ENERGY-EFFICIENCY ANALYSIS OF COOPERATIVE SENSING SCHEMES IN AD HOC WLAN COGNITIVE RADIOS

A Thesis by

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Bachelor of Technology, Jawaharlal Nehru Technological University, 2007

Submitted to Department of Electrical Engineering and Computer Science
and the faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Master of Science

December 2011

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

Vinod Namboodiri, Committee Chair

Huzefa Kagdi, Committee Member

Anil Mahapatro, Committee Member

DEDICATION

To my husband, beloved parents, and sister for their enduring support and motivation

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my thesis advisor, Dr. Vinod Namboodiri, for believing in me and guiding me at every step of this thesis. I am greatly indebted to him for all his advice and technical knowledge, without which would have made it impossible for me to accomplish this work. One simply could not wish for a better and friendlier advisor. I would also like to thank him for sparing his invaluable time reviewing this work.

I am grateful to Dr. Ravi Pendse for giving me an opportunity to work for him as a graduate research assistant. I owe him a debt of gratitude for being the motivation behind my decision of going for the thesis option.

I would like to extend my special thanks to Dr. Huzefa Kagdi and Dr. Anil Mahapatro for their time and effort to serve on my committee.

I am extremely thankful to my husband, my parents and sister for their tremendous moral support and valuable insights during the course of this thesis. They have been instrumental in my finishing this thesis. Thanks are also due to my in-laws.

Last, but most importantly, I am thankful to almighty God for giving me the strength and courage to work throughout this thesis.

I would also like to thank my friends Sanju, Girish, and Toolika for their support and suggestions.

ABSTRACT

Wi-Fi has become a ubiquitous wireless technology in a relatively short period of time. Each of us has a wireless gadget competing for the Wi-Fi bandwidth and thus has to compromise on the data speeds in order to share the limited Wi-Fi spectrum. Contrary to this Wi-Fi crowding phenomenon which is yet to worsen with the ongoing explosive growth of wireless devices, studies show that 90% of the time, spectrum designated to legacy technologies like the television (TV) spectrum was found to be unoccupied and not every channel was in use always. Cognitive Radio (CR) Technology is the riposte to this dichotomy. A CR is an intelligent device which scans the radio spectrum for free channels and uses them to its own advantage. However, in order to access the vacant spectrum and reap the benefits, the CRs need to coordinate among themselves using cooperative spectrum sensing schemes. This thesis work studies and analyzes the energy efficiency of two such generic cooperative sensing schemes - Distributed and Centralized, in an ad hoc WLAN backdrop. Furthermore, the corresponding enhanced and adaptive versions of these two schemes are proposed, where only a fraction of the nodes scan as opposed to all nodes in the network. Using an analytical energy model for sensing, the energy costs of the proposed cooperative sensing schemes are quantified. A comparative numerical analysis is further performed to demonstrate the amount of energy savings of the proposed schemes over their generic counterparts and non-cooperative schemes.

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LIST OF ABBREVIATIONS

ACK	Acknowledgment
BWRC	Berkeley Wireless Research Center
CH	Cluster Head
CM	Cluster Member
CR	Cognitive Radio
CTS	Clear to Send
DIFS	DCF Interframe Space
DSA	Dynamic Spectrum Access
FCC	Federal Communications Commission
IEEE	Institute of Electrical and Electronics Engineers
MAC	Medium Access Control
OSA	Opportunistic Spectrum Access
PDR	Probability Detection Ratio
PU	Primary User
RTS	Request To Send
RP	Reporting Period
SC	Sensing Cycle
SNR	Signal-to-Noise Ratio
SP	Scanning Period
SR	Sensing Report
SU	Secondary User
TV	Television

LIST OF ABBREVIATIONS (continued)

TVWS	Television White Spaces
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

1.1 What is a Cognitive Radio?

The world has witnessed a great deal of change in the past decade when it comes to wireless technologies. Be it Wi-Fi, WiMAX, wireless sensor networks (WSNs), or any other sub-technology belonging to one of these areas, such technologies have permeated so deep into our society that it is hard to imagine our lives without them. However, with demand comes scarcity. The spectrum allocated to these technologies is greatly limited and, hence, the scarcity that emphasizes the great need to deal with and overcome this issue. Figure 1 and Figure 2 show the spectrum measurements taken by Berkeley Wireless Research Center (BWRC) and the Shared Spectrum Company, respectively.

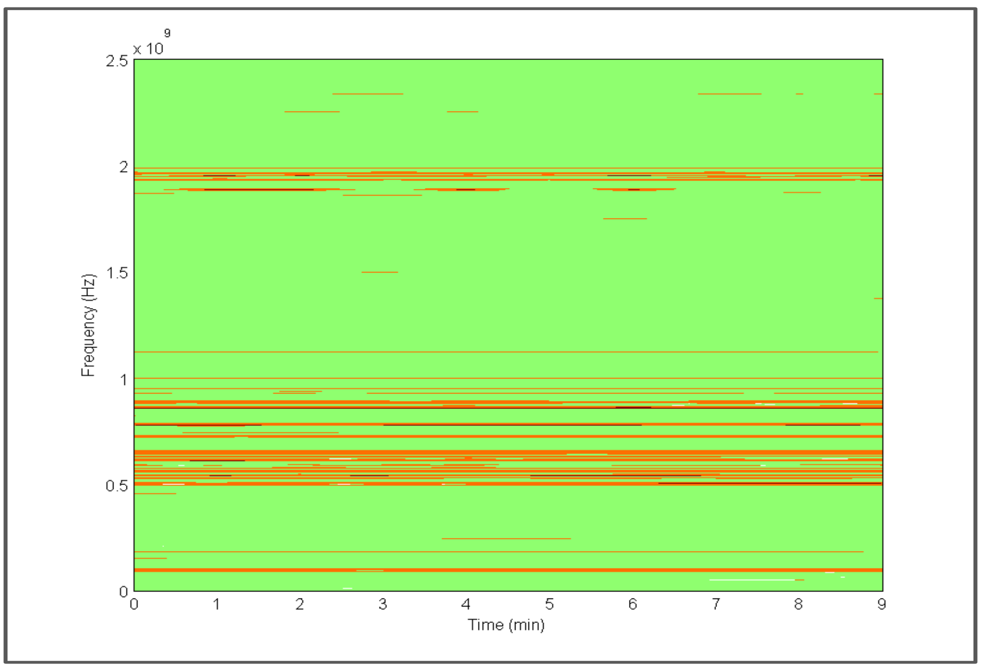


Figure 1. BWRC spectrum measurements [1]

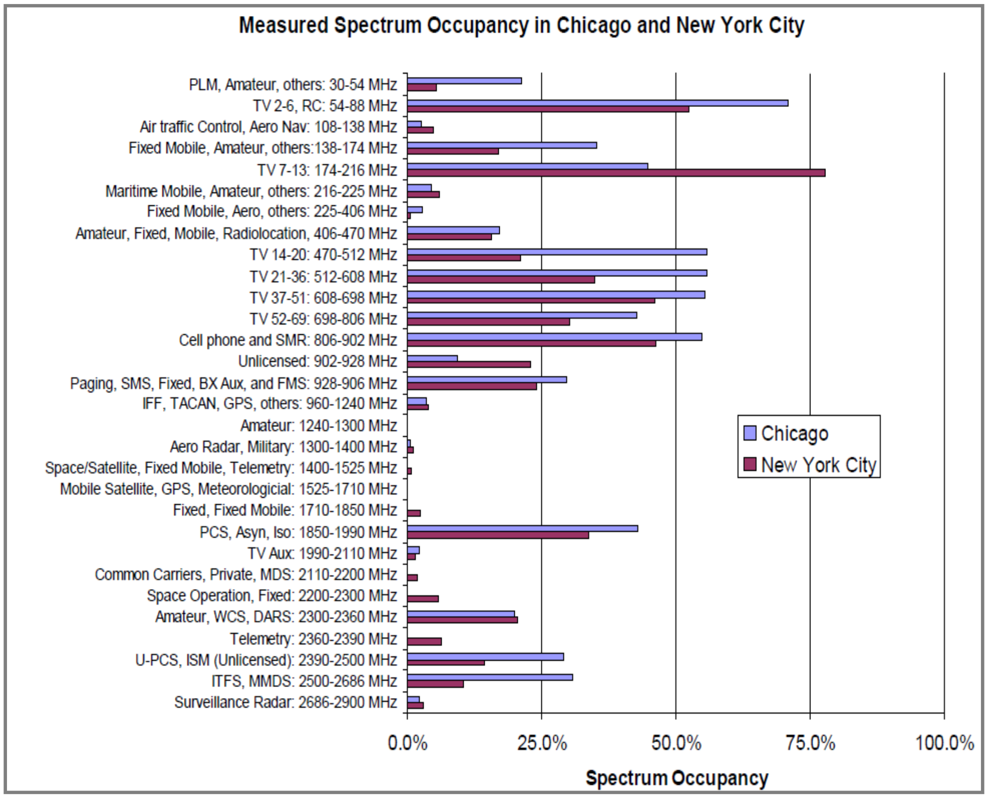


Figure 2. Spectrum measurements in New York City and Chicago conducted by Shared Spectrum in 2005 [2]

It is clearly noticeable that only a few frequency bands are in use, while about 70% of the remaining spectrum (primarily belonging to legacy radio technologies) remains unused for longer periods of time [2] [3]. This is where opportunistic spectrum access (OSA) comes into the picture. Through OSA, users can utilize the spectrum that is currently being unused, especially when it comes to the licensed spectrum of legacy technologies. One example is the television (TV) spectrum. However, for a radio to use the spectrum opportunistically it should be aware and intelligent enough to look out for such vacant spectrum bands. Hence, there is a great need to build better and intelligent radios, and this is where “cognitive radio” (CR) comes into play. Cognition is the psychological result of perception, learning, and reasoning. This term was first coined by Mitola and Maguire [4] in their research work, although lately, this term has become synonymous with “dynamic spectrum access” (DSA), in the sense that the goal of DSA/OSA is achieved through the cognition of radio.

1.2 Need for Cognitive Radios

Cognitive radios opportunistically cash in on the licensed spectrum, which is allocated to rightful owners and is not used in time, frequency, space, and code dimensions of a signal at a given instant (also called spectral opportunities). This makes their communications efficient in terms of throughput, energy, and delay metrics. Studies have shown that 90% of the time, the valuable licensed spectrum was found to be unoccupied [3]. In contrast to this license band vacancy, with the advent of portable gadgets, the unlicensed spectrum for technologies like Wi-Fi is being crowded most of the time.

