
Energy-Efficiency of Cooperative Sensing Schemes in Ad Hoc WLAN Cognitive Radios

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Abstract

In cognitive radio networks, the secondary users need to coordinate among themselves to reap the benefits of cooperative spectrum sensing. In this paper, we study and analyse the energy efficiency of two generic cooperative sensing schemes in an ad hoc WLAN backdrop – distributed cooperative sensing scheme and centralized cluster based cooperative sensing scheme. We further propose corresponding enhanced and adaptive versions of these two schemes where only a fraction of nodes sense in each sensing cycle, as opposed to all the nodes in the network. Using an analytical energy model for sensing, we quantify the energy costs of each of these schemes and perform a comparative numerical analysis to demonstrate the amount of energy savings of the proposed cooperative schemes over their generic counterparts and non-cooperative schemes.

Keywords: cognitive radio, cooperative sensing, energy efficiency, WLAN.

1 Introduction

The world has witnessed a great deal of change this decade when it comes to wireless technologies. Be it Wi-Fi, WiMAX, WSNs or any other subtechnology belonging to one of these areas, these technologies have permeated

so deep into our lives that it is hard to imagine our lifestyles without them. However, with demand comes scarcity. The spectrum allocated to these technologies is greatly limited and hence the scarcity which emphasizes the great need to deal with and overcome this issue. The spectrum measurements taken by BWRC and the shared spectrum company clearly show 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 [1, 2]. This is where the opportunistic spectrum access (OSA) comes into picture. Through OSA, users can utilize the spectrum currently being unused especially when it comes to licensed spectrum of legacy technologies. One example is the 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 the phrase ‘cognitive radio’ comes from. Cognitive Radios (CRs) opportunistically cash in on the licensed spectrum allocated to rightful owners that is not being used in time, frequency, space and code dimensions of a signal at a given instant (also called spectral opportunities) in order to make their communications efficient in terms of throughput, energy and delay metrics. Lately this term has become synonymous with the term Dynamic Spectrum Access (DSA) in the sense that the goal of DSA/OSA is achieved through the cognition of the radio.

Dealing with the Wi-Fi crowding phenomenon is critically important for sustainable wireless computing for our future generations. One of the most recent endeavors in this direction was made by FCC which approved and reallocated the use of Television White Spaces (TVWS) for Wi-Fi. Such renovated Wi-Fi technology capable of using TVWS via cognition was renamed as White-Fi (IEEE standard 802.11af), sometimes also called ‘Wi-Fi on Steroids’. TV channels 2–52 have been opened up for unlicensed usage by the general public. Though the FCC recently has agreed to ditch the spectrum sensing requirement and instead encourage the use of online databases for spectrum vacancy [22, 23], 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.

In the field of CR technology, the rightful users of the licensed spectrum are termed the Primary Users (PUs) whereas the other CR users trying to use this spectrum opportunistically are the Secondary Users (SUs). The SUs, before dynamically accessing this licensed spectrum should make sure that it is not being used by any PU in their local vicinity so as to avoid interference

to the PUs. The key component to achieve this is the sensing of the spectrum with high reliability.

As the transmitter based sensing techniques like energy detection [4, 5], matched filtering [6], cyclostationary [7] feature detection rely solely on the PU signal detection, there is a high chance for the cognitive user to be blinded by fading, shadowing and interference which might further degrade the accuracy of these techniques. The effects of these degradations have been studied in [8]. To overcome these blinding phenomena, cooperative sensing has been found to be far superior to just local/non-cooperative sensing as it solves the hidden node problem in addition to the others mentioned.

Based on the architecture, cooperative sensing schemes can be categorized into *distributed* and *centralized* cluster based schemes.

In a distributed cooperative sensing scheme, the 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 [10]. Distributed collaboration schemes are discussed in [11]. In [12, 13] Relay based cooperation is discussed where a few SUs act as relays to other SUs. In [13] the Amplify and Relay (AR), Detect and Relay (DR) schemes are proposed for sensor networks.

