available nodes should participate in sensing to achieve the optimum results. Instead of utilizing all SUs,[52] and [87] found the optimal number of nodes that should scan under specific conditions. The minimum number of nodes to satisfy the minimum required false alarms and spectrum efficiency is found in [52]. The network total energy is reduced since the number of required SUs to sense the spectrum is reduced. In [87], the optimal number is derived under the SNR, BER, and transmission distance parameters. The better the channel conditions, the lower the BER, and the closer the SU to both the PU and the FC, the less transmission power that is required.

The compromise between [97], [53], and [52], [87] is proposed by [19]. Not all SUs sense the channels or the minimum number of channels that satisfies particular conditions. Only eligible ones can participate in the scanning. Based on particular criteria, the SU gains or loses the trust to sense. Trusted nodes sense the spectrum, while those that are not trusted refrain from sensing the spectrum. This waives the unnecessary transmission and hence reduces the amount of energy consumed. The authors of [97] added the effect of assigning more SUs to sense one specific channel and keep some channels without scanning. In addition, they considered the QoS of the SU. Their results show that assigning more SUs achieves a higher scanning performance. However, this keeps some channels from being sensed, which leads to spectrum deficiency [77].

Similarly mechanisms have been proposed for cluster-based scanning. Three different pieces of work focused on determining the optimum number of SUs that should scan the spectrum [20], [61], and [49]. A channel-sensing zone is defined based on the PU's maximum transmitted power [49]. The SU with the best remaining energy within that zone is selected as the DN. The DN selects the remaining zone members using available information about the received signal strength indication. Based on each node's residual energy and its neighbors' residual energy, the sensing nodes are determined. The energy of each cluster is minimized because only few nodes can scan and only one of them can communicate with the FC. The network's lifetime is increased as well. The cluster formation in [61] is slightly different. The DN is selected based on the best channel conditions toward the FC. The remaining nodes in the cluster are selected based on their relative residual energy. This technique differs from [61] in the way the cluster members and the DN are selected. Like [20] and [61], sensing zone boundaries are confined by the transmission range of the PU [49]. Simply, all one-hop neighbors within that range are the cluster's members. There is no FC here since the ad hoc scenario is assumed. Furthermore, the reinforcement learning-based sensing algorithm is selected. In [23], the sensing group is divided into subsets. Each subset of SUs is active only for a certain period of time. The remaining subsets are set to sleep. This proposal extends

the network's lifetime by optimizing the number of subsets, the nodes in each subset, and the sleeping scheduling.

Power and Time Allocation

Time and power allocation is a useful technique to efficiently save energy. In general, the sensing duration is divided into two periods of time: sensing time and transmission time. Sensing time is the same that the SU spends sensing the spectrum, while the transmission time represents the time while the SU communicates with either the FC or the DN in the cluster. Excluding [61], all papers mentioned in the scheduling section assume a fixed-sensing duration.

The existence of such a period that satisfies the optimal balance between energy consumption and system throughput is proven by [24] and [63]. The sensing duration is selected to satisfy the best throughput. Subsequently, optimum sensing and transmission times are calculated based on each other. Longer sensing duration makes the transmissions time shorter which causes more accurate results and better spectrum utilization. The optimization problem for the above scenario was not solved in [24]. Numerical results show that it is possible to save up to 47% of the energy by varying transmission and sensing times. In [63], however, researchers analyzed the time spent in each state: sensing, transmitting, and idle in the SUs. They quantified the time for both sensing and transmissions that satisfied the best throughput and minimized the energy consumed under different power capacities. The sensing time is divided into the number of time slots in [32]. The number of these time slots is selected intelligently. Each SU scans different channels in the assigned time slot. This technique needs no communication of control messages between users. Compared to the other sensing mechanisms, the proposed one was shown to be less energy consuming.

A sensing strategy of when to sense and when to transmit, in order to achieve maximum energy efficiency, is studied in [94] and [83]. The optimal power allocation is considered as well. The proposed algorithm for both was evaluated numerically to prove its efficiency

in terms of spectrum access and energy saving. In addition to this, in [83] the authors considered a protection technique for the PU.

Sensing duration and power allocation have an intimate relationship, and both can contribute to saving the energy consumed by the CR. The joint sensing and power allocation problem is studied in [89], [73], and [26]. In [89], a non-convex game is used to solve the proposed problem with some relaxation on the Nash equilibrium (NE). In [73], however, the proposed problem is convex. An algorithm to increase the transmission rate while not increasing the power required is proposed and is proven to be efficient. The work in [26] introduced an orthogonal frequency division multiple access risk return model. Based on that model, a convex optimization problem was set and simplified in a way that reduces the computation complexity and hence the power consumed. The proposed model takes into consideration both system reliability and interference constrain, let alone the power allocation. The ad hoc network scenario is assumed in [11]. The optimization problem was set based on the maximum power limit and the required data rate. An efficient power allocation algorithm is proposed. The proposed algorithm was shown to be efficient in terms of the battery lifetime.

2.2.2 Co-Existence

The non-sensing model of the DSA expresses the co-existence condition of the SU and the PU. This is the case when the SU is using the same channel at the same time with the PU even when it is active. Here, the SU must adjust its transmitted power so that it does not interfere with the PU. A power control (PC) technique is being used to adjust the SUs power in most of the papers in this area. In general, power control is used to purposely adjust the transmitted power of the transmitter to achieve one or more goals. These goals could be maximizing throughput, minimizing delay, guaranteeing fairness, improving capacity, and improving energy efficiency [56], in addition to utilizing the spectrum [14]. Satisfying one goal might contradict satisfying another. Hence, tradeoff between goals becomes an

indispensable need in PC. For example, the higher the transmitted power, the better the throughput. However, higher transmitted power means that more energy is consumed.

Applying game theory to achieve the required balance between goals is coherently used in the literature. However using game theory is not the only way to control power, as explained later in this section. A game is defined by a set of players, a set of actions for each player, and the payoffs for each player that are defined by the utility function [5]. The players' strategy is declared once the required actions and plan are completely set. Each game has a solution, and this solution should be unique for the game to be successful. In CR, the players could be the SUs or both the SUs and PUs. Actions and payoffs vary from game to game. Most of the actions are related to power control, while most of the payoffs are spectrum access for the SUs and financial reward for the PUs. Players in the cognitive radio network (CRN) are usually individual players, and they play selfishly to satisfy their individual interest. In other words, a non-cooperative game is involved in these games. The following two sub-sections classify the related works into either game approaches or non-game approaches for power control.

Game Approach for Power Control

Different network scenarios, utility functions (UF), and suggested solutions for the same problem are proposed in the literature. One scenario proposed by [14] is that the SU communicates a secondary access point (SAP), while the PU communicates a primary access point (PAP). Only the uplink is considered in the calculation. It is also assumed that the PAP communicates the maximum allowed SU transmitted power to the SAP. Although, the primary network helps the SU to access the spectrum, PUs never play the game with SUs. The goal of each SU is to receive its packets correctly with as minimum as possible transmitted power, although, the utility function is set to be the ratio between the throughput and the transmitted power. It was proven that there is a unique point for that UF that benefits the SU with the minimum required transmitted power. Extended work by the same authors is done in [15]. The same scenario is assumed, yet they added a receiver design

with the ability to compute and predict the transmitted power at NE. They finally defined a procedure that helps in performance production for a large network.

Based on the capabilities of the SUs, two different scenarios are suggested in [28]. The first assumes that some radios have the ability to sense, while others do not. In other word, radios are categorized into cognitive and non-cognitive. The second scenario assumes different sensing capabilities for radios. Their capabilities to sense vary gradually from zero non-cognitive to super cognitive best-sensing capability. To assure fairness between radios, both scenarios impose the power control game, as it is the only way for non-cognitive radios to access the spectrum. The utility function in [28] is similar to that in [14] and [15], yet the game is Stackelberg and includes hierarchy in the decision making. Results shows that non-cognitive radios outperform cognitive radios in terms of energy savings. At this point we can conclude that, in general, non-sensing DSA is more energy efficient than sensing DSA. The work in [18] focuses on increasing a system's capacity and throughput without necessarily increasing the transmitted power. The authors assumed code division multiple access (CDMA) technology because it decreases interference at the PUs side, increases SU throughput, and increases the system capacity. Unlike [14], [15], and [28], the utility function in [18] was obtained based on the relationship between the signal-to-interference-ratio (SIR) threshold and the SIR of the user. Simulation results agree with their calculations, which prove the system's overall efficiency, including energy.

The authors in [59] worked on two scenarios: orthogonal and non-orthogonal signals. The Stackelberg game was set similar to [28]. But the utility function in the case of the orthogonal signals was built to be more instantaneous. This allows the SU to exploit the spectrum more efficiently and to benefit from every time slot instead of counting on the average model of the UF. It was shown that the long-term energy constraint in this model is efficient and reduces the interference to a great extent and hence reduces the power required to transmit. The more practical utility function is proposed in [88]. It considers the dynamic channel parameters like gain and noise since in reality both of them are time-variant parameters.

Their proposed PC is shown to be beneficial relative to long-term energy efficiency as well. Joint power and rate control are considered in [74]. The utility function is similar to both [5] and [15], but with dual pricing parameters. The pareto efficiency and the ability to reduce the power level was simulated and obtained numerically as well as theoretically.

The previous works in this section have focused on the power control approach when the game includes only a set of SUs. The influences of PUs are considered in [47] and [38], where the PU is considered to be part of the game and must set its own UF. Two utility functions were set in [47] for the PU and SU. The SU's utility is similar to that in [28] while the PU's utility consists of three parts. The first part is to assure the QoS of the PU, and the other two parts are pricing factors. The PU is assumed to be rewarded for collaborating with the SU to share the spectrum. Participation of the PU was proven to be energy efficient for the SUs. The authors of [47] have recently introduced another work in [38]. They integrated a penalty part to the PU's UF. The PU is penalized if it did not meet the transmission quality. Receivers in [47] are different than in [15], which also contributed to developing the overall results. Other than boosting the QoS, the new system has increased the number of SUs that can transmit efficiently.