Hence, dealing with the Wi-Fi crowding phenomenon is critically important for sustainable wireless computing for future generations. One of the most recent endeavors in this direction was made by the Federal Communications Commission (FCC), which approved and reallocated the use of television white spaces (TVWS) for Wi-Fi. This renovated Wi-Fi technology capable of using TVWS via cognition was renamed White-Fi (IEEE standard 802.11af), sometimes also called “Wi-Fi on Steroids.” TV channels 2 to 52 have been opened up for unlicensed usage by the general public. Although the FCC recently agreed to eliminate the spectrum-sensing requirement and instead encourage the use of online databases for spectrum vacancy [5] [6], it would still be an undeniable component when considering an “on the fly” ad hoc Wi-Fi network that does not have access to these online databases.

1.3 Cognitive Radio Components

In the field of CR technology, the rightful users of the licensed spectrum are termed primary users (PUs), whereas other CR users trying to use this spectrum opportunistically are referred to as secondary users (SUs). A typical cognitive radio network is shown in Figure 3.

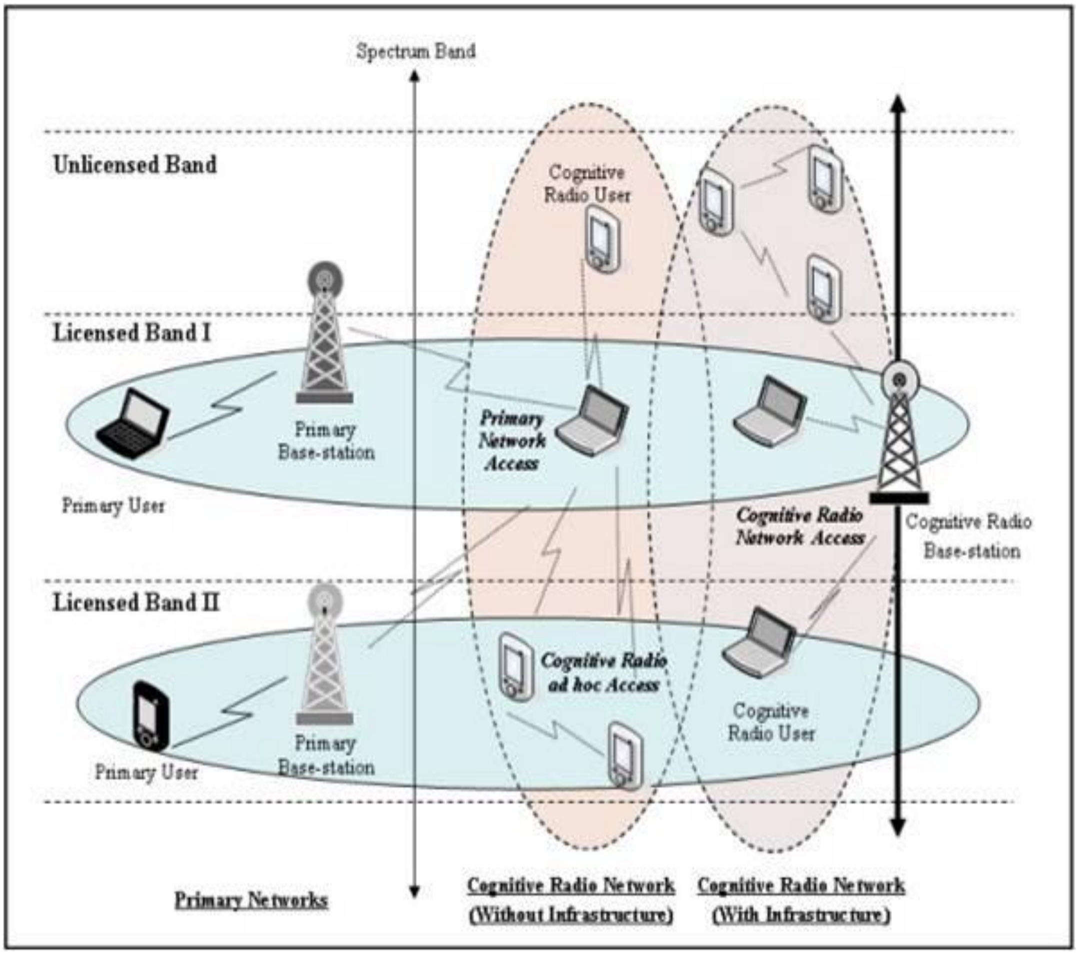


Figure 3. Cognitive radio network [7]

The SUs, before dynamically accessing this licensed spectrum, should ensure that it is not being used by any PUs in their local vicinity, so as to avoid interference to the PUs. If a PU is detected at any point, the SUs should be able to switch to a different channel seamlessly. The functionalities addressing these challenges are defined in the cognitive radio spectrum management framework [7], as shown in Figure 4.

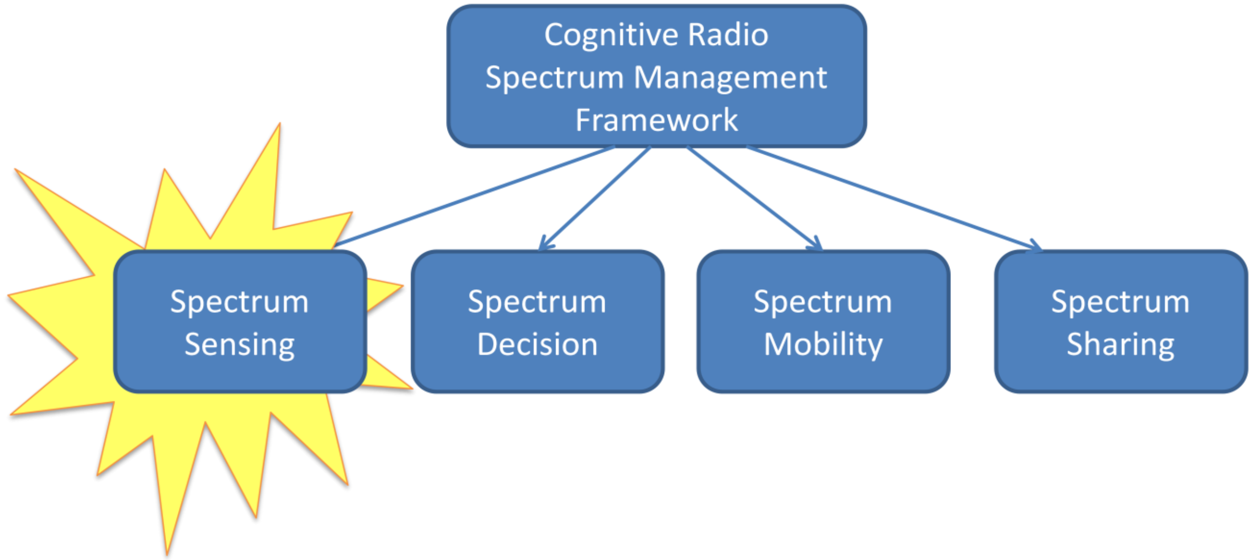


Figure 4. Cognitive radio spectrum management framework

The essential components of the cognitive radio spectrum management framework are as follows:

- Spectrum Sensing: An SU can dynamically use only the vacant portions of the spectrum that are not being used by PUs. For this, the SUs must monitor such spectrum bands to detect spectrum opportunities, which are also called spectrum holes.
- Spectrum Decision: Once the spectrum is sensed and its availability is known, a decision on which spectrum band/channel to use must be made. This decision also depends on internal and external spectrum polices, if any.
- Spectrum Mobility: If a PU is detected while SUs are opportunistically using the spectrum, then the SUs should be able to transition to a different channel and still have a seamless communication without any disruption.
- Spectrum Sharing: In a given geographical vicinity, there could be multiple SUs trying to access a particular spectrum band for network communications. Hence, there should be a proper coordination between SUs to avoid any spectrum overlapping.

The most critical cornerstone of all these components is “spectrum sensing,” which is extensively discussed in this thesis work.

1.4 Sustainability through Cognitive Radios

With the advent of wireless technologies came the unprecedented growth of portable devices. Sustainability of such devices has become more important than ever, and one of the key metrics used to measure the sustainability of portable computing is energy. However, one of the biggest drawbacks, and a killer of such battery-operated portable devices, is energy drain due to the wireless interface card. Wireless node contention is a major contributor to this problem. In addition, the explosive growth of portable and mobile computing devices has opened up revolutionary, newer computing paradigms like virtualization, cloud computing, thin-client architecture, and multimedia applications. These newer paradigms are mainly dependent on the communication interface of the client/user, which eventually becomes the chokepoint [8]. Cognitive radio technology is the contemporary and cutting edge technology solution to these challenges. Cognitive radios not only increase data rates significantly by exploiting the unused spectrum, but they also decrease the node contention, thereby reducing energy wastage caused by back-offs and idle times and thus contributing to the sustainability of portable devices.

1.5 Need for Energy-Efficient Cognitive Radios

The main advantage of deploying cognitive radios is that they utilize the unused spectrum to increase data rates significantly and reduce idle times of the wireless devices. However, spectrum sensing—the technique through which the cognitive radio gains cognition and multidimensional awareness of spectrum availability—is, in itself, a highly energy-intensive process. Cognitive radio would not be an appealing or feasible solution until, and unless, these spectrum-sensing energy costs are reduced. Otherwise, the energy-intensive spectrum-sensing process would completely undermine the benefits that cognitive radios provide through opportunistic spectrum access.

1.6 Problem Description

As explained previously, there is a great need for energy-efficient cognitive radios to undermine and counterbalance the costs of the energy-intensive channel-scanning process. However, there is a limited amount of literature that examines the energy-cost aspect of the cognitive radio spectrum-sensing technology. A previous study of interest for this thesis, is the work of Namboodiri [9], which looks at the positive and negative impacts of CR medium access control (MAC) layer sensing in terms of energy. This work, however, does not look at the energy costs of cooperative sensing, and the techniques (optimal scan and greedy scan schemes) proposed here are non-cooperative sensing schemes. This thesis work is subsequent to the work of Namboodiri, with the goal of minimizing the energy spent in spectrum sensing for each node and the network as a whole through cooperative sensing schemes. Using an analytical energy model for sensing, the energy costs of each of the generic cooperative schemes are quantified. A comparative numerical analysis is performed to demonstrate the amount of energy savings of the proposed cooperative schemes over their generic counterparts and non-cooperative schemes.

1.7 Contributions

The following are specific contributions made in this thesis work:

- Development of an energy model to study and quantify the energy costs of a broader class of existing generic cooperative MAC layer sensing schemes—one based on a distributed architecture, and one based on a centralized architecture.

- Proposal for corresponding new α-schemes—α-distributed and α-centralized, where only a fraction of the nodes (α) scan, as opposed to all nodes in the generic distributed and centralized schemes scanning.
- Numerical evaluation and comparison of energy consumption costs of generic distributed and centralized schemes against α-distributed and α-centralized schemes.
- Study of the optimal values of α and number of nodes in the network, N.
- Conclusive energy-comparison study of non-cooperative sensing schemes and cooperative schemes.