In a centralized cooperative sensing system model, there is a common receiver which collects all the sensing information done by the SUs (CRs). Our interest is mainly on the cluster based schemes where the SUs are grouped into clusters or teams for collaboration; the reason being that to design an energy efficient cooperative sensing scheme, grouping would be a key component to cash in on the team collaboration instead of placing the burden of sensing a very large spectrum on each SU [14]. By grouping the SUs into clusters and selecting the most favourable SU in every cluster to report to the common receiver, the sensing performance can be greatly enhanced [15]. Guo and Peng [16] studied the optimal number of clusters required to minimize the communication overhead without loss in the detection performance. In [17], a two level hierarchical cluster based architecture is proposed where the low level collaboration is among the SUs within a cluster and high level collaboration is among the cluster heads chosen for each cluster. Other grouping techniques are studied in [18–21].

Most of the work done till to date on cooperative sensing in CR networks mainly focuses on increasing the throughput and spectrum sensing efficiency/accuracy. However, there is limited literature that looks at the energy cost aspect of the cognitive radio technology. One work that does and is our point of interest is [9] which looks at the positive and negative impact

of CR MAC layer sensing in terms of energy. However, this work 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. Our work in this paper is a subsequence to that, with a goal to minimize the energy spent in spectrum sensing for each node and the network as a whole through cooperative sensing schemes. Also, there are many variations of cooperative sensing schemes with no consensus over which specific scanning scheme performs the best. Hence, we chose to look at a generic class of distributed and centralized schemes and apply our energy model to evaluate their energy consumption. We also propose the improved versions of both the generic distributed and centralized scheme and demonstrate the relative energy savings through evaluations. The following are the specific contributions made in this paper:

- We developed 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.
- We proposed corresponding new α -schemes: α -distributed and α -centralized, where only a fraction α of the nodes scan as opposed to all the nodes in the generic distributed and centralized schemes.
- We numerically evaluated and compared the energy consumption costs of the generic distributed and centralized schemes against the proposed α -distributed and α -centralized schemes.
- We studied optimal values of α and number of nodes in the network N .
- We made a conclusive energy comparison study of non-cooperative sensing schemes and cooperative schemes.

The rest of the paper is organized as follows: Section 2 gives an overview of the current sensing schemes and the proposed α -schemes along with the system model. Further energy consumption analysis equations are developed in Section 3 and energy savings analysis is done. Numerical evaluations of these equations is carried out in Section 4, followed by an interpretation of their significance.

2 Overview of Sensing Schemes

Spectrum sensing is a key critical component in the cognitive radio technology since the ability of cognition is achieved through this spectrum sensing

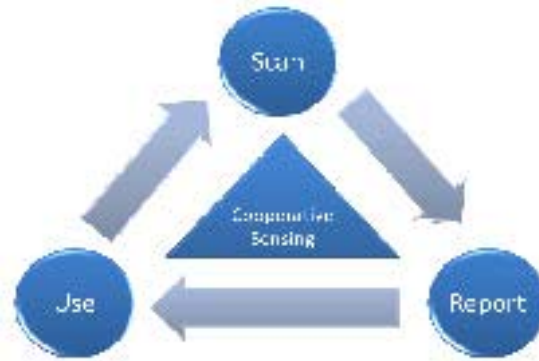


Figure 1 Cooperative sensing cycle.

functionality of the CR. These spectrum sensing schemes can be roughly classified into two categories: non-cooperative sensing and cooperative sensing.

2.1 Non-Cooperative Sensing

Non-cooperative sensing schemes also called as local sensing schemes require each node in the network to sense the spectrum for free channels individually. These nodes do not share the scanned information with their neighbours and hence no reporting is involved in a non-cooperative sensing cycle. The non-cooperative sensing we use as reference in our work is the optimal scan scheme from [9]. In this optimal scan scheme, every node has to scan all the channels before choosing the optimal channel among them.

2.2 Cooperative Sensing

In cooperative sensing schemes, all the nodes in the network sense/scan the spectrum and share this information with all the neighbouring nodes in the reporting phase (see Figure 1). This process reduces the CR blinding due to interference, 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 single channel.