Non-Game Approach for Power Control This section introduces different methods to control the power to assure a safe co-existence between the PU and the SU. Power control in this section can be categorized as centralized and decentralized [38]. For the centralized PC, a particular node controls the power for the rest of the node within its transmission range. In the decentralized PC, each node controls its own power based on the available information at that node. More information about the PU is required for the decentralized structure. Two distributed PC schemes were proposed by [38], whereby the SU must switch between them to meet the QoS requirements for both SU and PU that were previously defined. The proposal was shown to be efficient using the minimum required transmitted power.

A power control for the ad hoc cognitive network is suggested by [65]. The problem was formulated to maximize the energy efficiency of the SU. Two different solutions were

introduced: centralized and distributed. Results showed that both are efficient in terms of energy, and the proposal is flexible to suit different spectrum access technologies. The work in [34] uses the energy required to achieve particular requirements as metric. They eventually introduced an inverse power control technique. The technique states that if the transmitted power of the SU exceeds a certain limit and brings about any quality degradation to the PU, then it interrupts the SU's transmission. The inverse power control proved its ability to save energy. The only side effect is that at some point, when the SU does not meet the conditions, it should stop transmitting. The SU then might have to sense for another channel.

The power allocation mechanism when the sensing is imperfect and includes errors is considered in [62], imperfect sensing is used to express the case when co-existence is required instead of finding free channels. In this case, the SU should adjust the power so that it does not interfere with the PU. The proposed algorithm helps to save valuable resources, like battery life and spectrum. Similar to [15], the work in [66] assumes the hybrid network structure. When the SU shares the same frequency as the PU, it must decide the amount of required transmitted power. Otherwise, the SU must find a free channel on which to transmit. A convex problem and its solution to optimize the power allocation and minimize energy consumed are addressed. The authors in [91] studied the energy consumption supported by adaptive modulation and power allocation. They defined two steps where the cognitive radio can control the power. The analysis shows that the CR can greatly increase the power efficiency and reduce the energy consumed. Joint power and rate control channel access are proposed in [74]. The goal here is to maximize the system capacity and reduce the consumed power. Similar to [65], the system model assumes an ad hoc scenario.

2.3 Hardware and Protocol Design

The other broad area of work in cognitive radios is in the area of hardware and protocol design. In these areas we examine research done and how they relate to energy consumption. Note that there can be overlaps between hardware, protocol design, and even DSA discussed

in the previous section; for example, an proposed approach may be jointly implemented in software and hardware, but may be related to DSA. However, papers presented in this section can be termed to be primarily a contribution in hardware or protocols for CRs as opposed to just a DSA algorithm or mechanism improvement.

2.3.1 Hardware

The energy-related hardware work in the literature sheds light mainly on three parts of the CR device: antennas, power amplifiers, and software defined radios. This is justified for the PAs and SDRs since they are considered to be the most power consuming parts of radios [96]. It is also justified for antennas, as correctly exploiting the antennas helps in increasing the gain of the signal, increasing the transmission rate, reducing the noise, and hence reducing the required transmitted power [35]. The literature is filled with papers in these areas and many other areas concerning the hardware; however, only a few of them correlate the work with cognitive radios. In general, papers on antennas and power amplifiers support the co-existence approach of the DSA, while works on SDRs address the sensing approach of the DSA. Antennas and PAs can be considered power-control tools, while SDRs support algorithms like scanning and scheduling.

The framework proposed by [35] supports the co-existence approach using the relaying technique. SUs are supported by multiple input multiple output (MIMO) antennas that help in improving the spectrum efficiency. Under this scenario, an optimization problem was set and solved using Stacklberg game theory to maximize the utility function of both SUs and PUs. Results show higher utility functions compared with utilities with no MIMO techniques. This work shows how antennas could help in bringing better channel conditions to the system and how they contribute in energy efficiency. Unlike [35], the work in [98] assumed a non-cooperative scenario. Radios are assumed to have MIMO interfaces. The goal of each node is to maximize its energy efficiency. A power-control problem was set to satisfy QoS and solved using game theory. The contribution of the power amplifier in minimizing

energy usage is addressed by the same authors in two works, [30] and [29]. In [30], they suggested a framework that showing the effects of components like the PA characteristics on the energy consumed by the cognitive radio for a given quality of service. They concluded that minimizing the energy consumed in transmission is useless when considering the adaptive modulation without considering the PA efficiency characteristics. Similarly in [30], the authors worked on the system and the circuit levels together to extend their work in [29]. They first proposed a unified PA efficiency model that eases the analysis of the impacts of the PA on the energy efficiency. Then they considered a realistic PA in their investigation. The proposed unified model was shown to be applicable in reality and for all of the PA classes. In addition, it was shown that the ability of the new model of PAs to utilize radio resources is better than the older classes of PAs.

As mentioned above, most papers on software defined radios concentrated on the sensing approach of the DSA. Starting with the multi-standard wireless SDR design proposed by [13], suggests a top-down methodology that supports the spectrum sensing idea. In addition to the cost of hardware and the scalability, power management and energy efficiency were considered in the design. The design was tested and showed high performance in terms of energy efficiency and power management. The second work in the area of SDRs is done by [3] using a homogenous multiprocessor system on a chip, the authors are suggesting a new algorithm for CR using fast Fourier transform (FFT) realized on hardware. The algorithm was evaluated and results show that using the FFT technique helped in decreasing the computation time and decreasing the energy consumed accordingly.

Another hardware work, which is on neither the SDR nor on the PA is proposed by [93]. A VLSI filter design that reduces the power consumed in the sensing process is introduced. Three steps toward the goal are pursued. First, the filter works on reducing the complexity of the conventional sensing tools by using a cascading filter bank. These banks use FFT blocks to reduce the sensing time and hence minimize the power consumed. Second, a new sensing scheme is proposed that helps enhance the channel parameters signal-to-noise ratio (SNR).

Finally, an interference cancelation method is proposed. The proposed VLSI design was finally evaluated to show an impressive reduction in the sensing duration and consequently the energy.

2.3.2 Protocol Design

The channel access aspect of protocols for CRs can be classified based on the type of network architecture: infrastructure/centralized or ad-hoc/decentralized. 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 [48] for infrastructure CR networks is a random-access protocol that relies on differentiated access to the medium for packets from or to primary users, 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 [36]. 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 the responsibilities of forming packet-forwarding routes and time synchronization, if required. Proposed protocols in the literature can be classified further based on whether nodes have one or multiple radios [51]. Comprehensive scanning is not realistic for real-time data transmission. The authors worked on sensing order in [40]. Further reading on MAC protocols for CR can be found in the survey in [22]. The work in [96] 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 [55] 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 [28] presents techniques for reducing energy consumption of a cognitive radio. Their work mainly targeted towards

physical layer adaptations involving the power amplifier, modulation, coding, and radiated power.

The dynamic nature of cognitive radio networks makes the design of higher-layer protocols challenging. Routing, for example, takes place in three consecutive steps: finding all possible routes, selecting a particular route, and then maintaining the selected route [33]. Many routing protocols for CRs are proposed in the literature. However, this section concentrates only on chosen that have considered energy consumption in their designs. The work in [33], for example, generally compared routing in the cognitive networks with routing in non-cognitive networks. A survey for the available routing protocols was also done. Then, the authors applied two of them, load distribution (LD) and transmission power control (TPC) to the CRN in order to reduce and balance the energy respectively. They finally suggested additional energy-efficient protocols for future work. Another energy-efficient routing protocol for the ad hoc CRNs is introduced by [41]. The protocol considered the QoS of the users as well. The proposed on-demand protocol is the joint routing and channel slot allocation protocol. This protocol assumes that only one node acts as a controller that controls the data and messages exchanged among the nodes. Because of this architecture, the energy consumed by the entire network is reduced. In addition, the on-demand nature of the protocol contributes to the energy savings of each node. After evaluating the protocol, the ability to increase the lifetime of each node was shown. As a result, the protocol improved the entire lifetime of the network. The authors of [41] have proposed another similar energy aware protocol in [42] which considers the effect of contention on energy and proposes balancing the energy consumed across nodes.

Instead of designing a routing protocol, the proposed work in [71] suggests a network architecture and algorithm that optimizes the routing information in a way that preserves the capacity of the battery. In addition, each node must use an algorithm that helps that particular node in monitoring its own battery and link quality. The proposed technique was tested many different times and succeeded about 87.5% of the times. A cross-layer design

is considered in [69] and [46]. In [69] authors considered the power control at the physical-layer level. Their design was built on the game theory technique. They introduced a power savings model that leaned toward energy efficiency as well. Their evaluation, however, was on the MAC level. They monitored the system performance for different parameters including energy. The authors in [46] first analyzed the energy performance of the TCP traffic applied on the CRN, considering parameters like SNR, modulation schemes and frame size in their analysis. The analysis output was used to design a cross-layer protocol to achieve energy efficiency without modifying the original TCP traffic. The simulated results show how the lower parameter could affect the energy on the TCP.

2.4 Concluding Remarks of This Chapter

In this chapter we classified prior research done in the area of CRNs with energy consumption implications into three broad categories: dynamic spectrum access, hardware, and protocol design. In each category there have been a great amount of work done to improve the performance, functionality, quality of service, and even legality of this new paradigm. Many of the proposed approaches have implications to the energy consumption of CRNs, and were thus described in this chapter, even if exploring energy consumption aspects was not the primary focus. In this section we would like to point out some additional research directions in the area of CRNs with a more explicit focus on energy consumption where more work needs to be done. Some of these directions are complementary to existing work done to advance CRNs and constitute another stage in making CRNs more viable in special use (e.g. military) and everyday communicating devices.