1.8 Organization of Thesis

Chapter 1 discusses the basics of cognitive radio, the need for cognitive radios, cognitive radio components, how cognitive radios help in sustainability of portable devices, and the need for energy-efficient cognitive radios. The remainder of this thesis work is organized as follows: related literature work is discussed in chapter 2; an overview of current sensing schemes and proposed α-schemes is discussed in chapter 3; in chapter 4, a system model is developed, and based on this, further energy consumption analysis equations are developed in chapter 5; an energy savings analysis is performed in chapter 6; and further mathematical evaluation of these equations and the interpretation of results is presented in chapter 7.

CHAPTER 2

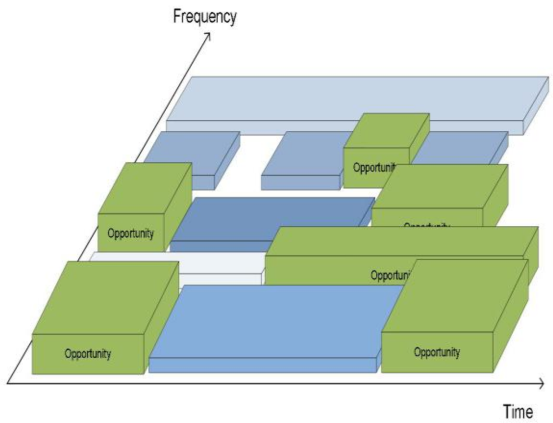
LITERATURE REVIEW

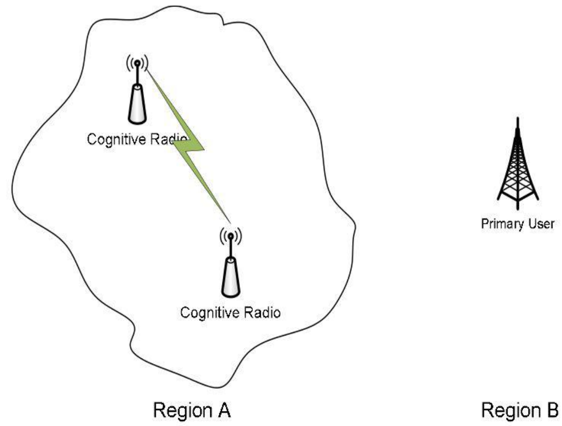
In this chapter, we first discuss about spectrum sensing, the key component of the CR framework and how vacant spectrum can be hunted in different dimensions of the signal. In the next subsection, the metrics that are used to measure the performance of CR networks through PU detection are discussed. In the third subsection, we look at the physical layer spectrum sensing techniques. The fourth subsection mainly discusses the MAC layer spectrum sensing techniques and prior work done in this area, which also gives an insight as to where this thesis work fits.

2.1 Spectrum Sensing

Cognitive radio spectrum sensing is the sensing of the radio frequency spectrum for spectrum opportunities or holes in the spectrum space. These spectrum opportunities can be defined in terms of a signal's frequency, time, space, and code dimensions/properties. Figure 5 is a pictorial representation of the sensing that is possible in some of the most popular multiple dimensions of the signal. Most of the conventional sensing methods available make use of frequency, time, and space, but the spectrum opportunities in the code dimension of a signal still have a considerable room for improvement [10].

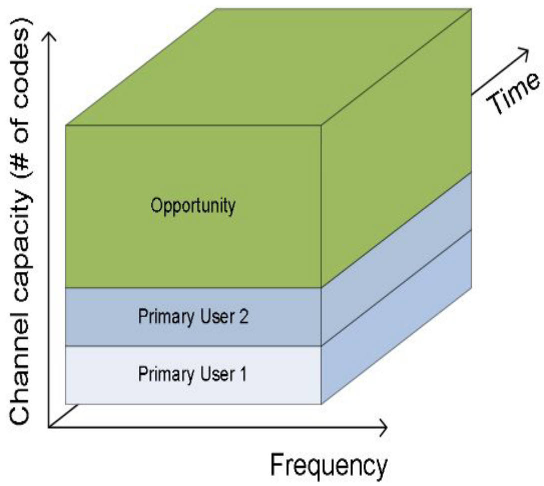
With the advent of multidirectional antennas, spectral opportunities in newer dimensions such as the angle dimension have opened up. If a PU and SU are in the same geographical location, the SU can still access the spectrum in a different angular direction other than that of the PU and not cause any service disruptions as depicted in the figure below.

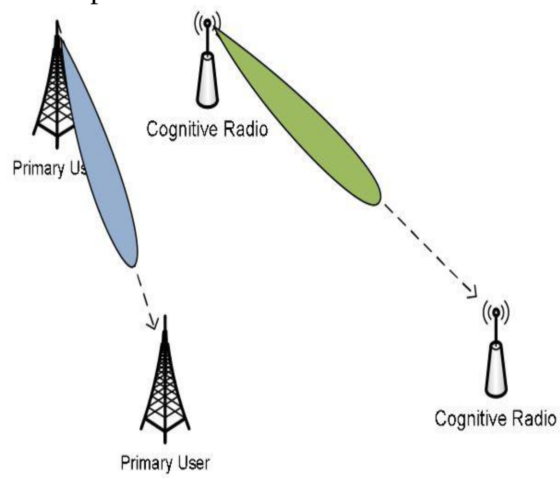




(a) Spectrum opportunities in frequency and time

(b) Spectrum opportunities in geographical space





(c) Spectrum opportunities in code

(d) Spectrum opportunities in angle

Figure 5. Spectrum opportunities in multidimensional radio-frequency space [10]

The next section discusses cognitive radio metrics frequently used to gauge the effectiveness of spectrum-sensing schemes.

2.2 Metrics

The following are two key metrics needed to measure the performance of cognitive radio networks:

- <u>Spectrum Accuracy</u>: Spectrum accuracy defines the accuracy with which a cognitive radio network detects PUs. It is generally expressed in the form of probability detection ratios (PDRs). The most commonly used PDRs are probability of detection and probability of false alarms [11]. Probability of detection is the probability with which the PU is detected. The better the probability of detection, the lesser the interferences to PUs. The probability of false alarms is the probability that a SU detects/believes the existence of a PU, even when it is absent. A higher probability of false alarm indicates the loss of spectrum opportunities. Hence, the ideal values of probability of detection and false alarm are 1 and 0, respectively.

- Spectrum Efficiency: Spectrum efficiency is a metric used to measure the ability of an SU to efficiently detect and use the spectrum opportunities available in all dimensions of the signal. Spectrum efficiency greatly depends on the sensing time of the cognitive radio. The lesser the sensing time, the greater the spectrum efficiency.

CR spectrum sensing techniques could be viewed from two perspectives, based on the network protocol stack:

- Physical layer spectrum sensing
- MAC layer spectrum sensing

These two techniques are discussed in detail separately in the next sections.

2.3 Physical Layer Spectrum Sensing

Physical layer spectrum sensing schemes, also called transmitter-based detection techniques, are used to detect signal transmissions of the primary users by the secondary users through local observations. The most extensively used transmitter-detection techniques are energy detection [12] [13], matched filter detection [14], and cyclostationary feature detection [15], which are further discussed below.

- Energy Detection: In this technique, the CR measures the received signal strength indicator and compares it to a threshold to find if a channel/spectrum band is idle or not. This is the most commonly used spectrum sensing/detection technique for its simplicity and low implementation complexity. In this technique, the receivers need not have the knowledge of the primary signal. However, the accuracy of this technique depends solely on the threshold that is being used, and even when thresholds are set to be adaptive, the presence of high interference and noise level increases the chance of false alarms [10].
- Matched Filter Detection: This is the most optimal method of detection, which maximizes the received signal-to-noise ratio (SNR). In this technique, the signal must be demodulated; hence, the CR should have prior knowledge of the PU-transmitted signal properties, such as modulation type and order, signal structure, and packet format [13]. The time taken to detect a signal with a considerably good probability of detection and false alarm rates is less here when compared to other detection techniques [14]. The biggest issue with this technique is that the CR requires a dedicated receiver for each type of PU signal.
- Cyclostationary Feature Detection: This technique detects the PU signal by extracting its cyclostationary features. In general, every signal that is modulated with carrier signals like sine waves, pulse trains, or cyclic prefixes can be characterized by a cyclostationary process for its periodicity in mean, autocorrelation, and other statistics. Such cyclostationary features can also be added explicitly to further aid in spectrum sensing. Unlike the modulated signal, which is cyclostationary, the noise is wide-sense stationary without any correlation, and this is how the cyclostationary feature detector exploits this periodicity for the detection of the signal [16].

Apart from this waveform-based sensing, radio identification-based sensing, multitaper spectral estimation, and time frequency analysis are a few other physical layer sensing techniques used in the detection of primary user signals.

2.4 MAC Layer Spectrum Sensing

MAC layer spectrum sensing schemes are techniques that lay the foundation and rules for the efficient use of spectrum opportunities. They play a key role in the determination of sensing schedules for SUs and other such orchestration details required for achieving the maximum spectrum efficiencies possible. Based on whether spectrum detection and spectrum decisions are made individually or collaboratively, CR MAC sensing schemes can be classified into "local" spectrum sensing and "cooperative" spectrum sensing, which are explained below in detail.

- Local Spectrum Sensing: In local spectrum sensing, each CR node (SU) makes a decision on the presence of the primary user, based on its local sensing measurements alone. This is a device-centric scheme and does not require any communication with neighboring nodes in making spectrum decisions. In reference to this, local spectrum sensing is also known as a non-cooperative sensing scheme. Depending on how the channels are scanned for the PU, different types of non-cooperative schemes have been proposed, of which a few notable schemes are discussed below.
    - Greedy Scan: In this scanning technique, each node scans a channel, one after another, until it finds a better channel than the current one [9].
    - Selective Scan: Here, each node selectively scans each channel from its list of channels previously found favorable with a higher probability than the channels that were previously found unfavorable [8].

- ○ Sticky Scan: This is a reactive technique in which each node switches or scans for a new channel only when its energy consumption in the present channel exceeds a set threshold [8].
- ○ Optimal Scan: In this technique, each node scans all available channels, one by one, and then chooses the best one among them [9].

Before moving forward to discuss cooperative spectrum sensing, it is important to examine the drawbacks of non-cooperative sensing and how cooperative mechanisms provide solutions to these. Because of the intrinsic nature of the wireless media, there are high chances for the nodes to be blinded by shadowing, fading, interference, and hidden-node problems, which, if taken individually, degrade the accuracy of these techniques and alter the spectrum decisions. The effects of these degradations have been studied by Ghasemi and Sousa [17]. To overcome this blinding phenomenon, cooperative sensing has been found to be far superior than local/non-cooperative sensing alone, as it solves the hidden-node problem in addition to the others mentioned. The various versions of cooperative sensing schemes are discussed in the following section.