In this paper, we discuss more of the parallel cooperative sensing [24] where all the nodes are designated different channels to be scanned. Each node individually scans the designated channels in parallel (concurrently) and

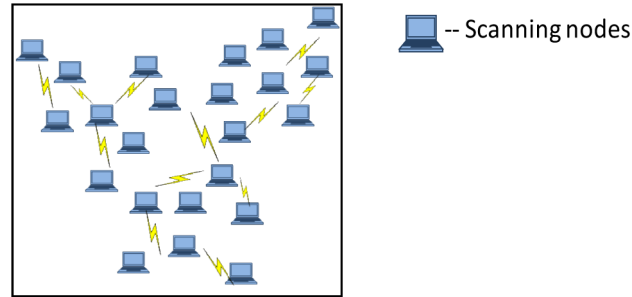


Figure 2 Distributed scheme.

then conveys this information in the form of sensing reports (SR). Each SR is of a constant size with an SR field of fixed bit map based on the total number of channels to be scanned by the network of nodes.¹

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 mainly two broad classes of architectures – distributed and centralized. The generic distributed sensing scheme we refer in this work belongs to the distributed architecture and is hereafter referred to as ‘distributed sensing scheme’ and the generic centralized cluster based scheme belongs to the centralized architecture which is hereafter referred to as the ‘centralized cluster based scheme’.

2.2.1 Distributed Sensing Scheme

In this distributed sensing scheme, each node scans its share of channels during the SP and shares this information with all its neighbors in the RP (see Figure 2).

2.2.2 Centralized Cluster Based Sensing Scheme

In this centralized cluster based scheme (see Figure 3), the whole 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. There are two

¹ A fixed size of SR simplifies protocol design and allows dynamic re-configurations of protocol parameters (like the number of nodes that will scan the spectrum) without impacting other protocol fields.

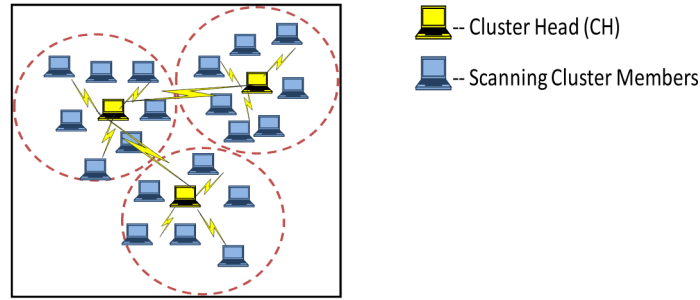
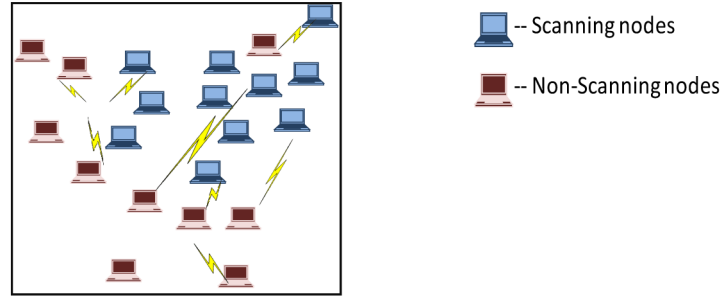


Figure 3 Centralized scheme.

levels of communication happening here, one at the intra cluster level and the other at the inter cluster level between the CHs. At the end of the inter cluster level information exchange, all the nodes in the network have a global view of the channel information for the whole network.

2.3 Proposed α -Sensing Schemes

Next, we propose the α -sensing schemes to make the conventional schemes more energy efficient. In the α -sensing schemes only a fraction of 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 simultaneously the scanning of all the channels is collectively completed by the end of the sensing cycle. The α -sensing approach provides a 'smooth' way to handle and evaluate reduction in number of sensing nodes as opposed to schemes that some fixed number of nodes as sensing agents. These schemes are practical to implement with the fraction of nodes chosen based on their SNRs, PDRs (Probability Detection Ratios), shadow correlation, energy remaining, etc., to attain better spectrum sensing accuracies. The level of correlation among nodes could also be used to choose a value of α ; a higher value of α can be used when expected correlation is low and vice-versa. We will concern ourselves more with the impact of a certain value of α in the rest of the paper leaving the selection of α for future work. The following subsections describe two types of α -sensing and how they could be implemented practically.