2.4.1 Scanning Algorithms for SUs

The goal of any scanning algorithm employed in SUs is to find and compare possible spectrum to which a radio could switch to. Scanning spectrum is an energy-intensive process as it involves monitoring one channel at a time for specific time intervals. Monitoring a

channel involves processing (receiving and discarding) all communication in the form of packets on that channel. Even when a channel is idle with no packets communicated, the receiver has to wait in a high power idle mode as opposed to a lower power sleep mode. It is not clear from prior work what is the best approach to scan for spectrum in an energy-efficient manner. On one hand, locating spectrum that is ideal for communications (for e.g. in terms of bit error rates) will reduce energy consumed for subsequent communications on that spectrum. On the other hand, continuous scanning to locate such spectrum is energy-intensive presenting a tradeoff. Some preliminary work has been done in this area [9], but there is a need for more studies.

2.4.2 Modeling of energy consumption of SUs

A more broader approach to studying the energy consumption of SUs is needed, that includes not just modeling energy consumption for dynamic spectrum access, but also modeling the impact of PU detection and various protocols and cross-layer interactions. To the best of our knowledge, there is no work focusing specifically on modeling various aspects of the energy consumption of SUs. Most of prior work has focused on the performance aspects of SUs, but not on the energy aspects. SUs could easily be battery-operated mobile devices that will need to consider battery life in addition to performance in locating desirable spectrum and utilizing it. Developing such energy consumption models would allow researchers to study tradeoffs between performance and energy consumption, and also include energy as another dimension to be considered as part of decision making in CRNs.

2.4.3 Prototype implementations to evaluate energy consumption of CRNs

With greater number of hardware platforms available to implement and deploy CRNs like the USRP and USRP2 from Ettus Research, it has become easier to study hardware and protocol implementation aspects. However, these platforms are still cumbersome to use for energy consumption studies. For example, it is not easy to isolate the energy consumed by the transceiver from the rest of the platform. Additionally, the form factor of these platforms are

likely to be much more bigger and bulkier as there built as general-purpose hardware while actual deployments in the future will be more specialized, application-specific hardware. Thus, there is a need to build and make available more CRN platforms to the research community that are friendly to energy consumption studies. Researchers also need to work on studying CRNs to understand the energy consumed by various hardware components and subsequently improve associated analytical models. Prototype implementations are also the best way to study various protocols, their effectiveness, and energy footprint.

CHAPTER 3

SCANNING SCHEMES AND ENERGY CONSUMPTION ANALYSIS OF AN AD-HOC WLAN CR NODE UNDER STATIC CHANNEL CONDITIONS

3.1 Introduction

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 is the 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.

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 [57], 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 [55].

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 chapter 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 chapter we make the following technical contributions: (i)

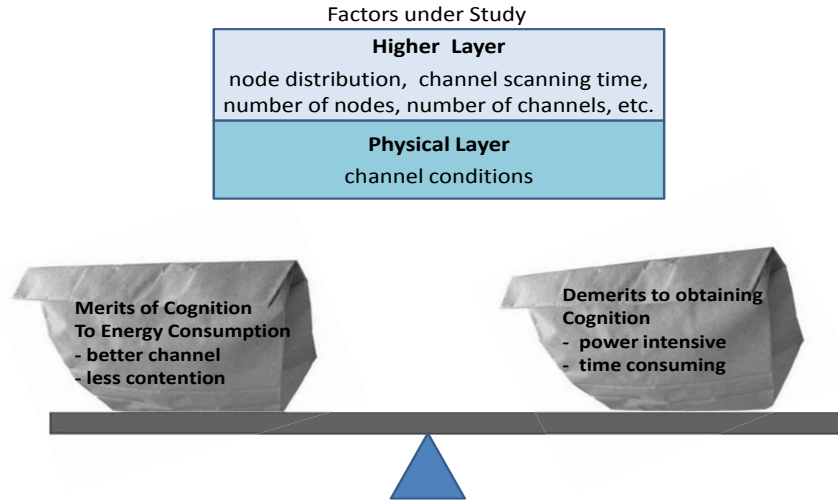


Figure 3.1: Determining how a CR-based node in the ad hoc WLAN scenario compares to a non-CR node in terms of energy consumption considering the energy cost of scanning for spectrum, and possibly any energy saved by finding a better channel.

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 chapter. 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. [7, 43, 44, 45]). In this chapter 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 off not employing CR techniques. This chapter helps to 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 chapter is organized as follows. Section 3.2 briefly surveys the literature on research in the cognitive radio area and discusses the significance of our contribution. In Section 3.3, we define the problem in terms of an energy model and state our goals formally. Section 3.4 presents our analysis of energy consumption with a conventional radio and with a CR-based radio. Section 3.5 evaluates the impact of various parameters on CR-based radio's energy consumption as compared to a conventional radio. Finally, concluding remarks are presented in Section 3.6.

3.2 Literature on Energy Consumption of CR

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 chapter.

The sensing aspect of CR mainly deals with finding the right spectrum to use for communication, as introduced in the seminal paper [57]. This involves finding spectrum that pro-

vides 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 [94, 21, 64, 16, 33, 75, 80, 51]. 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 [7, 43, 44, 45]. Some important considerations include the determination of the duration to sense the channel [82, 25] and the duration to communicate packets [50]. There are two types of channel sensing, cooperative, or collaborative, and non-cooperative. Regardless of the sensing method, detection and decision making methods are almost the same for both types. One detection criteria is energy detection (ED), where the PU is detected based on the energy it emits while it is active. ED is considered the simplest technique and requires no prior knowledge about the PU signals that makes it the most preferred over cyclostationary feature detection and the compressed sensing [67]. In the sense of the total network energy and sensing overhead, non-cooperative sensing is more efficient since not all nodes have to do the same job; one node is selected to handle the control and messaging between the nodes. In addition, non-cooperative sensing requires no synchronization between the SUs which makes it easier for implementation [67]. However, the main idea behind CR is the spectrum efficiency. So, when it comes to accuracy and spectrum utilization, cooperative sensing excels, let alone its throughput capability. Cooperative sensing overcomes important problems like shadowing and fading effects as well. 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 SUs. Since scanning is energy intensive, energy consumed in scanning is classified as the number one problem that might delay the advance of CR [79]. In [39] authors proposed new MAC protocol to optimize scanning time while the authors of [40] worked on finding an ideal ordering of channels to sense.

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 [48] for infrastructure CR networks 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 CR uses the notion of superframes and slots at the base station to control access to the medium [36]. 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 [51]. 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 CR can be found in the survey in [22].

The work in [96] 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 [84] explores energy consumption aspects of CRNs but not on CR-techniques for a broader class of radios independent of PUs. The work in [28] presents techniques for reducing energy consumption of a cognitive radio. Their work 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 four approaches to scan for better spectrum.

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. 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 [55] where the benefits of CR-techniques would be most apparent and useful.

3.3 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.

3.3.1 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.

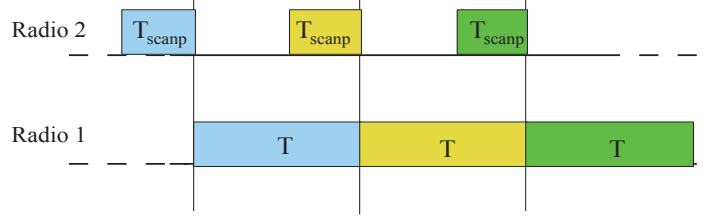


Figure 3.2: Model of communication and periodic scanning with two radios at a CR node.

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 [51, 22]. This occurs for a duration of T_{scanp} before the next unit of time T begins, as shown in Figure 3.2. Later in this chapter, the overall time to scan T_{scanp} considered is shown to depend on the nature of the scanning scheme chosen and not a constant as shown in Figure 3.2 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}_{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 cognitive radio, \hat{E}_{CR} can be modeled as

$$\hat{E}_{CR} = \hat{E}_{pkt}^{k,\gamma} + \frac{\hat{E}_{scan}}{T/\hat{T}_{pkt}^{k,\gamma}}, \quad (3.1)$$

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

$$\hat{E} = \hat{E}_{pkt}^{n,\gamma_0}, \quad (3.2)$$

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

The CR-based node under consideration saves energy for packet communication if

$$\hat{E}_{CR} < \hat{E}. \quad (3.3)$$

Let $f(\gamma)$ be the expected number of re-transmissions needed per packet for a specific channel condition γ . 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

$$\hat{E}_{CR} = \{1 + f(\gamma)\} \hat{E}_{pkt}^k + \frac{\hat{E}_{scan}}{T/\hat{T}_{pkt}^k \{1 + f(\gamma)\}}, \quad (3.4)$$

and

$$\hat{E} = \{1 + f(\gamma_0)\} \hat{E}_{pkt}^n, \quad (3.5)$$

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 chapter we consider only the impact of node contention in our analysis and do not study the impact of channel conditions. Thus, in Equations 3.4 and 3.5 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 γ for different channels once we understand the relative impact of channel contention and channel scanning in terms of energy consumption in this chapter. The results of this chapter 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 3.6.

Thus, now we define a “better” channel as one that has less number of nodes contending for the channel than the *current* channel¹. A new channel is sought to alleviate contention. In Equation 3.4 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.

3.3.2 Application Scenario and Assumptions

It is assumed that every node always has packets to send. This assumption makes sense when comparing a conventional radio to a CR-based radio, as better spectrum is sought when there is high contention on one channel and a different channel with less contention is sought. We assume an ad-hoc WLAN environment in this chapter where nodes are free to choose the channels they wish to communicate on, with no centralized deployment authority similar to the scenario outlined in [6]. This chapter’s focus is on how nodes compete with each other to find and utilize spectrum. As we are not studying a typical CRN 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 the 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

¹At various places in the chapter, we term the newly found channel as the *chosen* channel or *selected* channel.

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.

3.4 Energy Consumption Analysis

In this section we analyze for the components of \hat{E}_{CR} and \hat{E} as given in Equations 3.4 and 3.5. 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}_{pkt}^k . We begin by describing the basic energy model and analyzing the building blocks required to compute \hat{E}_{pkt}^k . Subsequently, we propose four spectrum-scanning algorithms and analyze the energy required to scan, \hat{E}_{scan} , for each of them.