- Cooperative Spectrum Sensing: In cooperative sensing, nodes in a group make a decision about the presence of a primary user by sharing their spectrum-sensing decisions, which are based on individual, local sensing measurements. This collaboration helps the nodes to obtain a global perspective about the presence of a PU in a channel and thus increases both spectrum detection accuracies and efficiencies.

The next two paragraphs provide a quick overview of the prior work done in cognitive network cooperative sensing schemes, with more emphasis placed on two well-known CR cooperative sensing implementations—distributed and centralized cluster-based schemes.

In a distributed cooperative sensing scheme, SUs share the sensed information among themselves and make individual decisions. The advantage here is that there is no need for a common receiver infrastructure and high bandwidths [18]. Distributed collaboration schemes are discussed in the literature [19]. Laneman [20] and Chen and Motani [21] discuss relay-based cooperation, where a few SUs act as relays to other SUs. In the work of Chen and Motani [21], amplify and relay (AR) and detect and relay (DR) schemes are proposed for sensor networks.

In a centralized cooperative sensing system model, there is a common receiver that collects all sensing information done by SUs (CRs). The author's interest is mainly on cluster-based schemes, where SUs are grouped into clusters or teams for collaboration, because to design an energy-efficient cooperative sensing scheme, grouping would be a key component to take advantage of team collaboration instead of placing the burden of sensing a very large spectrum on each SU [22]. By grouping SUs into clusters and selecting the most favorable in every cluster to report to a common receiver, sensing performance can be greatly enhanced [23]. Guo and Peng [24] did a study on the optimal number of clusters required to minimize the communication overhead without loss in the detection performance. In the work of Shen and Zhao [25], a two-level hierarchical cluster-based architecture is proposed, where a low-level collaboration is among the SUs within a cluster, and a high-level collaboration is among the cluster heads chosen for each cluster. Other grouping techniques have been studied in [26, 27, 28, 29].

Although many variations of cooperative sensing schemes exist, the author's objective is to study the amount of energy consumption in both categories. Also, improved versions of both the generic distributed and centralized schemes are proposed, and the relative energy savings, through evaluations, are demonstrated.

Until now, most of the work on cooperative sensing in CR networks mainly focused on increasing throughput and spectrum-sensing efficiency/accuracy. Not much has been done on analyzing the energy efficiency of these schemes.

Also, since there is no consensus over which specific scanning scheme performs the best, the author chose to look at a generic class of schemes and apply the developed energy model to evaluate their energy consumption.

Chapter 3 provides a brief overview of the existing sensing schemes and the proposed α-schemes.

CHAPTER 3

OVERVIEW OF SENSING SCHEMES

Spectrum sensing is a key critical component in cognitive radio technology, since the ability of cognition is achieved through the spectrum-sensing functionality of CR. These spectrum sensing schemes can be roughly classified into two categories: non-cooperative sensing and cooperative sensing.

3.1 Non-Cooperative Sensing Schemes

Non-cooperative sensing schemes, also known as local sensing schemes, involve each node in the network individually sensing the spectrum for free channels. These nodes do not share the scanned information with their neighbors, and hence, no reporting is involved in a non-cooperative sensing cycle. The non-cooperative sensing scheme used in this work is the "optimal scan scheme" from the work of Namboodiri [9]. In this optimal scan scheme, every node must scan all channels before choosing the optimal channel among them.

3.2 Cooperative Sensing Schemes

In cooperative sensing schemes, all nodes in the network sense/scan the spectrum and share this information with all neighboring nodes in the reporting phase. This process reduces CR blinding due to interference and fading, and hence increases the probability of PU detection. To be precise, the collaboration of SUs can be used to either increase the number of channels scanned or improve the detection probabilities by having multiple nodes scan a channel. In this work, the author looks at more of a parallel cooperative sensing [30], where all nodes share the different channels to be scanned, scan the designated channels in parallel (concurrently), and then convey this information through their sensing reports (SRs). The main functionalities performed by a CR in the cooperative sensing scheme are scanning, reporting, and using the channel, as depicted in Figure 6.

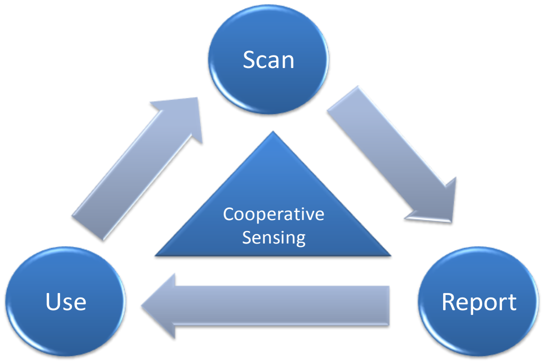


Figure 6. Cooperative sensing cycle

Each sensing cycle (SC) has a scanning period (SP) and a reporting period (RP). Based on how the reporting/sharing is accomplished in the reporting period, cooperative sensing can be categorized into two broad classes of architectures: distributed and centralized.

3.2.1 Distributed Sensing Scheme

In a distributed sensing scheme, shown in Figure 7, each node scans its share of channels during the SP and shares this information with all its neighbors in the RP.

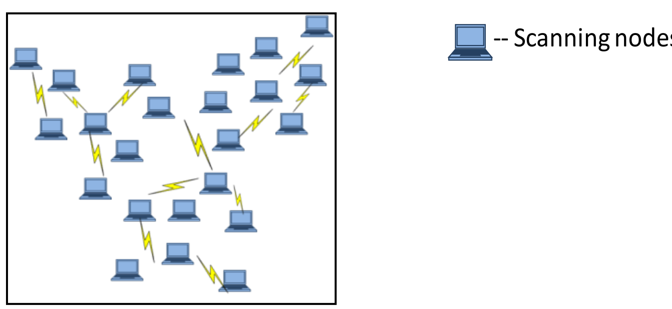


Figure 7. Distributed sensing scheme

3.2.2 Centralized Cluster-Based Sensing Scheme

In the centralized cluster-based sensing scheme, as shown in Figure 8, the entire network of nodes can be divided into clusters (based on some higher-layer protocol). Each cluster has a cluster head (CH), which does not carry out the scanning. Only the cluster members (CMs) in each cluster scan their share of the channels and convey this information to their respective CH. The CHs then share this information with the other remaining CHs in the network. Two levels of communication are occurring here—one at the intra-cluster level and the other at the inter-cluster level between CHs. At the end of the inter-cluster level information exchange, all nodes in the entire network have a global view of the channel information/spectrum map of all the channels scanned.

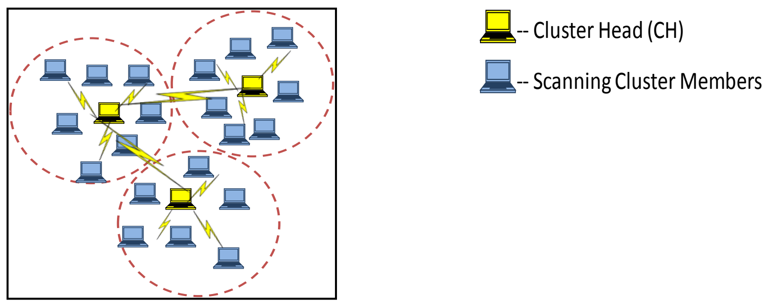


Figure 8. Centralized sensing scheme

3.3 Proposed α-Sensing Schemes

In this section, α-sensing schemes are proposed in an effort to make the conventional schemes more energy efficient. In α-sensing schemes, only a fraction of the nodes share the burden of scanning the channels in each sensing cycle. This is a form of load sharing, which saves energy for the other fraction of nodes in that sensing cycle and, at the same time, makes all channel scanning complete by the end of the sensing cycle. This fraction of nodes can actually be chosen based on their SNRs and PDRs in order to attain better spectrum-sensing accuracy. The α-schemes can also be enhanced for robustness by having multiple nodes (>1) scan each channel. In case of a node failure, the remaining network still receives that specific channel information from the other remaining nodes scanning that channel.

3.3.1 α-Distributed Sensing Scheme

In the α-distributed sensing scheme, as shown in Figure 9, only an "α" fraction of nodes scans the channels in a given sensing cycle. However, they still share this information with all neighbouring nodes, which is similar to the conventional distributed sensing scheme. This saves energy, since each node must scan only α percentage of the times on average, in any given number of sensing cycles. This subset of α nodes can be chosen based on a probabilistic random number generator. For every scanning period, each node, through a probabilistic method (random number generator) decides to participate in scanning if the generated value is less than the "α" value. In this way, on average, each node in the network scans once in "$\left(\frac{1}{\alpha}\right)$" sensing cycles. Also, each scanning node could choose the particular channels to be scanned through some unique mapping hash function based on their node id or MAC address in this α-distributed scheme.

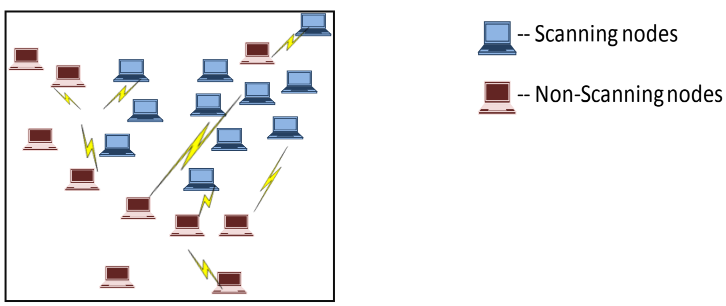


Figure 9. α-Distributed sensing scheme

3.3.2 α-Centralized Cluster-Based Sensing Scheme

In the α-centralized sensing scheme, as shown in Figure 10, instead of all the cluster members in the cluster scanning for channels, only a fraction α of them share the scanning responsibility and report this information to their respective CHs. The CH in turn shares this information with other CHs similar to the centralized scheme. Once the CHs receive all the other cluster scan information, each CH shares a final report with the CMs of its cluster. In this scheme, the fraction α of the CMs in each cluster is chosen by the CH and the channels each node should scan are assigned by the CH.

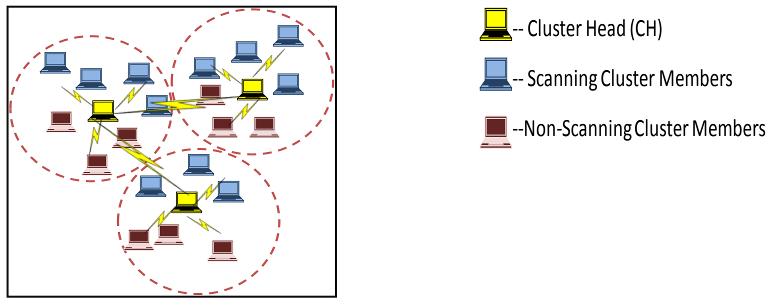


Figure 10. α-Centralized scheme

Although another option of choosing a fraction α of the clusters itself, instead of a fraction of the CMs from each cluster is possible; keeping in mind the spatial diversity benefits of the clusters when the channel characteristics are varying, it is preferably better to have the scanning carried out in all the clusters across the network for better sensing accuracies rather than a few clusters.