Figure 4 α -distributed scheme.

2.3.1 α -Distributed Sensing Scheme

In the α -distributed sensing scheme (see Figure 4), only an α fraction of nodes scan the channels in a given sensing cycle. However they still share this information with all their neighbouring nodes just similar to the generic distributed sensing scheme. This saves energy, as each node has to scan only an α percentage of the times on an 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 SP, each node, through a probabilistic method (random number generator) decides to participate in scanning if the generated value is less than the α value. This way on an average each node in the network scans once in $(1/\alpha)$ sensing cycles.

2.3.2 α -Centralized Cluster Based Sensing Scheme

In this α -centralized sensing scheme (see Figure 5), instead of all the CMs in the cluster scanning for channels, only a fraction α of the CMs share the scanning responsibility and report this information to the CH. 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 its CMs. The fraction α of the CMs in each cluster is chosen by the CH.

Though another option of choosing a fraction α of the clusters instead of fraction of CMs from each cluster is possible, keeping in consideration the spatial diversity benefits of the clusters in the case of varying channel characteristics, it is better to have the scanning carried out in all the clusters for better sensing accuracies. To further study these schemes, the system model and the analytical energy model are developed in the next section.

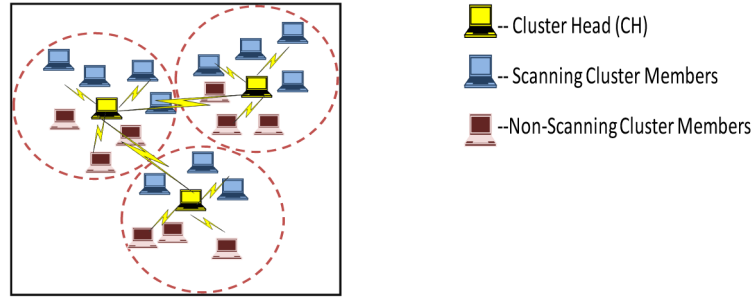
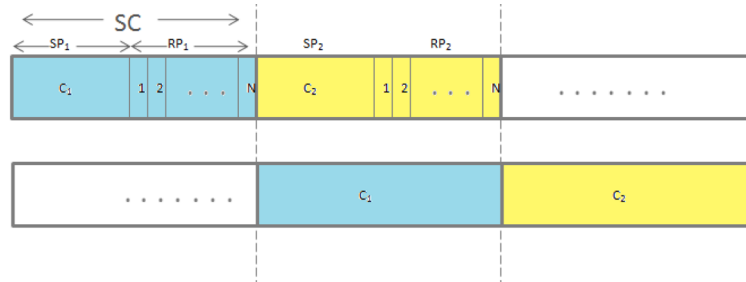
Figure 5 α -centralized scheme.

Figure 6 Time frame structures of scanning and reporting, data transmission respectively.

2.4 Basic Common Aspects of the Cooperative Sensing Model

We envision a static crowded ad hoc WLAN scenario where all the nodes are connected in a clique network and hence are in the hearing range of each other. Each node has two transceivers/radios – one completely dedicated for the sensing and reporting purpose and the other radio for data transmission (see Figure 6). The radio for sensing and reporting shifts to the channel(s) that needs to be scanned during the SP and finally switches to the control channel for reporting purposes which is shown in the first time frame structure. The other physical radio for data transmission switches to the vacant channel over which it could transfer the data after the first sensing cycle as shown in the second time frame structure. We assume a perfect channel scheduling.

At the end of the SP, each node shares a sensing report with all the remaining nodes through a single broadcast packet regardless of the number of channels scanned. Since the nodes perform parallel scanning, at the end of the reporting period every node would have the spectrum map of all the channels. We do not presume the existence of a fusion center in this ‘on the fly’ net-

work 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 take up this role for its cluster. Section 5 later discusses the impact of changes to the assumed model on our results.