3.4.1 Energy Model

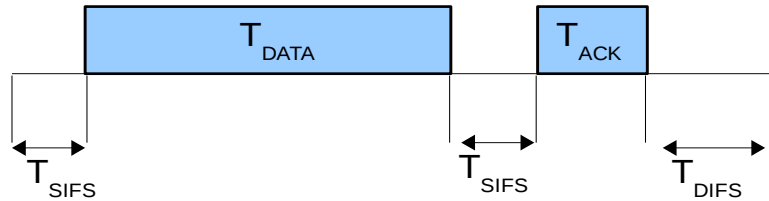


Figure 3.3: Packet communication in the basic access mode of IEEE 802.11 standard

We base our analysis on Figure 3.3 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.

3.4.1.1 Transmission Energy

A successful transmission has the energy cost

$$E_{tx} = P_{tx}T_{data} + P_{rx}T_{ack} + P_{idle}T_{difs}, \quad (3.6)$$

while a packet collision incurs the following cost

$$E_{coll} = P_{tx}T_{data} + P_{idle}(T_{ack} + T_{difs}) \quad (3.7)$$

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.

3.4.1.2 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

$$E_{rx} = P_{rx}T_{data} + P_{tx}T_{ack} + P_{idle}T_{difs}. \quad (3.8)$$

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

$$E_d = P_{rx}T_{hdr} + P_{idle}T_{difs} + P_{sleep}T_{nav} \quad (3.9)$$

where $T_{nav} = T_{data} - T_{hdr} + T_{ack}$ is the time duration of network allocation vector (NAV) (as defined in [36]) 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

$$E_{rxc} = P_{rx}T_{hdr} + P_{idle}(T_c - T_{hdr} + T_{difs}) \quad (3.10)$$

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

3.4.1.3 Energy Consumed for Backoff

We base our analysis on [95] and [12] 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, ρ_{nc} can be expressed as

$$\rho_{nc} = (n - 1)\tau(1 - \tau)^{n-2}, \quad (3.11)$$

where τ denotes the probability that a node transmits at a given tick time [12]. The probability that more than one node attempts to transmit can be given as

$$\rho_c = 1 - (1 - \tau)^n - n\tau(1 - \tau)^{n-1} \quad (3.12)$$

The average energy consumed per tick can then be expressed as [95]

$$\begin{aligned} \hat{E}_{tick} &= (1 - \rho_{nc} - \rho_c)P_{idle}T_{slot} + \rho_{nc}\{p_r E_{rx} \\ &+ (1 - p_r)E_d + \hat{E}_{tick}\} + \rho_c(E_{rxc} + \hat{E}_{tick}) \end{aligned} \quad (3.13)$$

where p_r is the probability that a packet on the medium is destined to the given node.²

²For our evaluations later in this chapter, we take $p_r = \frac{1}{n-1}$ for the scenario where any of the other nodes could be the possible destination.

3.4.2 Energy Consumed to Communicate on a Channel

The IEEE 802.11 DCF has been well analyzed by previous work in [95, 12]. 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

$$\hat{E}_{pkt}^k = E_{tx} + \frac{p_k}{1 - p_k} E_{coll} + \hat{R}(p_k) \hat{E}_{tick}, \quad (3.14)$$

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 $\hat{R}(p) = [W_0 \frac{(1-p) - p(2p)^m}{1-2p} - 1]$ 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{T}_{pkt}^k in Equation 3.4 (without using the notation that includes γ) using the analysis above summing up all the time components.

3.4.3 Energy Consumed to Scan Channels

The energy consumed by the scanning process (\hat{E}_{scan} in Equation 3.4) 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_{scan} and T_{sw} be the time spent in scanning a 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.

1 Optimal Scanning

In this technique, all channels are scanned before the optimal channel among them is chosen. In the context of this chapter, 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}_{scan} can be written as

$$\hat{E}_{scan} = M\hat{E}_{chscan} + (M - 1)P_{sw}T_{sw} + p_{sw}P_{sw}T_{sw} \quad (3.15)$$

where p_{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 3.15 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}_{chscan} depends on what fraction of the scanning period T_{scan} is spent in receiving packets (collision-free or collided), and what fraction is spent in the idle mode. Using the analysis in [95], and appropriate modifications, we can express this as

$$\hat{E}_{chscan} = \frac{T_{scan}}{T_{tick}} [(1 - \rho_{nc} - \rho_c)P_{idle}T_{slot} + \rho_{nc}E_d + \rho_c E_{rxc}] \quad (3.16)$$

where ρ_{nc} and ρ_c are the probability of receiving a collision-free or a collided packet respectively as expressed in Equations 3.11 and 3.12, and E_d and E_{rxc} are the energy consumed in receiving a collision-free packet and a collided packet respectively as expressed in Section 3.4.1. The term $P_{idle}T_{slot}$ is the energy consumed to stay in idle mode. The multiplicative factor $\frac{T_{scan}}{T_{tick}}$ accounts for the number of ticks in a scanning period T_{scan} , with T_{tick} found as

$$\begin{aligned} T_{tick} &= (1 - \rho_{nc} - \rho_c)T_{slot} + \rho_{nc}(T_{hdr} + T_{difs} + T_{nav}) \\ &\quad + \rho_c(T_{hdr} + T_c - T_{hdr} + T_{difs}) \end{aligned} \quad (3.17)$$

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 Δ , 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 Δ . 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

$$Pr(X = k) = q(1 - q)^{k-1} \quad \forall k = 1 \text{ to } M - 2. \quad (3.18)$$

This gives the probability that the last channel will be scanned as

$$Pr(X = M - 1) = 1 - \sum_{k=1}^{M-2} q(1 - q)^{k-1} \quad (3.19)$$

taking into account that regardless of whether this last channel is better or not, there are no more channels to scan. Based on Equation 3.18, we can further calculate the probability that the radio will switch from the current channel as

$$p_{sw} = \sum_{k=1}^{M-1} q(1 - q)^{k-1}, \quad (3.20)$$

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

From Equations 3.18 and 3.19 we can calculate the expected value of the number of channels scanned using the greedy algorithm as

$$E_X = \frac{[1 - (1 - q)^{M-2}]^2}{q} + (M - 1)(1 - q)^{M-2} \quad (3.21)$$

Thus, energy to scan can be expressed as

$$\hat{E}_{scan} = E_X[P_{sw}T_{sw} + \hat{E}_{chscan}] + p_{sw}P_{sw}T_{sw}, \quad (3.22)$$

where \hat{E}_{chscan} calculated as in equation 3.16.

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,

$$q = Pr(Z < n - \Delta n) = F_Z(n - \Delta n) - Pr(Z = n - \Delta n) \quad (3.23)$$

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 Δ .

Previous work by [4] 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

$$q = F_Z(n - \Delta n) - (1 - g)g^\lambda, \quad (3.24)$$

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

$$Pr(Y = 1) = r \tag{3.25}$$

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 3.20 and 3.25 due to the similarity to our greedy algorithm

$$Pr(Y = k) = (1 - r)q(1 - q)^{k-2} \quad \forall k = 2 \text{ to } M - 1. \tag{3.26}$$

So the probability to scan M th channel:

$$Pr(Y = M) = [1 - r - (1 - r) \sum_{k=2}^{M-1} q(1 - q)^{k-2}] \tag{3.27}$$

From equations 3.25, 3.26, and 3.27 the expected average number of channels to be scanned can be calculated as

$$E_Y = r + (1 - r) \left[1 + \frac{1 - (1 - q)^{M-2}}{q} + (3 - M)(1 - q)^{M-2} \right]. \tag{3.28}$$

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,

$$r = Pr(Z \leq n_c) = F_Z(n_c). \tag{3.29}$$

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

$$\hat{E}_{scan} = E_Y \hat{E}_{chscan} + (E_Y - 1)P_{sw}T_{sw} + (1 - r)P_{sw}T_{sw} \quad (3.30)$$

where \hat{E}_{chscan} is calculated using Equation 3.16.

4 Selective Scanning

In this scanning scheme a node scans all M channels when it is turned on and then selects a subset αM 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 3.15 (and using Equation 3.16 for E_{chscan}) we can write down the energy to scan under this scheme as

$$\begin{aligned} \hat{E}_{scan} = & \frac{1}{C} [(C - 1) \{ (\alpha M - 1) (\hat{E}_{chscan} + P_{sw}T_{sw}) + p_{sw}P_{sw}T_{sw} \} + M \hat{E}_{chscan} \\ & + (M - 1)P_{sw}T_{sw} + p_{sw}P_{sw}T_{sw}] \end{aligned} \quad (3.31)$$

where we amortize the energy consumed for $C - 1$ periods where we only scan α 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.

3.5 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 3.4.3. 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 4.1. 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 [60] 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.

3.5.1 Preliminary Evaluation - Energy for Communication versus Scanning

Equation 3.1 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.

Table 3.1: Values for parameters used in evaluations

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

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 3.4(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 3.4(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 receive packets from those nodes during scanning.

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 3.5. This result shows that for lower values

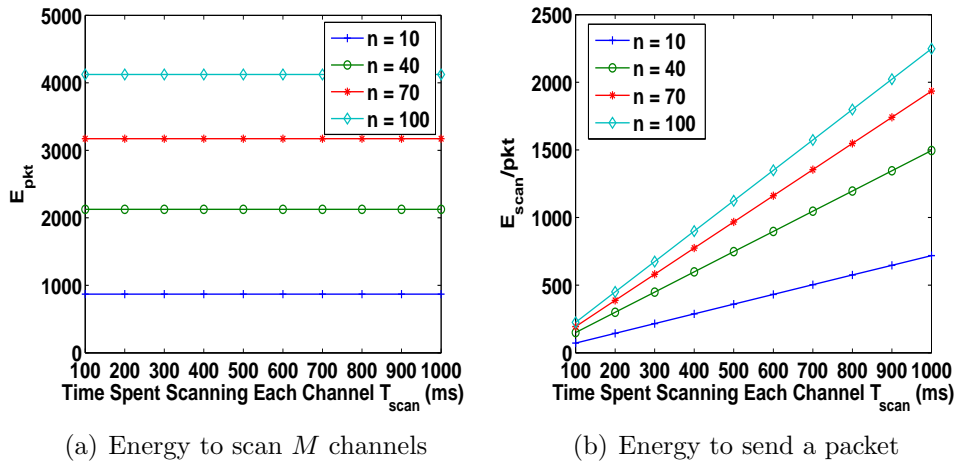


Figure 3.4: Comparison of energy to communicate packets versus energy to scan a channel. This plot provides an idea of the energy benefits of reducing channel contention by finding a ‘good’ channel versus energy spent in finding this ‘good’ channel.