Both the α-distributed and α-centralized schemes could be designed to have minimal energy overhead. In the α-distributed scheme, based on the length of sensing cycle, the number of nodes in the network and the number of channels to be scanned, each of the nodes can calculate an α value and using a random number generator chose to sense or stay idle in that sensing cycle. Now, this calculation of the α value and random number generation require a few CPU cycles on each node during which energy has to be spent/consumed. However this energy is usually lower than the energy consumed to communicate and hence can be ignored. In the α-centralized scheme, the cluster heads can first calculate the α value and based on it, randomly choose the scanning nodes and then assign the channel scanning responsibility to these chosen nodes.

To further study these schemes, the system model and the analytical energy model are developed in the chapter 4.

CHAPTER 4

SYSTEM MODEL

4.1 Basic Common Aspects of Cooperative Sensing Model

As the basis of the system model, the author envisions a crowded ad hoc WLAN scenario where all nodes are connected in a clique time synchronized network and, hence, are in hearing range of each other. Each node has two transceivers/radios: one completely dedicated for sensing and reporting, and the other for data transmission. The radio for sensing and reporting shifts to the channel(s) that needs to be scanned during the scanning period and finally shares the reports over the control channel during the reporting period. The other physical radio for data transmission switches to the vacant channel over which it could transfer the data. The frame structures of scanning, reporting, and data transmission are shown in Figure 11.

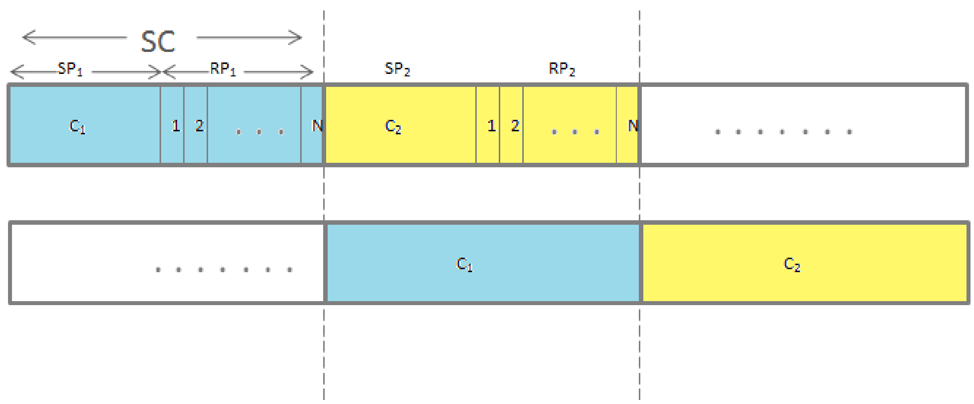


Figure 11. Time frame structures of scanning and reporting, and data transmission, respectively

At the end of the scanning period, each node shares a sensing report with all remaining nodes through a single broadcast packet, regardless of the number of channels scanned. In this work, the author assumes that the sensing reports a node receives from the other nodes are uncorrupted and trustworthy. Since the nodes perform parallel scanning, at the end of the reporting period, every node would have the spectrum map of all channels. The author does not presume the existence of a fusion center in this "on the fly" network for both the distributed and centralized architectures. In the distributed scheme, each node acts as a fusion center for itself; while in the centralized scheme, the cluster head can assume this role for its cluster.

4.2 Orchestration

The total number of channels to be sensed "C" by the network of "N" nodes are decided prior to the start of the sensing cycle. Since there is no reporting involved in the non-cooperative sensing scheme, each node scans all C channels in the scanning period.

In the distributed cooperative sensing scheme, each node scans its share of designated channels in the scanning period. In the reporting period, it broadcasts this information to its $(N-1)$ neighbors in the form of sensing report (SR) and similarly decodes the $(N-1)$ SRs it receives from its scanning neighbors. In the centralized scheme, each cluster member scans its share of designated channels and sends an SR to the cluster head. The cluster head, after collecting all SRs from its CMs, broadcasts an SR with the scan information of its cluster to all other CHs in the network. Similarly, after receiving all SRs from its peer CHs, each CH then sends a final consolidated SR with all channel scan information to its CMs. Once these final SRs from the corresponding CHs are shared, all CMs and CHs have a global view of all channels scanned by the entire network.

In case of a network partition due to failure of a node, whichever nodes are connected shall behave as independent sets and should still be able to carry out cooperative scanning in smaller groups (both in the case of distributed and centralized). For smaller groups, the number of channels to be scanned could be chosen to be lower to reduce the sensing burden.

4.3 Energy Model of Sensing Cycle

Energy consumed by each node per sensing cycle E_S is the sum of the total energy to scan all assigned channels E_{Tscan}, total energy to switch between these channels E_{Tsw}, total energy to transmit/broadcast the SR(s) to other nodes E_{Tx}, and total energy to receive SRs from all other nodes E_{Rx} :

$$E_S = E_{Tscan} + E_{Tsw} + E_{Tx} + E_{Rx}$$

Based on the above system and energy model developed, appropriate equations for energy-consumption analysis are derived in chapter 5. The variables used are defined in TABLE 1.

TABLE 1

DEFINITION OF VARIABLES USED [9]

Variable	Definition
P_{scan}	Power consumed to scan channel (700 mW)
P_{sw}	Power consumed to switch once between channels (750 mW)
P_{tx}	Power consumed to transmit packet (750 mW)
P_{rx}	Power consumed to receive packet (750 mW)
T_{scan}	Time to scan channel (50 ms)
T_{sw}	Time to switch once between channels (0.06 ms)
T_{data}	Time to transmit data packet (0.08 ms)
E_{scan}	Energy consumed to scan channel = P_{scan} T_{scan}
E_{sw}	Energy consumed to switch once between channels = P_{sw} T_{sw}
E_{srt}	Energy consumed to transmit SR = P_{tx} T_{data}
E_{srd}	Energy consumed to decode/receive SR = P_{rx} T_{data}
C	Number of channels
N	Number of nodes in network
N_S	Number of scanning nodes in network
α	Fraction factor
K	Number of clusters into which entire network of N nodes is divided/grouped
M	Number of cluster members (CMs)
M_S	Number of scanning CMs

CHAPTER 5

ENERGY CONSUMPTION ANALYSIS OF SENSING SCHEMES

5.1 Non-Cooperative Sensing Scheme

Since there is no reporting period in a non-cooperative sensing scheme, the energy consumed by each node is simply the sum of energy to scan the designated channels and the energy consumed to switch between those channels. Each node scans $C\ (\geq 1)$ channels and hence must switch $(C-1)$ times when hopping from one channel to another. Therefore,

$$E^{S}_{non-coop} = \ CE_{scan} + (C-1)\ E_{sw}$$

where $E^{S}_{non-coop}$ is the energy consumed for each node during the scanning period.

The total energy consumed by all N nodes in the network to sense C channels in this non-cooperative sensing scheme is given by

$$E_{non-coop} \ = \ NE^{S}_{non-coop}$$

$$E_{non-coop} \ = \ NCE_{scan} + N(C-1)E_{sw} \tag{1}$$

5.2 Distributed Sensing Scheme

In this generic scheme, each node scans $\frac{C}{N}(\geq 1)$ channels in each scanning period as long as $N > 1$. If $N > C$, not every node must scan the channels. Hence, the total energy for the entire network in the distributed scheme is given by the following generic equation:

$$E_{dist} = N_S E^{S}_{dist} + (N - N_S)E^{NS}_{dist} \tag{2}$$

where $N_S = Min(N, C)$ is the number of scanning nodes, E^{S}_{dist} is the energy consumed by the scanning node, and E^{NS}_{dist} is the energy consumed by the non-scanning node.

For a scanning node, E^{S}_{dist} is the sum of energy to scan the designated $\left(\frac{C}{N_s}\right)$ channels, switch between those channels, transmit one scanning report with channel scan information and receive $(N_s - 1)$ SRs from the other scanning nodes. For a non-scanning node, E_{dist}^{NS} is the energy to decode all SRs received from the scanning nodes.

$$E_{dist}^{S} = \left(\frac{C}{N_s}\right) E_{scan} + \left(\frac{C}{N_s} - 1\right) E_{sw} + E_{srt} + (N_s - 1) E_{srd} \tag{3}$$

$$E_{dist}^{NS} = N_s E_{srd} \tag{4}$$

Substituting equations (3) and (4) into (2) gives rise to the following energy equation for the entire network of nodes of distributed scheme:

$$E_{dist} = CE_{scan} + (C - N_S) E_{sw} + N_S E_{srt} + N_S (N - 1) E_{srd} \tag{5}$$

Since $N_S = Min(N, C)$, the following two cases are possible:

If $N \leq C$, then

$$E_{dist} = CE_{scan} + (C - N) E_{sw} + NE_{srt} + (N^2 - N) E_{srd} \tag{6}$$

If $N > C$, then only C nodes are required to scan:

$$E_{dist} = CE_{scan} + CE_{srt} + (NC - C) E_{srd} \tag{7}$$

5.3 α-Distributed Sensing Scheme

In this scheme, for a chosen value of α $(0 < \alpha \leq 1)$, only αN nodes perform the scanning, while the remaining nodes do not scan for that scanning period. Hence, for a given number of sensing cycles, the nodes in this scheme would have to scan only for α percentage of the cycles on average, while they save on their energy for the remaining $(1 - \alpha)$ percentage of the cycles. Practically, since the sensing nodes αN cannot be either less than 1 or, for that matter, greater than *C*, the author arrives at the following bound for α:

$$\left(\frac{1}{N}\right) \leq \alpha \leq Min\left(\frac{C}{N}, 1\right) \tag{8}$$

Because of this α bound, the possibility of $\alpha N > C$ in this α-scheme can be completely ruled out.

Substituting $N_S = \alpha N$ in equations (2 to 4) gives the following energy equations for each of the scanning node and for the entire network, equations (9) and (10), respectively.

$$E_{\alpha-dist}^{S} = \left(\frac{C}{\alpha N}\right) E_{scan} + \left(\frac{C}{\alpha N} - 1\right) E_{sw} + E_{srt} + (\alpha N - 1) E_{srd} \tag{9}$$

$$E_{\alpha-dist} = C E_{scan} + (C - \alpha N) E_{sw} + \alpha N E_{srt} + \alpha (N^2 - N) E_{srd} \tag{10}$$

where $E_{\alpha-dist}^{S}$ is the energy consumed by the scanning node, and $E_{\alpha-dist}$ is the energy consumed by the entire network of nodes.