2.5 Orchestration

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

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

2.6 Energy Model of Sensing Cycle

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

Table 1 Definition of variables used [9].

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

3 Energy Consumption Analysis of Sensing Schemes

3.1 Non-Cooperative Sensing Scheme

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

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

where $E_{non-coop}^S$ is the energy consumed for each node during the scanning period. Total energy consumed by all the N nodes in the network to sense C channels in this non-cooperative sensing scheme is given by

$$\begin{aligned} E_{non-coop} &= N E_{non-coop}^S \\ E_{non-coop} &= N C E_{scan} + N(C - 1) E_{sw} \end{aligned} \quad (1)$$

3.2 Distributed Sensing Scheme

In this generic scheme, each node scans $C/N (\geq 1)$ channels in each SP as long as $N > 1$. If $N > C$, not every node has to scan the channels. Hence the

total energy for the whole network in the distributed scheme is given by the following generic equation:

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

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

E_{dist}^S for a scanning node is the sum of energy to scan the designated (C/N_S) channels, switch in between those channels, transmit one SR with the channel scan information and receive $(N_S - 1)$ SRs from the other scanning nodes. E_{dist}^{NS} for a non-scanning node is the energy to decode all the SRs received from the scanning nodes.

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

$$E_{dist}^{NS} = N_S E_{srd} \quad (4)$$

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

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

Since $N_S = \min(N, C)$ we have the following two cases:

If $N \leq C$, then

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

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

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

3.3 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 SP. Hence for a given number of sensing cycles, the nodes in this scheme would have to scan only for an α percentage of the cycles on an average while they can 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 , we arrive at the following bound for

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

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

Substituting $N_S = \alpha N$ in Equations (2–4) gives the following energy equations for each of the scanning node and for the whole network respectively:

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

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

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

3.4 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 $N = K(M+1)$. Each cluster of $M+1$ nodes thus has one cluster head (CH) and M cluster members (CMs). The CMs alone do the scanning and send their SRs to their respective CHs. Each CH then shares this information with the remaining CHs. A final SR is then broadcasted from the CH to its CMs.

Each cluster has to scan (C/K) (≤ 1) channels and hence the energy consumed for each cluster per sensing cycle is

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

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, 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, we consider a basic access mode of IEEE 802.11 [29] without RTS/CTS and ignore the

energy for the ACK in the case of unicast transmission. For simplification, we further ignore the energy for the DIFS.

$$E_{cent}^{CH} = K E_{srt} + (M_S + (K - 1)) E_{srd} \quad (12)$$

Each CM transmits an SR to the CH after scanning $(C/K M_S)$ channels and decodes the final SR that it receives from its CH.

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

The energy consumed by the non-scanning CMs is

$$E_{cent}^{NS} = E_{srd} \quad (14)$$

$$E_{cent} = K E_{cent}^C \quad (15)$$

Substituting Equations (11–14) in (15) gives the energy equation for the whole network of nodes in the centralized scheme:

$$\begin{aligned} E_{cent} &= C E_{scan} + (C - K M_S) E_{sw} + K (M_S + K) E_{srt} \\ &\quad + K (M_S + M + K - 1) E_{srd} \end{aligned} \quad (16)$$

Similar to the distributed scheme, if $M > (C/K)$, then not every CM has to scan in the cluster and hence we have the following two cases:

If $M \leq (C/K)$ then

$$\begin{aligned} E_{cent} &= C E_{scan} + (C - K M) E_{sw} + K (M + K) E_{srt} \\ &\quad + K (2M + K - 1) E_{srd} \end{aligned} \quad (17)$$

If $M > (C/K)$ then

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

3.5 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 neither be less than 1 and nor can it be greater than (C/K) . (C/K) is the number of assigned channels for each cluster which would be

the required number of scanning nodes too. Translating this to a mathematical bound gives the following:

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

Because of this α bound we can completely rule out the possibility of $M_S > (C/K)$ in this scheme.