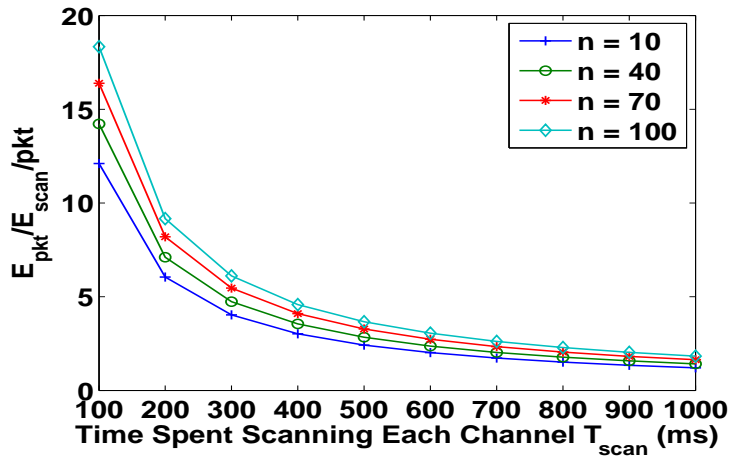


Figure 3.5: Comparison between per packet transmission energy and scanning energy

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 $\frac{E_{pkt}}{E_{scan}/pkt}$ as any energy reduction in the numerator due to reduced contention (Figure 3.4(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 3.4(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.

3.5.2 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 3.6. We fix M to a value of 20, and study the impact of a varying T_{scan} with node ratio fixed at 0.25. T_{scan} , the time to scan one channel, was varied from 100 to 1000 ms in steps of 100.³ We look at multiple values of n , the number of nodes on the original channel.

³In practice, a node would set the value of T_{scan} based on how much time it would require to estimate number of nodes on a channel. 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_{scan} , greater the accuracy of information obtained.

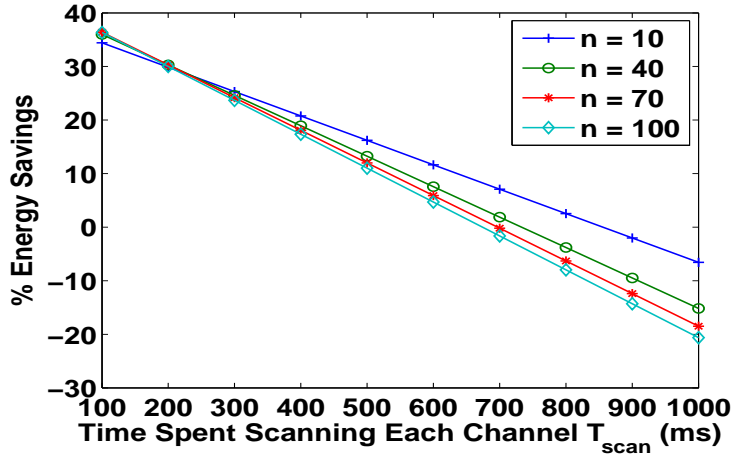


Figure 3.6: Optimal Scanning: Percentage energy savings for varying T_{scan} .

In Figure 3.6, it can be observed that there is a linear decrease in energy savings with increasing T_{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_{scan} is fixed and node ratio varied as shown in the bottom portion of Figure 3.7, 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.

Key Results

1. Increasing values of T_{scan} reduce the benefits of using a cognitive radio due to greater scanning overhead, but in a linear fashion.
2. 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.

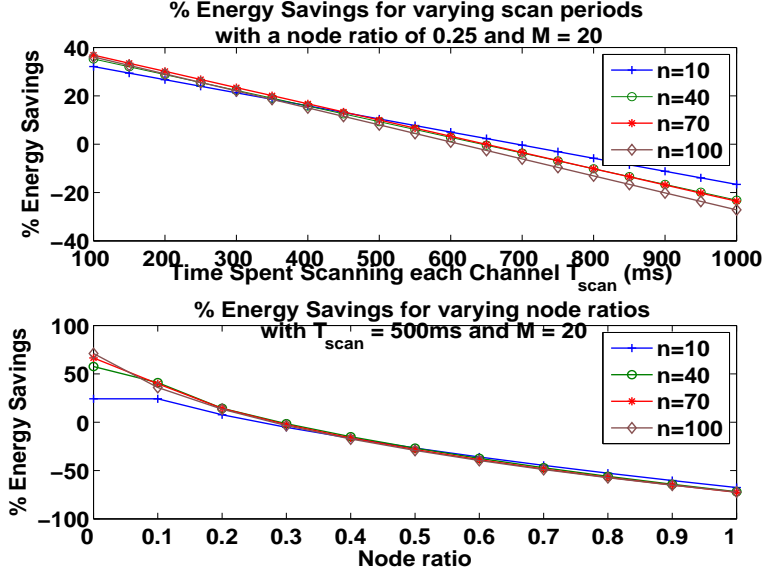


Figure 3.7: Percentage energy savings for varying parameters and $M = 20$ (a) The node ratio is kept at 0.25(b) The node ratio is varied from 0.01 to 1 while keeping T_{scan} fixed.

3. 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.

3.5.3 Greedy Scanning

For these experiments, as mentioned in Section 3.4.3, the distribution of nodes on channels is assumed to be geometric with a parameter g and an average of λ .

Figure 3.8 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 3.8a. To check if increasing Δ keeps providing greater energy savings, we varied Δ for different fixed values of $N = 400$, $M = 20$, and $T_{scan} = 200$ ms as shown in Figure 3.8b.⁴ We find that increasing Δ does indeed provide greater savings. Keeping Δ large, however, can have the disadvantage in practical scenarios

⁴In Figure 3.8b the line for $n = 0.5\lambda$ flattens out for large Δ because the Δ times n has hit the minimum threshold of two nodes needed on a channel for communication.

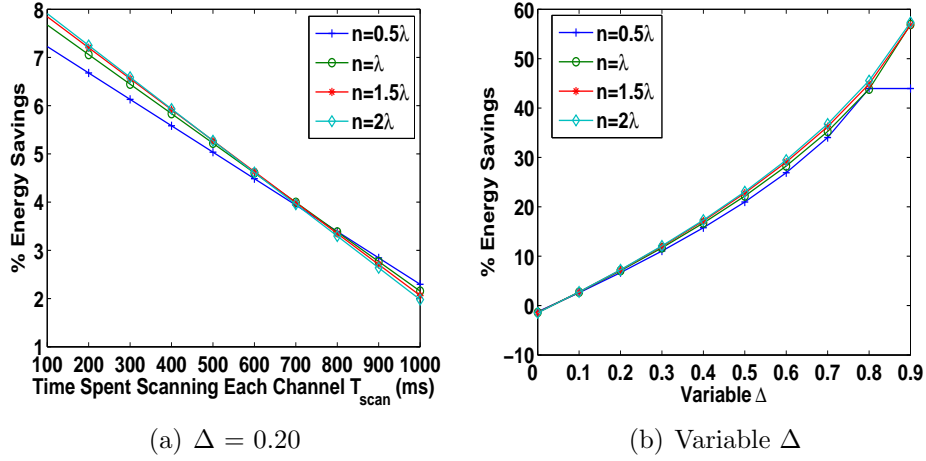


Figure 3.8: Greedy Scanning: Energy savings for a) variable scanning time and b) variable Δ .

that no channel satisfying the condition may be found, thus possibly compromising on any lesser node reduction that may have been available.

3.5.4 Sticky Scanning

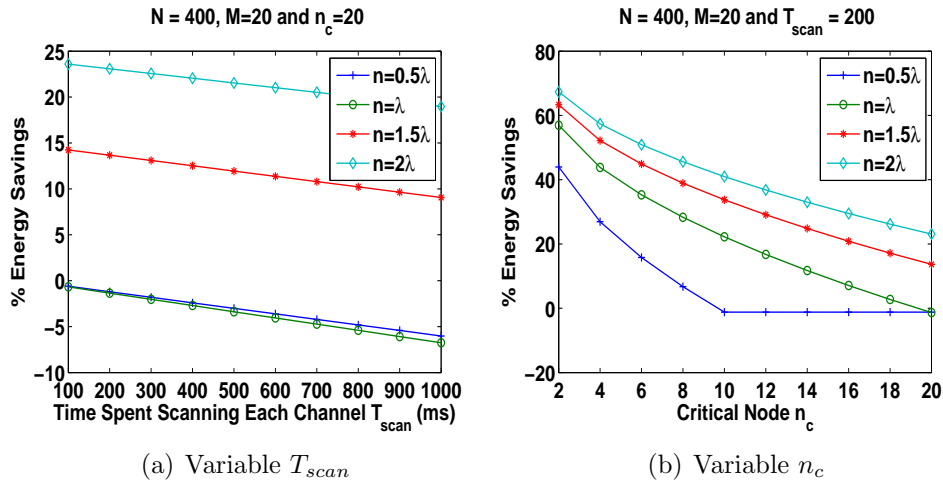


Figure 3.9: Sticky Scanning: Energy Saving with variable T_{scan} and n_c .

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 3.9a shows energy savings as a function of T_{scan} . In Figure 3.9b, with the values of $N = 400$, $M = 20$, and $T_{scan} = 200\text{ms}$, we can see that $n_c = 2$, the smallest possible value, is easily the optimal value emphasizing that for these small values of λ (equal to 20), M , and T_{scan} chosen, *the energy saved due to reduced contention outweighs the energy cost of scanning*. In Figure 3.9b 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 .

3.5.5 Selective Scanning

Figure 3.10 shows the impact of varying C and α on energy savings for a cognitive radio. Increasing α 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.