5.4 Centralized Cluster-Based Sensing Scheme

In this generic centralized scheme, the network of N nodes is divided into K clusters, each cluster having a group of $M + 1$ nodes such that $N = K(M + 1)$. Thus, each cluster of $M + 1$ nodes has one cluster head (CH) and M cluster members (CM). The CMs alone do the scanning and send their sensing reports to their respective CHs. Each CH then shares this information with the remaining CHs. A final SR is then broadcast from the CH to its CMs. In this work, we do not consider the energy consumed for cluster formation and cluster head election.

Each cluster must scan $\left(\frac{C}{K}\right)$ (≥ 1) channels; hence, the energy consumed for each cluster per sensing cycle is

$$E_{cent}^{C} = E_{cent}^{CH} + M_S E_{cent}^{S} + (M - M_S) E_{cent}^{NS} \tag{11}$$

where $M_S = Min(M, \frac{C}{K})$ is the number of scanning CMs, E_{cent}^{CH} is the energy consumed by the CH, E_{cent}^{S} is the energy consumed by the scanning CM, and E_{cent}^{NS} is the energy consumed by the non-scanning CM.

Each CH transmits K SRs: one SR containing the scanned channel information of the cluster is unicast to each of the remaining $(K - 1)$ CHs, and one SR is broadcast back to the

CMs after receiving all SRs from the $(K-1)$ CHs. Thus each CH has to decode all the M_S SRs from its CMs and $(K-1)$ SRs from the other CHs. For simplicity of evaluation, a basic access mode of IEEE 802.11 [31] without request to send/clear to send (RTS/CTS) is considered, and the energy for the acknowledgment (ACK) in the case of unicast transmission is ignored. For easier simplification, the energy for the DCF interframe space (DIFS) is also ignored.

$$E_{cent}^{CH} = KE_{srt} + \left(M_S + (K-1)\right)E_{srd} \tag{12}$$

Each CM transmits an SR to the CH after scanning $\left(\frac{C}{KM_S}\right)$ channels and decodes the final SR that it receives from its CH.

$$E_{cent}^{S} = \left(\frac{C}{KM_S}\right)E_{scan} + \left(\frac{C}{KM_S} - 1\right)E_{sw} + E_{srt} + E_{srd} \tag{13}$$

The energy consumed by the non-scanning CMs is

$$E_{cent}^{NS} = E_{srd} \tag{14}$$

$$E_{cent} = KE_{cent}^{C} \tag{15}$$

Substituting equations (11 to 14) into (15) gives the energy equation for the entire network of nodes in the centralized scheme:

$$E_{Cent} = CE_{scan} + (C - KM_S)E_{sw} + K\,(M_S + K)E_{srt} + K\,(M_S + M + K - 1)E_{srd} \tag{16}$$

Similar to the distributed scheme, if $M > \left(\frac{C}{K}\right)$, then not every CM must scan in the cluster, and hence, the following two cases are possible:

If $M \leq \left(\frac{C}{K}\right)$, then

$$E_{cent} = CE_{scan} + (C - KM)E_{sw} + K\,(M + K)E_{srt} + K\,(2M + K - 1)E_{srd} \tag{17}$$

If $M > \left(\frac{C}{K}\right)$, then

$$E_{cent} = CE_{scan} + (C + K^2)E_{srt} + \big(C + K(M + K - 1)\big)E_{srd} \tag{18}$$

5.5 α-Centralized Cluster-Based Sensing Scheme

In this scheme, only αM CMs in each cluster do the scanning, while the remaining $(M - \alpha M)$ CMs do not scan for that SP. αM can be neither less than 1 nor greater than $\left(\frac{C}{K}\right)$. $\left(\frac{C}{K}\right)$ is the number of assigned channels for each cluster, which would also be the required number of scanning nodes. Translating this to a mathematical bound gives

$$\left(\frac{1}{M}\right) \leq \alpha \leq Min\left(\frac{C}{KM}, 1\right)$$

Because of this α bound, the possibility of $M_S > \left(\frac{C}{K}\right)$ in this scheme can be completely ruled out.

Substituting $M_S = \alpha M$ in equations (11 to 15) gives the following energy equation for the entire network of nodes in the α-centralized scheme:

$$E_{\alpha-cent} = CE_{scan} + (C - K\alpha M)E_{sw} + K(\alpha M + K)E_{srt} \tag{19}$$

$$+ K\big((1 + \alpha)M + (K - 1)\big)E_{srd}$$

In chapter 6, the author analyzes the energy savings and optimal values of α and N based on the above-derived equations.

CHAPTER 6

ENERGY SAVINGS AND OPTIMAL VALUES

6.1 Energy Savings

Lemma 1:

The distributed cooperative sensing scheme is more energy efficient than the non-cooperative scheme, only when the number of nodes N is greater than one, and the communication energy is less than $\frac{(NC-C)E_{scan}+(NC-N-C+N_S)E_{sw}}{NN_S}$.

Proof:

The distributed scheme saves energy over the non-cooperative scheme, if and only if total energy consumption for the entire network of nodes in the distributed scheme is less than the total energy consumption for the same network of nodes in the non-cooperative scheme. This is represented by the following relation:

$$E_{dist} \leq E_{non-coop} \tag{20}$$

Since communication is possible only when the network has more than one node, for the distributed scheme to be valid and equation (20) to hold, the following condition should be met:

$$N > 1$$

Solving equation (20) using equations (1) and (5) gives the following condition for communication energy:

$$E_{src} \leq \frac{(NC-C)E_{scan} + (NC-N-C+N_S)E_{sw}}{NN_S}$$

where $E_{src} = E_{srt} = E_{srd}$, $N_S = Min(N, C)$ for the distributed scheme, and $N_S = \alpha N$ for the α-distributed scheme.

For ease of simplification, E_{srt}, E_{srd} in equation (5) are jointly denoted by E_{src}, which is the communication energy in general. ■

Lemma 2:

The centralized cluster-based cooperative sensing scheme is more energy efficient than a non-cooperative scheme, only when the number of clusters and the number of cluster members is at least one and the communication energy is less than $\frac{(NC-C)E_{scan}+(NC-N-C+KM_S)E_{sw}}{K\,(2M_S+2K+M-1)}$.

Proof:

The centralized scheme saves energy over the non-cooperative scheme, if and only if total energy consumption for the entire network of nodes in the centralized scheme is less than the total energy consumption for the same network of nodes in the non-cooperative scheme. This is represented by the following relation:

$$E_{cent} \leq E_{non-coop} \tag{21}$$

For a network to form a cluster, there should at least be one cluster and one cluster member in the cluster, and hence the following condition:

$$K \geq 1,\ M \geq 1$$

Solving equation (21) using equations (1) and (16) gives the following condition for the communication energy:

$$E_{src} \leq \frac{(NC-C)E_{scan}+(NC-N-C+KM_S)E_{sw}}{K\,(2M_S+2K+M-1)}$$

where $E_{src} = E_{srt} = E_{srd}$, $M_S = Min(M, \frac{C}{K})$ for the centralized scheme, and $M_S = \alpha M$ for the α-centralized scheme. ■

6.2 Optimal Values for α-Distributed Scheme

6.2.1 Optimal α for Maximum Energy Savings

The optimal α for a given N is defined as the value of α, where the energy savings of the α-distributed scheme over the distributed are the maximum. The energy savings can be looked at, from two different perspectives—energy savings for the entire network of nodes and energy savings per scanning node in the network. The author first examined the optimal α for maximum energy savings, considering the entire network of nodes over one sensing cycle paired with various constraints to form a set of optimization problems.

<u>Optimization Problem 1: Optimal α for Entire Network of Nodes</u>

$$\text{Maximize } f(\alpha) = \left(\frac{E_{dist} - E_{\alpha-dist}}{E_{dist}}\right) \text{ such that } \left(\frac{1}{N}\right) \leq \alpha \leq Min\left(\frac{C}{N}, 1\right)$$

The α value, considered "optimal" in the context of this work, is the value of α where the α-distributed scheme shows the maximum energy savings over the distributed scheme considering the entire network of nodes for a given sensing cycle. $f(\alpha)$ is maximized at $\alpha = \left(\frac{1}{N}\right)$, which becomes the optimal α. However, considering the shadowing phenomenon, battery characteristics of the wireless nodes and, most importantly, the limited scanning and reporting periods, this value should be chosen with discretion in order to avoid poor spectral efficiencies and accuracies, and shorter operating lifetimes, respectively [32]. Hence, a constraint to limit the sensing and reporting time in a given sensing cycle is needed, as shown in the next optimization problem.

<u>Optimization Problem 2: Optimal α for Entire Network of Nodes with Time Constraint</u>

$$\text{Maximize } f(\alpha) = \left(\frac{E_{dist} - E_{\alpha-dist}}{E_{dist}}\right) \text{ such that } \left(\frac{1}{N}\right) \leq \alpha \leq Min\left(\frac{C}{N}, 1\right) \text{ and } L \leq l$$

where L is the total time for the SC as defined below:

$$L = \left(\frac{C}{\alpha N}\right) T_{scan} + \left(\frac{C}{\alpha N} - 1\right) T_{sw} + \alpha N\, T_{data} \tag{22}$$

In the evaluation section, the optimal values where $f(\alpha)$ is maximized and the constraint $L \leq l$ ms is satisfied are plotted.

Also, for further study of the relative energy cost comparison of a scanning node in a distributed scheme versus a scanning node in a α-distributed scheme, the function $f(\alpha)$ is maximized with a "per-scanning-node" energy constraint, as shown in the next optimization problem.

<u>Optimization Problem 3: Optimal α for Entire Network of Nodes with Per-Scanning-Node Energy Constraint</u>

Maximize $f(\alpha) = \left(\frac{E_{dist} - E_{\alpha-dist}}{E_{dist}}\right)$ such that $\left(\frac{1}{N}\right) \leq \alpha \leq Min\left(\frac{C}{N}, 1\right)$ and $g(\alpha) \geq 0$

where $g(\alpha) = \left(\frac{E^S_{dist} - E^S_{\alpha-dist}}{E^S_{dist}}\right)$.

The $g(\alpha) \geq 0$ constraint was taken into account, considering the fact that for a given sensing cycle, although the α-distributed scheme saves energy for the network of nodes N on the whole, it should not burden each scanning node with a very high number of channels to be scanned, thus causing the node to die more quickly. This constraint ensures that the energy of the scanning nodes in the α-distributed scheme is either less than or at least equal to the energy of the scanning node in the distributed scheme. The optimal α with this constraint is always the upper bound of α given by $Min\left(\frac{C}{N}, 1\right)$. However if the constraint is relaxed to be less than zero, i.e., $g(\alpha) \leq 0$, the optimal α would move to the lower bound, which is $\left(\frac{1}{N}\right)$. Thus, $g(\alpha)$ helps to explain the fact that the per-scanning-node energy cost of the α-distributed scheme versus that of the scheme distributed over one sensing cycle is always higher, except at $Min\left(\frac{C}{N}, 1\right)$, where it equals the distributed scheme. In the next optimization problem, the author shows that the energy savings over a cumulative n sensing cycle period are however positive.