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

$$\begin{aligned} E_{\alpha-cent} = & CE_{scan} + (C - K\alpha M)E_{sw} + K(\alpha M + K)E_{srt} \\ & + K((1 + \alpha)M + (K - 1)E_{srd}) \end{aligned} \quad (19)$$

In the subsequent section, we analyse the energy savings and optimal values of α and N based on the above derived equations.

3.6 Energy Savings

Lemma 1. *Distributed cooperative sensing scheme is more energy-efficient than a 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 the total energy consumption for whole of 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:

$$E_{dist} \leq E_{non-coop} \quad (20)$$

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:

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

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

Lemma 2. *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 the total energy consumption for whole of 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:

$$E_{cent} \leq E_{non-coop} \quad (21)$$

For a network to form a cluster, there should at least be one cluster and one cluster member in the cluster and hence we have

$$K \leq 1, \quad M \leq 1$$

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 $E_{src} = E_{srt} = E_{srd}$, $M_S = \min(M, C/K)$ for the centralized scheme, and $M_S = \min(\alpha, M, C/K)$ for the α -centralized scheme. $\square$

3.7 Optimal α Values for the α -Distributed Scheme

3.7.1 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 – the

energy savings for the whole network of nodes and the energy savings per scanning node in the network. We first look at the optimal α for maximum energy savings considering the whole network of nodes over one sensing cycle paired with various constraints to form a set of optimization problems.

Optimization Problem 1: Optimal α considering the energy savings for the entire network of nodes:

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

The α value we consider optimal here, 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 $\alpha = (1/N)$ which thus 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, shorter operating lifetimes respectively [28]. Hence a constraint to limit the sensing and reporting time in a given sensing cycle is needed as shown below in the next optimization problem.

Optimization Problem 2: Optimal α considering the energy savings for the entire network of nodes along with the time constraint:

$$\begin{aligned} \text{Maximize } f(\alpha) &= \left(\frac{E_{dist} - E_{\alpha-dist}}{E_{dist}} \right) \\ \text{such that } \left(\frac{1}{N} \right) &\leq \alpha \leq \min \left(\frac{C}{N}, 1 \right) \text{ and } L \leq 1 \end{aligned}$$

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

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

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

Also, for further study of the relative energy cost comparison of a scanning node in distributed scheme versus a scanning node in α -distributed scheme, we maximize the function $f(\alpha)$ with a scanning node energy constraint.

Optimization Problem 3: Optimal α considering the energy savings for the entire network of nodes along with the per scanning node energy constraint:

$$\begin{aligned} \text{Maximize } f(\alpha) &= \left(\frac{E_{dist} - E_{\alpha-dist}}{E_{dist}} \right) \\ \text{such that } \left(\frac{1}{N} \right) &\leq \alpha \leq \min \left(\frac{C}{N}, 1 \right) \text{ and } g(\alpha) \geq 0 \end{aligned}$$

where

$$g(\alpha) \geq 0 = \left(\frac{E_{dist}^S - E_{\alpha-dist}^S}{E_{dist}^S} \right)$$

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, causing the node to die quicker. This constraint makes sure that the energy of the scanning nodes in the α -distributed scheme is either less than or at least equal to the energy of scanning node in the distributed scheme. The optimal α with this constraint is always the upper bound of α given by $\min(C/N, 1)$. 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 $(1/N)$. $g(\alpha)$ thus helps to explain the fact that the per scanning node energy cost of α -distributed scheme versus that of the distributed over one sensing cycle is always higher except at $\min(C/N, 1)$ where it equals the distributed. In the next optimization problem, we show that the energy savings over a cumulative sensing cycle period are however positive.

Optimization Problem 4: Optimal α considering energy savings for the entire network of nodes along with the per scanning node energy constraint over n sensing cycle period:

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

where

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

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

With this new constraint, the optimal α value is still $(1/N)$. 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 whole network over a given period of n sensing cycles and more noticeably at smaller α values.

3.7.2 Optimal N for Maximum Energy Savings

It is also interesting enough to analyse 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.