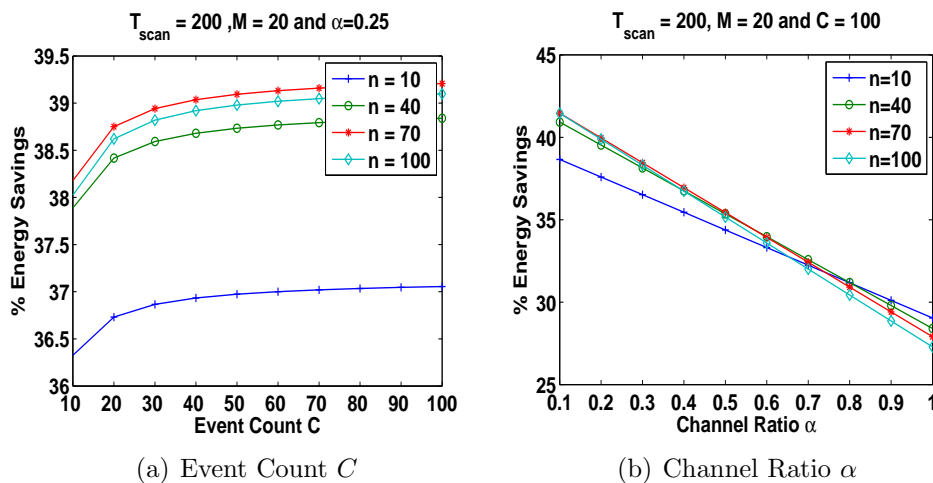


Figure 3.10: Selective Scanning: Energy savings for varying values of C and Channel Ratio α

3.5.6 Impact of varying number of channels M

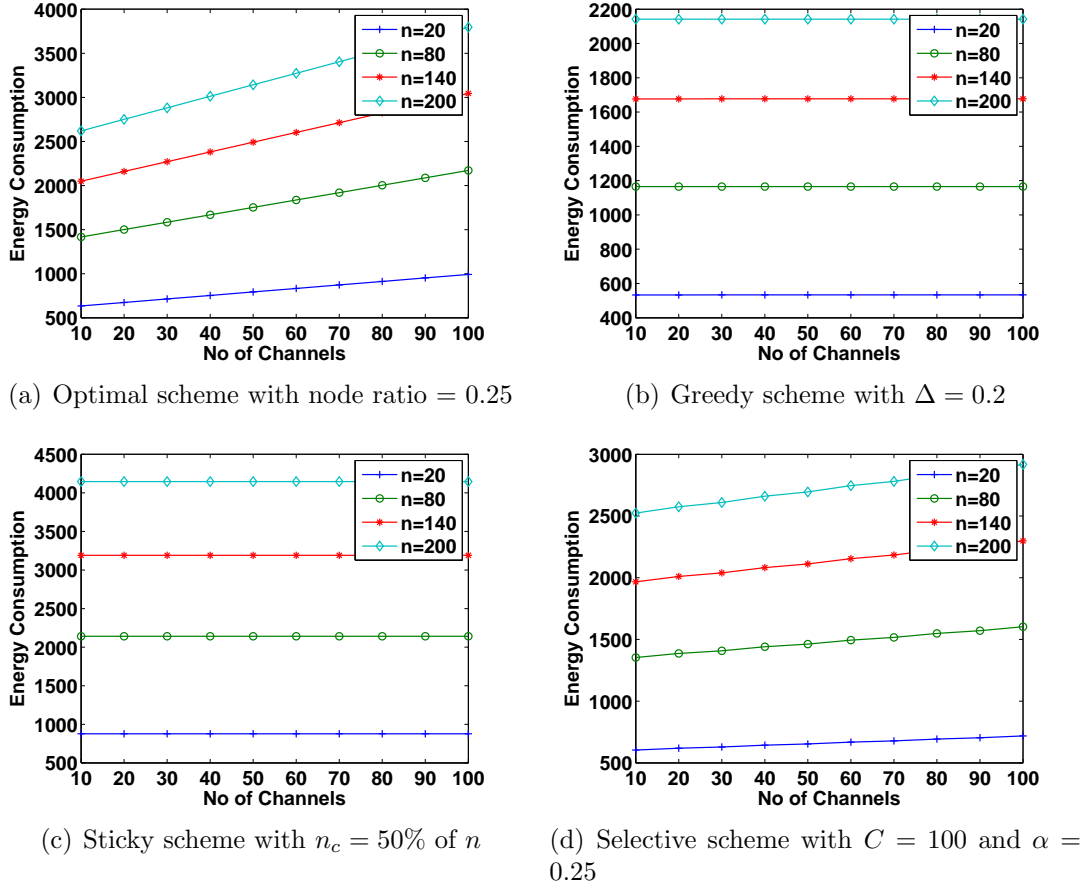


Figure 3.11: Energy consumed when using each of the four proposed scanning schemes with varying number of channels M . For all schemes, T_{scan} was kept fixed at 200 ms.

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 3.11 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. 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.

3.6 Concluding Remarks of This Chapter

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 λ 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. *Our main conclusion from these results is that energy consumed by node contention typically dominates that due to scanning.*

In the next chapter we 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 channel packet error rates, would be a new dimension along with the studied dimensions in this chapter. This new dimension is better explored through simulations as it allows the creation of a highly dynamic environment.

CHAPTER 4

STUDY THROUGH SIMULATIONS FOR THE CASE OF DYNAMIC CHANNEL CONDITIONS

4.1 Introduction

The goal of this chapter is to study the energy consumption of cognitive radio nodes under dynamic channel conditions. Through this chapter we make the following technical contributions: (i) compare different spectrum scanning algorithms under dynamic channel conditions with energy consumption as a metric, and (ii) provide an operating range of parameters where a CR node can save energy for each scanning algorithm considered. This work takes into account both the physical layer as well as higher layer aspects and builds on preliminary work in Chapter 3 where an analytical study was done on the conditions under which a CR node consumes less energy than a conventional non-CR node. The results obtained in Chapter 3 were limited to static scenarios without considering the impact of dynamic channel conditions that include diverse channel conditions and varying node populations. This study also does not make any idealized assumptions on channel packet error rates as was done in Chapter 3 and considers the impact of varying packet loss characteristics during channel selection.

In prior work, Mandayam [55] pointed 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, the focus of this chapter would specifically be on ad-hoc WLAN devices associated IEEE 802.11 standard MAC protocol and existing efforts in the area that includes the White-FI (IEEE 802.11af standard) with a goal of gaining 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 understanding 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 such as cellular data networks and wireless sensor networks.

The results of this chapter indicate that a CR node can save energy over a conventional non-CR node for most scanning schemes if channels have high variability in the number of nodes on them and under relatively high channel packet error rates. Further, this work identifies the relative merits and demerits of four scanning schemes from the overall design space and presents the range of operating conditions under which they are preferable.

The rest of the chapter is organized as follows. Section 4.2 describes our evaluation methodology and results followed by the conclusions of this chapter in section 4.3.

4.2 Evaluation

This section begins with a description of our evaluation methodology followed by results when considered each of the four possible scanning algorithms first described in Chapter 3.

4.2.1 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 channel packet error rate $f(\gamma)$ (Equations 3.4 and 3.5) to all M channels. The arrival and departure rates were assigned from a poisson distribution with the average rates β 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 3.2). The average arrival and departure rates were set to be equal, ie. $\beta = \mu$, 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 channel packet loss rate was assigned randomly to all M channels from a uniform distribution between 0 and 0.5, with channels with any greater losses 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. All the results were generated based on numerical evaluations of the expressions developed in the previous research using values for constants shown in Table 4.1 and of course parameter values derived from the simulator. The values in Table 4.1 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 described in the previous chapter. Experiments using other values yielded similar result trends with differences only in scale. 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.

4.2.2 Results for the Optimal Scan algorithm

When using the optimal scanning scheme, a CR node scans all channels and selects the best one. In ideal network condition, energy savings over a conventional radio would then depend only on the reduction in node contention the CR node can achieve through its scanning and switching capabilities. The experiments conducted included studying the

Table 4.1: Values for parameters used in evaluations for dynamic channel condition

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

impact of varying admission/departure rate of nodes on each channel and channel packet error rates.

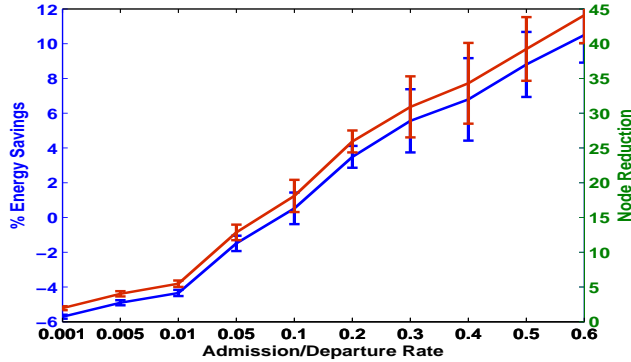


Figure 4.1: Optimal scanning: energy savings and node reduction for various channel load variabilities for ideal channel conditions.

In Figure 4.1, we can see energy savings and node reduction versus admission/departure rate with all channels have a ideal zero channel packet error rate characteristic. As expected, the CR node is always able to achieve node reduction compared to the current channel of the conventional radio. This reduction and energy savings are found to increase with higher admission/departure rate due to the greater variability across channels that favor the

technology that can always switch to the lowest contention channel. For less channel packet error rate with low arrival/departure rates, the CR does not save any energy and incurs the penalty of scanning with little or no benefits to show for it.

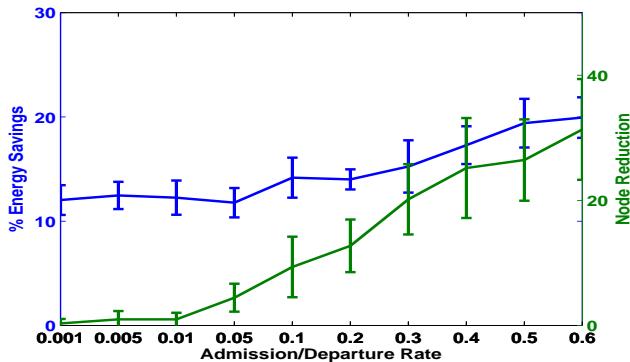


Figure 4.2: Optimal scanning: energy savings and node reduction for various channel load variabilities for ideal channel conditions.