<u>Optimization Problem 4: Optimal *α* for Maximum Energy Savings over *n* Sensing Cycle Period</u>

$$\text{Maximize } f(\alpha) = \left(\frac{E_{dist} - E_{\alpha-dist}}{E_{dist}}\right) \text{such that } \left(\frac{1}{N}\right) \leq \alpha \leq Min\left(\frac{C}{N}, 1\right) \text{ and } h(\alpha) \geq 0$$

where $h(\alpha) = \left(\frac{Min\left(\frac{C}{N}, 1\right)E_{dist}^{S} - \left(\alpha E_{\alpha-dist}^{S}\right)}{Min\left(\frac{C}{N}, 1\right)E_{dist}^{S}}\right)$.

The constraint $h(\alpha)$ defines that, for a given n sensing cycle period, each scanning node in the distributed scheme would have to scan $Min\left(\frac{C}{N}, 1\right) \times n$ times on average, while the scanning node in the α-distributed scheme would have to scan only for $\alpha \times n$ times on average.

With this new constraint, the optimal α value is still $\left(\frac{1}{N}\right)$. However, the numerical evaluation results of $h(\alpha)$ show that the constraint itself results in positive values, unlike the constraint $g(\alpha)$. This goes on to show that the α-distributed scheme saves energy from a scanning node's perspective as well as for the entire network over a given period of *n* sensing cycles and more noticeably at smaller *α* values.

6.2.2 Optimal N for Maximum Energy Savings

It is also interesting to analyze if there is an optimal *N* for a given *α* where the energy savings of the α-distributed over distributed are maximum. The next two optimization problems discuss the same.

<u>Optimization Problem 5: Optimal *N* for Maximum Energy Savings over One Sensing Cycle</u>

$$\text{Maximize } F(N) = \left(\frac{E_{dist} - E_{\alpha-dist}}{E_{dist}}\right) \text{ such that } \left(\frac{1}{\alpha}\right) \leq N \leq Min\left(\frac{C}{\alpha}, 1\right)$$

Solving $F(N)$ for maximization, shows that it is maximized at

$$N = Max\left(\frac{-E_{scan} + \sqrt{E_{scan}{}^{2} + E_{sw}E_{scan} + \left(\frac{C}{\alpha}\right)E_{src}E_{scan} + \left(\frac{C}{\alpha}\right)E_{sw}E_{src}}}{E_{src}}, C\right)$$

Similarly the per node energy savings over *n* sensing cycles are maximized in the next optimization problem.

<u>Optimization Problem 6: Optimal *N* for Maximum Energy Savings over *n* Sensing Cycles</u>

Maximize $G(N) = \left(\frac{Min\left(\frac{C}{N},1\right)E_{dist}^{S} - \left(\alpha E_{\alpha-dist}^{S}\right)}{Min\left(\frac{C}{N},1\right)E_{dist}^{S}}\right)$ such that $\left(\frac{1}{\alpha}\right) \leq N \leq Min\left(\frac{C}{\alpha}, 1\right)$

The function $G(N)$ for the highest magnitude of energy savings per scanning node over *n* sensing cycles is maximized at $N = C$

The values showing the trend of optimal *N* over a varying range of α for functions $F(N)$ and $G(N)$ are plotted separately in the next chapter.

The outcomes of all the above optimizations are completely dependent on α, which is the basis of the relation between distributed and α-distributed. Since this relation remains the same between centralized and α-centralized, the optimization results, and hence the inferences, are going to be similar. Therefore, the author does not examine optimizations for the centralized schemes in this work.

CHAPTER 7

EVALUATION

In this section, a numerical evaluation for all proposed generic equations in the preceding chapter 5 is done to quantify and show the energy savings of the α-schemes over their counterparts. All base values for E_{scan}, E_{sw}, E_{srt}, and E_{srd} are calculated from equations and values specified in TABLE 1 of this work. According to Verma et al. [33], where White-Fi must scan at least 50 TV channels, and according to Biswas et al. [34], where the notion of channels can simply be sub-bands obtained by dividing a given wide band, the author believes that $C = 100$ would be a suitable and practical value for the number of channels to be scanned. In the work of Liang et al. [11], it is shown that the optimal sensing time for a secondary user to detect the primary user with 90% probability is about 15 ms, and according to Kim and Shin [32], the false alarm probability had a linear down trend since scan time was varied from 20 ms to 100 ms. Therefore, the author infers that T_{scan}= 50 ms would be an appropriate value to achieve a good detection probability and low false alarm rates simultaneously. The total energy consumed for each of the schemes by varying the range of number of nodes N and the fraction factor α is evaluated in the following sub-sections.

7.1 Distributed vs. α-Distributed Scheme

Figure 12 shows the energy trends over a varying N for the distributed and α-distributed schemes. The lower the value of α, the lower the energy costs for the α-distributed scheme. These energy savings become more apparent for higher-node densities. However, at the point $\alpha N = C$, the energy cost of the α-distributed scheme equals the distributed scheme, and hence, the energy savings decrease from positive values to zero. This is due to the fact that the significance of the fraction factor α lies only in the range suggested in equation (6), further explaining the point that there is no reason to have scanning nodes greater than the required number, which would be the number of channels C for both the distributed and α-distributed schemes. Hence, the proposed α-distributed scheme holds significance as long as $\alpha N < C$.

Figure 13 shows that the average energy costs of a node for both distributed and α-distributed schemes keep decreasing with increasing node densities. A closer analysis indicates that this is due to the reduction in scanning energies, since with increasing node densities; the number of channels scanned on average by each node keeps decreasing. Although the reporting energy increases on average, this increase is greatly offset by the decrease in the scanning energy since $E_{scan} \gg E_{srt}(or)E_{srd}$.

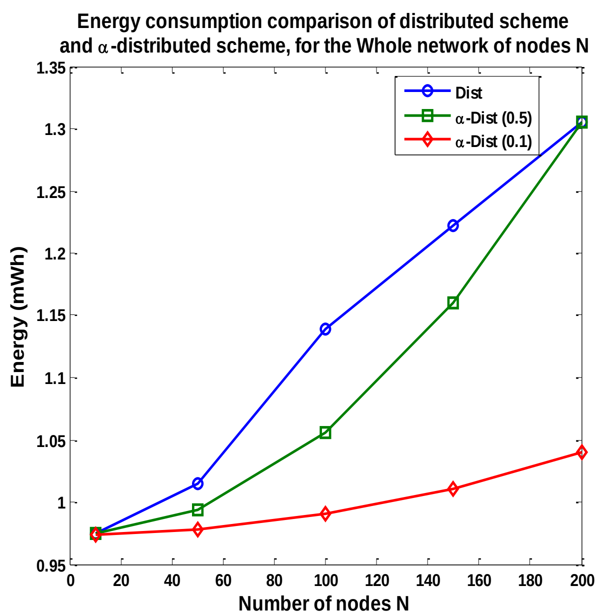


Figure 12. Total energy consumption of entire network of N nodes in distributed and α-distributed schemes

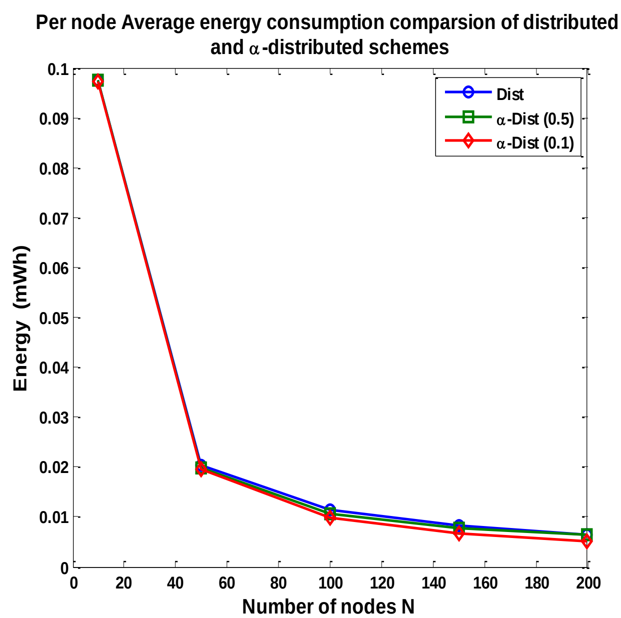


Figure 13. Average energy consumption of each node in distributed and α-distributed schemes

7.2 Optimal Values

The optimal α values for a given N where $f(\alpha)$ is maximized and the constraint of the sensing cycle time length L is satisfied are shown in Figure 14. It is clearly noticeable that the optimal α values decrease with increasing L. With higher L, each node gets to scan a greater number of channels and so fewer scanning nodes are needed, which results in a smaller α.

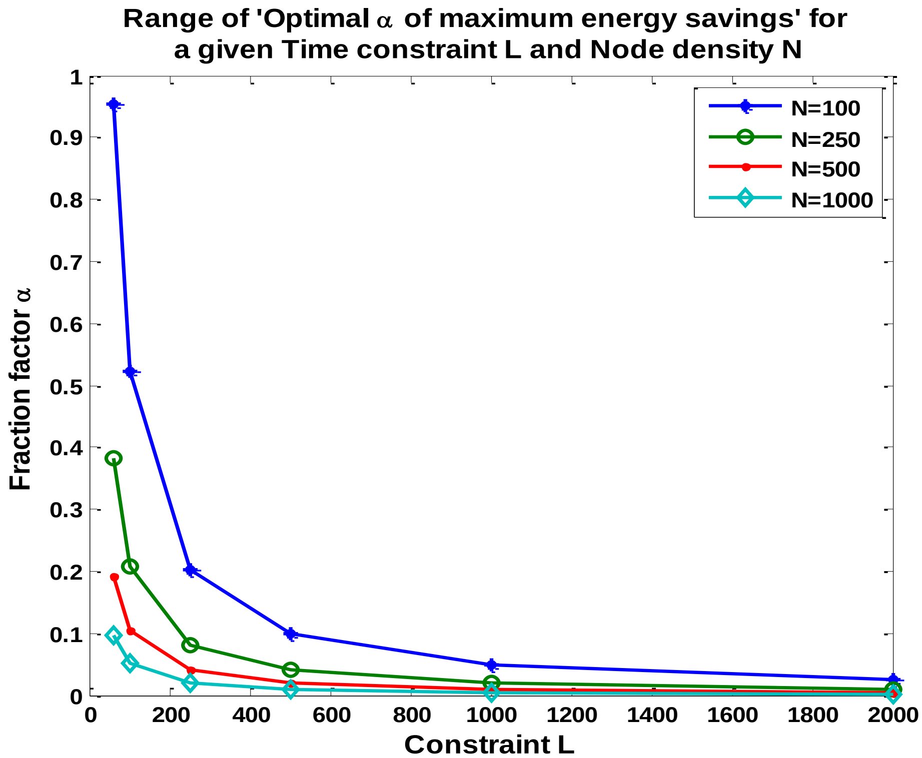


Figure 14. Optimal values of α where energy savings of α-distributed scheme over distributed scheme are maximum, for given N and L

Further examination of optimal values of N for a given α can be done using Figure 15 and Figure 16. The function $F(N)$ has the highest magnitude of energy savings at various values of N for varying α until α = 0.5, after which the optimal N stays at 100 (value of C). The optimal N for function $G(N)$ is always at $N = C = 100$, regardless of the value of α. The energy savings for both $F(N)$ and $G(N)$ predictably decrease with increasing α values.