In Figure 4.2, with non-ideal channels and a packet loss distribution across channels as described in 4.2.1, node reduction achieved increases with admission/departure rate but not at the same pace like in the ideal channel packet error rate condition case. Interestingly, there is positive energy savings even for lower channel load variability (due to low admission/departure rates), unlike that of the ideal channel condition case. In Figure 4.1, 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 4.3. When admission/departure rate increases, node reduction effect gets increased compared to the channel condition effect. So at a higher channel load variability rates, energy savings gap between ideal and non-ideal channel condition reduces. In conclusion, a CR node can save energy if it uses optimal scheme in the ideal network case with greater possibility to do so in non-ideal network scenario.

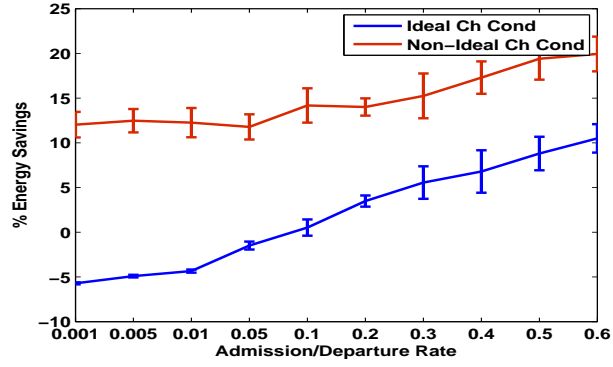


Figure 4.3: Optimal scanning: energy saving comparison between ideal and non-ideal channel conditions for various channel load variabilities

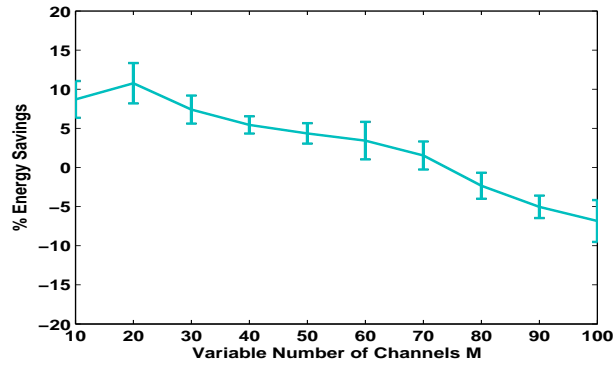


Figure 4.4: Optimal scanning: energy savings with varying number of channels M for ideal channel conditions

The next step was the study of the impact of number of channels in the system on possible energy consumption patterns by a CR node. The result shows in Figure 4.4 indicates that energy savings increases with the optimal scanning scheme when number of channels increase 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. But with any more channels, the requirement of scanning all channels becomes more of a burden on energy savings.

4.2.3 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. Thus, the CR node was set to find a channel that is estimated to consume 20 percent less energy compared to the current channel to carry out its packet communication.

Figure 4.5 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. This results in negative energy savings due to the energy expended for scanning. With greater load variability on channels, meeting the threshold reduction is easier and thus faster saving on energy spent on scanning.

Under non-ideal channel conditions (Figure 4.6), 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. This is in contrast to the optimal scheme where energy savings was possible for non-ideal channel conditions for all levels of channel load variability considered. This is possibly due to the difficulty in finding a better channel in low load variability conditions,

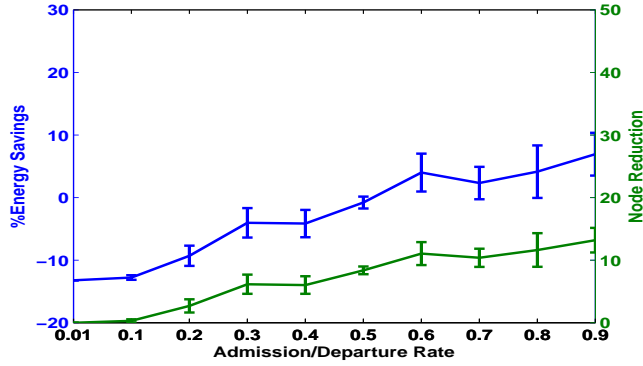


Figure 4.5: Greedy scanning: energy savings and node reduction for various channel load variabilities for ideal channel conditions.

while still expending as much energy for scanning as the optimal scheme. Energy savings for both ideal and non-ideal cases are presented in Figure 4.7.

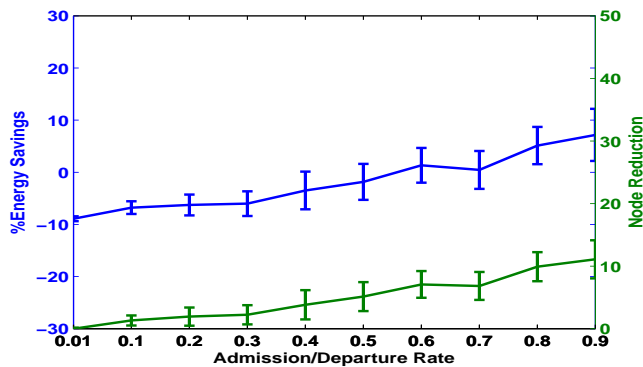


Figure 4.6: Greedy scanning: energy savings and node reduction for various channel load variabilities for non-ideal channel conditions.

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 4.8 for a fixed arrival/departure rate of 0.5. Energy savings for both ideal and non-ideal channel loss cases increases first and then decreases. This result suggests that lower values of Δ may be more suitable and

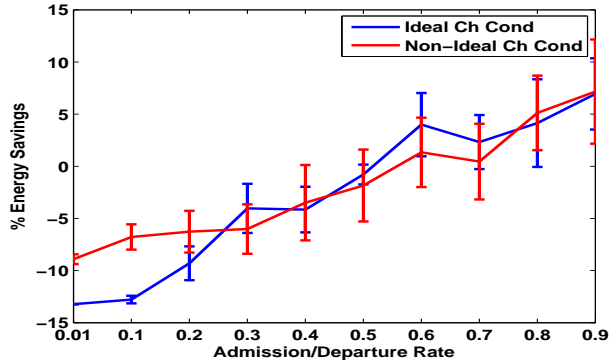


Figure 4.7: Greedy scanning: energy saving comparison between ideal and non-ideal channel conditions for various channel load variabilities

it is best not to 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 packet loss conditions (as was seen in Section 4.2.2).

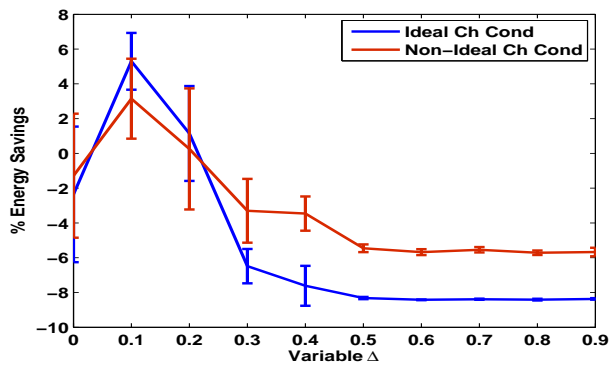


Figure 4.8: Greedy scanning: energy savings for variable values of Δ for both ideal and non-ideal channel conditions.

4.2.4 Results for the Sticky Scan algorithm

In the sticky scanning scheme, a CR node “sticks” to the current channel unless the energy consumed for communication per slot exceeds some predefined, critical energy threshold. If that happens, the scanning operation is used to find the first channel where energy consumed is below this critical threshold.

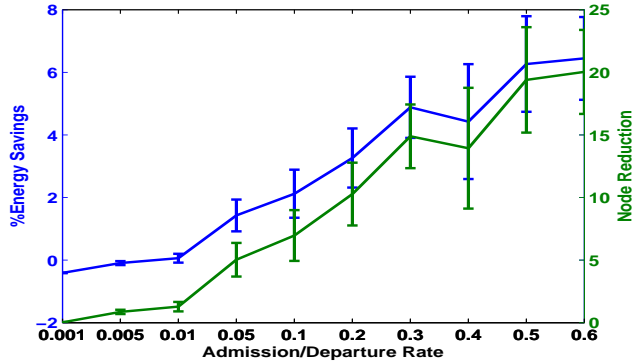


Figure 4.9: Sticky scanning: energy savings and node reduction for various channel load variabilities for ideal channel conditions.

Similar to the previous two schemes, as shown in Figure 4.9, node reduction and energy savings increase with higher channel load variability. For the chosen value of critical energy threshold, no additional benefits of the sticky scanning scheme are seen over the previous two. For the non-ideal channel case, as shown in Figure 4.10, there are more or less high energy savings independent of channel load variability. This is because when channel variability is low, the sticky scan scheme just stays on its current channel without needing to scan; when channel load variability is high, it scans and maintains energy savings. Compared to the optimal scheme, at high variability, the sticky scanning scheme may not find as many opportunities to increase energy savings due to its tendency to settle for something just satisfactory like the greedy scheme. Figure 4.11 compares energy savings under both the ideal and non-ideal channel scenarios.

The results above for the sticky scan scheme are for a specific critical energy consumption threshold of $7500 \mu J$; these results will vary for a different threshold. Thus, the next experiment was to study the impact on energy savings by varying this threshold for a fixed admission/departure rate of 0.5. As Figure 4.12 shows, at low thresholds, a CR node scans often to maintain a similar rate of energy consumption. At higher thresholds, the need to scan is rarer, but this also results in an “unwillingness to venture out” and find another,

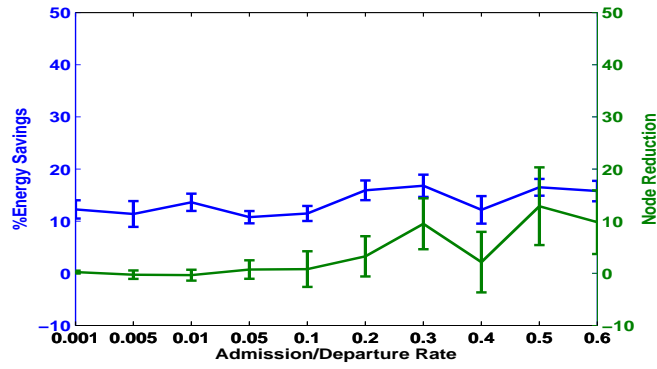


Figure 4.10: Sticky scanning: energy savings and node reduction for various channel load variabilities for non-ideal channel conditions.

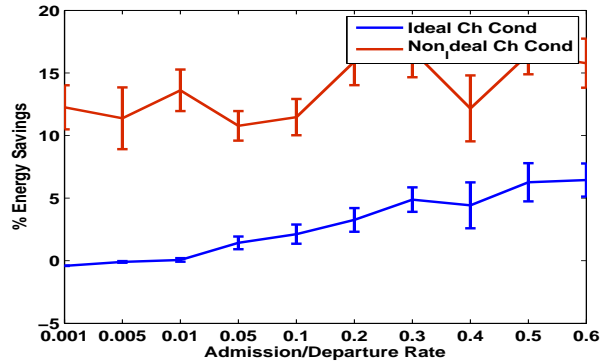


Figure 4.11: Sticky scanning: energy saving comparison between ideal and non-ideal channel conditions for various channel load variabilities

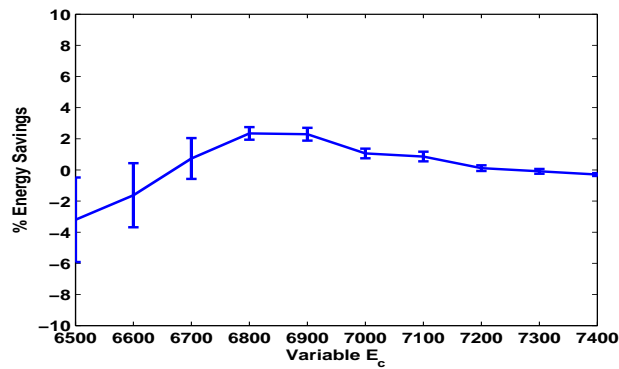


Figure 4.12: Sticky scanning: energy savings for various critical energy thresholds under ideal channel conditions.

better channel. Thus, interestingly, the sticky scanning scheme energy savings is a concave function of the critical energy threshold.

4.2.5 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 to be scanned is set to be 25% of M which equals to 5 when $M = 20$.

Being a scheme similar to the optimal scheme, at low channel load variabilities, only minimal node reduction is possible resulting in negative energy savings. However, it can be observed from Figure 4.13 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 4.14, just like all the other schemes. A comparison of energy savings for ideal versus non-ideal channels is given in Figure 4.15.

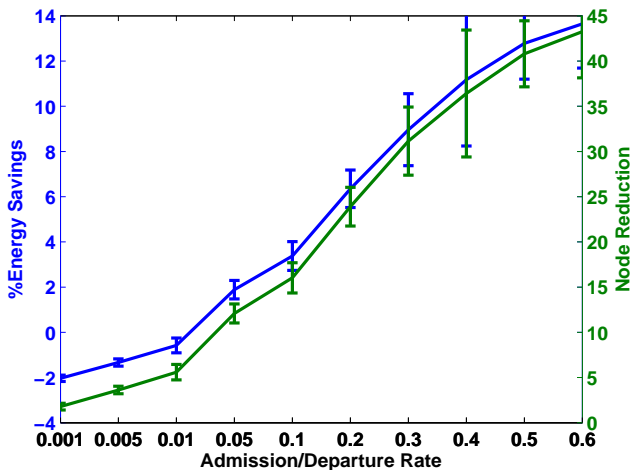


Figure 4.13: Selective scanning: energy savings and node reduction for various channel load variabilities for ideal channel conditions.

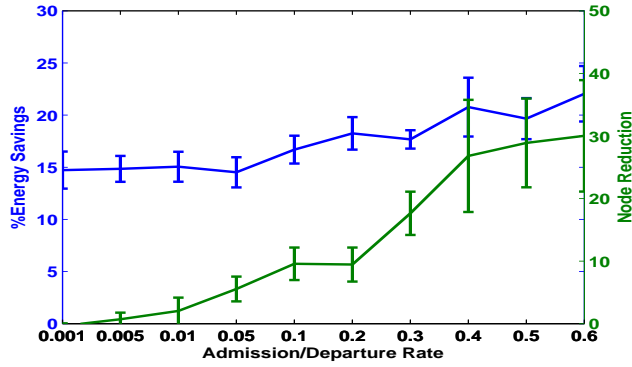


Figure 4.14: Selective scanning: energy savings and node reduction for various channel load variabilities for non-ideal channel conditions.

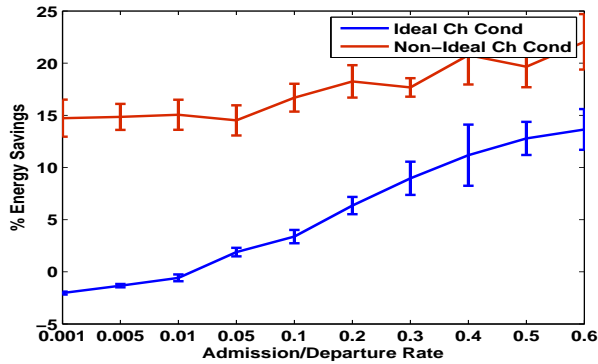


Figure 4.15: Selective scanning: energy saving comparison between ideal and non-ideal channel conditions for various channel load variabilities

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 4.16, timer values used are varied for both ideal and non-ideal channel scenarios. The result shows a fairly good balance between the two tradeoffs.

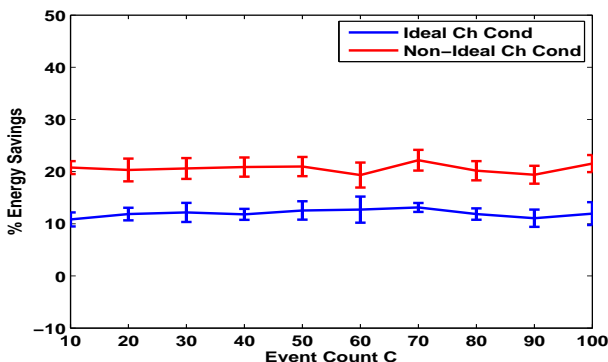


Figure 4.16: Selective scanning: energy savings for varying timer periods

The cardinality of the preferred subset is the other parameter of interest. A smaller cardinality 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 4.17 shows energy savings 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.

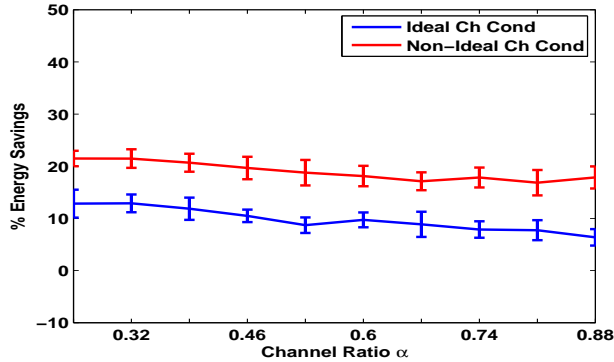


Figure 4.17: Selective scanning: energy savings for varying subset cardinalities.

4.3 Concluding Remarks of This Chapter

This chapter studied the energy consumption of CR nodes under dynamic channel conditions. The technical contributions made in this chapter include 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. This work considered different layers and evaluated all the proposed channel scanning schemes under dynamic channel conditions.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

Through the survey in Chapter 2 we classified prior research done in the area of CRNs with energy consumption implications into three broad categories: dynamic spectrum access, hardware, and protocol design. In each category there have been a great amount of work done to improve the performance, functionality, quality of service, and even legality of this new paradigm. Many of the proposed approaches have implications to the energy consumption of CRNs, and were thus described in this chapter, even if exploring energy consumption aspects was not the primary focus. Additional research directions in the area of CRNs with a more explicit focus on energy consumption where more work needs to be done were identified as (i) designing scanning algorithms for SUs, (ii) modeling of energy consumption of SUs, (iii) prototype implementations to evaluate energy consumption of CRNs.

In Chapter 3, we 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 to 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. Relative comparisons among the schemes show that the selective scanning scheme can perform better than its special case, the optimal scanning scheme, if α 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 Δ 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. The results in this chapter were for a static scenario with a constant channel packet error rate and fixed node populations. The analytical approach used in this chapter was not suitable

to study the impact of dynamic channel conditions. However, the analytical results in this chapter still serve as a useful guideline for static scenarios with more or less constant channel conditions across the spectrum under consideration.

In Chapter 4, we studied the energy consumption of CR nodes under dynamic channel conditions. This chapter took into account both the physical layer as well as higher layer aspects and evaluated four channel scanning schemes (first proposed in Chapter 3) under dynamic channel conditions. A CR node employing any of the four proposed scanning schemes was found to save energy even in highly dynamic channel scenarios with high channel load variability. However, in conditions of low channel load variability, the sticky and selective scanning schemes were found more likely to save energy over a conventional radio due to more conservative scanning approaches that don't waste energy looking for 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.

Future work building on this dissertation includes the directions identified in Chapter 2 (scanning algorithms, modeling energy consumption, prototyping) but for more general wireless network scenarios not limited to the ad-hoc WLAN scenario. Additionally, the results of this dissertation need to be empirically validated through large-scale CR network test beds that also have the capability for fine-grained energy consumption measurements. Finally, more work can be done on the coordination and control among ad-hoc CRNs with the goal of reducing the collective energy consumption as opposed to the single node perspective taken in this dissertation.

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