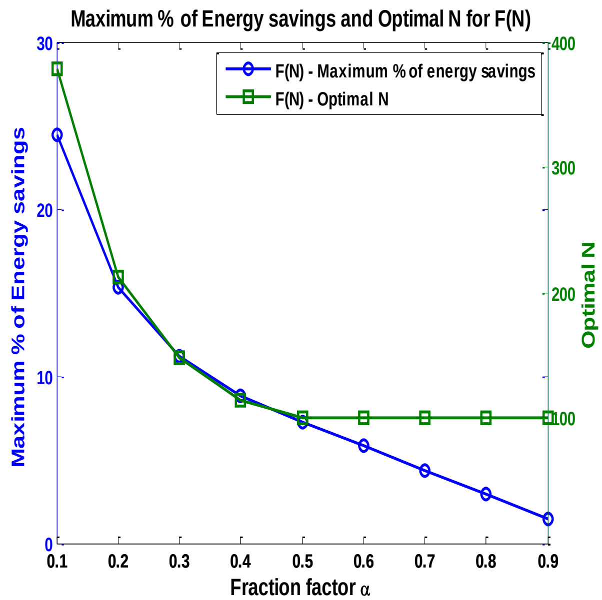


Figure 15. Percentage of energy savings and optimal *N* values where F(N) is maximized

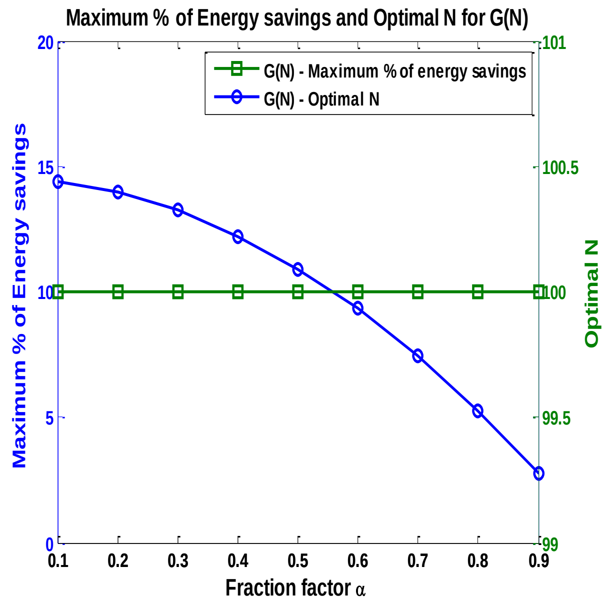


Figure 16. Percentage of energy savings and optimal *N* values where G(N) is maximized

7.3 Centralized vs. α-Centralized Scheme

Figure 17 shows the energy trends over a varying *N* for the centralized and α-centralized schemes. As expected, the centralized schemes in general have lower energy costs than the distributed schemes, and the α-centralized schemes have lower energy costs over the centralized scheme.

The α-centralized schemes have lower energy costs with decreasing α, and this can attributed to the lesser control overheads both for the cluster head and the cluster members. Also, the energy increase with increasing *N* is more linear in the centralized schemes, while this increase is inclined toward being exponential in the distributed schemes. This clearly shows that, in general, centralized schemes are more energy efficient and should be the first choice at higher *N* values. The values used in this plot were derived for $K = 1$. To gain further insight into the impact of K on energy consumption, Figure 18 is shown. It is clearly noticeable that a higher K

results in higher energy overhead. This overhead can be attributed to the increase of the intercluster communication between the cluster heads for reporting.

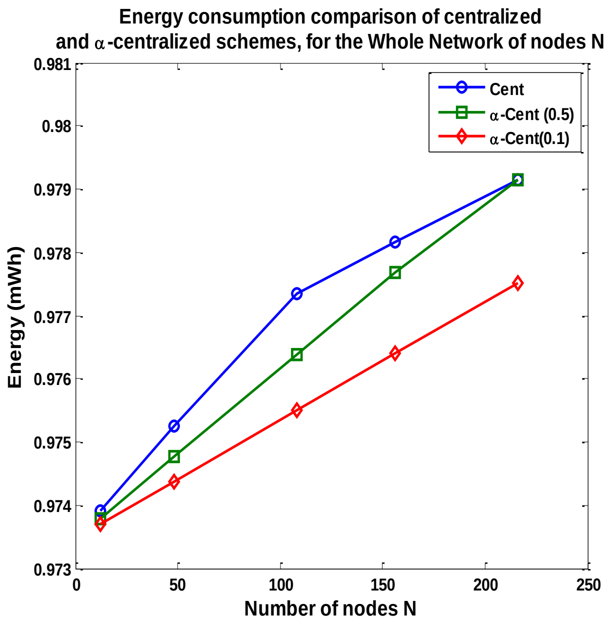


Figure 17. Total energy consumption for entire network of N nodes in centralized and α-centralized schemes

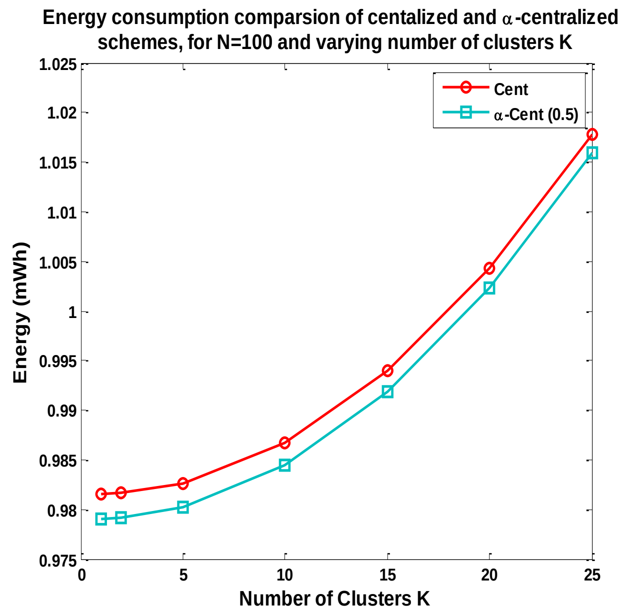


Figure 18. Impact of K on the total Energy consumption for entire network of N nodes in centralized and α-centralized schemes

7.4 Non-Cooperative vs. Cooperative Schemes

Cooperative schemes reduce the energy consumed for sensing through collaborative sharing of the scanning responsibility. Figure 19 proves this claim and shows that a logarithmic scale was used to capture the wide variation of the energy values of non-cooperative schemes and the lower energy values of cooperative schemes.

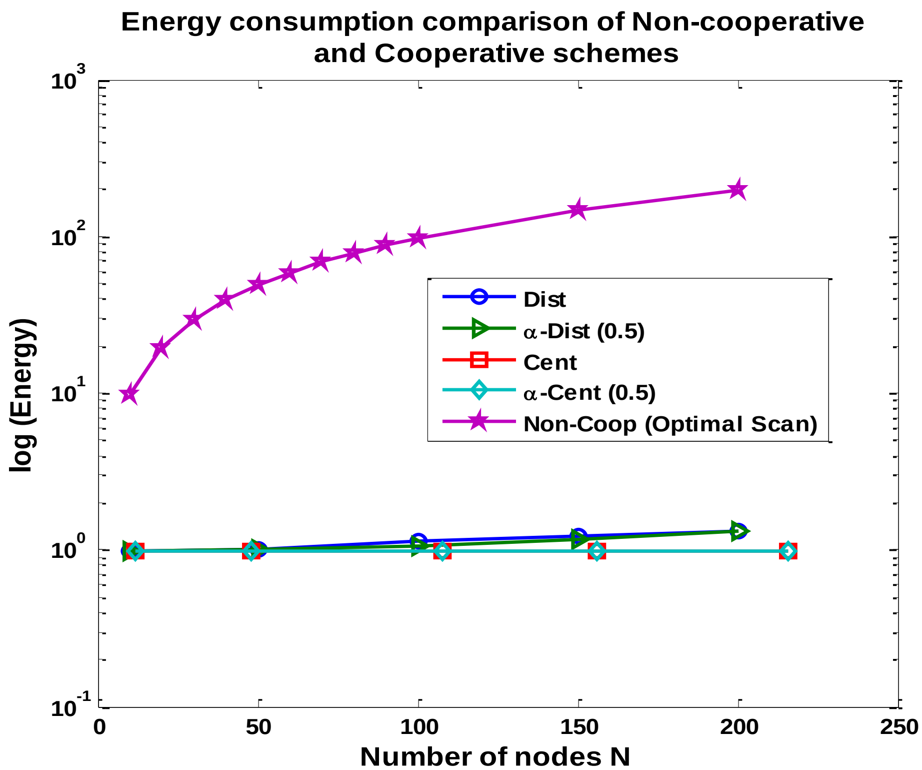


Figure 19. Energy consumption comparison of the Non-cooperative and Cooperative schemes

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

The energy model for sensing developed in this work provides a platform for energy accountability and comparison of non-cooperative sensing schemes and basic cooperative sensing schemes—both distributed and centralized along with proposed new α-schemes. An investigation of their energy costs shows that the cooperative schemes easily outperform the non-cooperative schemes, and regardless of the system conditions being constant across the generic and the α-schemes, the α-schemes are significantly more energy efficient than the generic schemes. Optimal values for the fraction factor α and number of nodes N derived contribute to further useful insights on relative energy savings.

In the system model of this work, ideal conditions such as a clique network, unvarying channel characteristics, uncorrupted/reliable sensing reports and sensing decisions have been considered. An improvised system model considering non-ideal conditions can be proposed in future work. The energy model could also be modified to include the percentage of corrupted/lost sensing reports and false spectrum decision. Further analysis can be done as to how they affect the probability of detection and false alarms that we have not considered in this work. Also, as part of future work, the energy equations and numerical evaluations done in this work can be validated using experimental results and simulations. Better algorithmic specifications on how the α nodes should be chosen (based on energy remaining etc.) and channel assignment is to be done, can be further proposed.

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