Optimization Problem 5: Optimal N considering energy savings for the entire network of nodes over one sensing cycle:

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

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 next optimization problem looks at maximizing the per node energy savings over n sensing cycles.

Optimization Problem 6: Optimal N considering the energy savings per node over n sensing cycles:

$$\begin{aligned} \text{Maximize } G(N) &= \left(\frac{\min \left(\frac{C}{N}, 1 \right) E_{dist}^S - (\alpha E_{\alpha-dist}^S)}{\min \left(\frac{C}{N}, 1 \right) E_{dist}^S} \right) \\ \text{such that } &\left(\frac{1}{\alpha} \right) \leq N \leq \min \left(\frac{C}{\alpha}, 1 \right) \end{aligned}$$

Using the Lingo optimization package, evaluating the function $G(N)$ for the highest magnitude of energy savings per scanning node over n sensing cycles shows that it 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 section.

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. So we do not look at optimizations for the centralized schemes in this work.

4 Evaluation

We do a numerical evaluation for all the proposed generic equations and show the energy savings of the α -schemes over their counterparts. All the base values for E_{scan} , E_{sw} , E_{srt} , E_{srd} are calculated from equations and values specified in Table 1 [9]. Following [25] where White-Fi has to scan at least about 50 TV channels and [26] where the notion of channels can just be sub bands obtained by dividing a given wide band, we believe $C = 100$ would be a suitable and practical value for the number of channels to be scanned. In [27] the authors show that the optimal sensing time for a SU to detect the PU with 90% probability is about 15 ms and in [28] the false alarm probability had a linear down trend as scan time was varied from 20 to 100 ms. So we infer that $T_{scan} = 50$ ms would be an appropriate value to achieve a good detection probability and low false alarm rates simultaneously. We also make the assumption that scanning takes longer time than data transmission, which holds true for most schemes practically except perhaps clear channel assessment (CCA) based schemes. We evaluate the total energy consumed for each of the schemes by varying the range of number of nodes N and the fraction factor α .

4.1 Distributed versus α -Distributed Schemes

Figure 7 shows the energy trends over a varying N for the distributed and α -distributed schemes. The lower the value of α , the lower are the energy costs for the α -distributed scheme. These energy savings become more apparent for higher node densities. However at the point 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

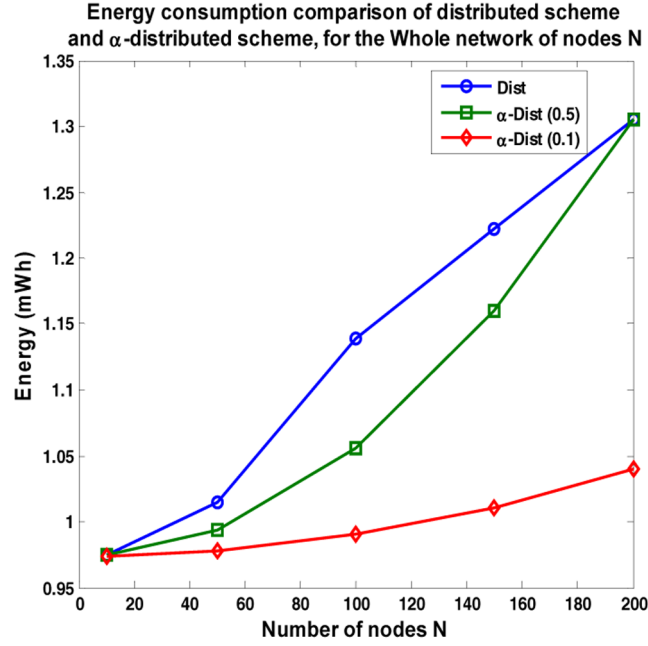


Figure 7 Total energy consumption of whole network of N nodes in distributed and α -distributed schemes.

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 the α -distributed schemes. Hence our proposed α -distributed scheme holds significance as long as $\alpha N < C$.

Figure 8 shows that the average energy costs of a node for both distributed and α -distributed keep decreasing with increasing node densities. A closer analysis indicates that this is due to the reduction in the scanning energies; since with increasing node densities, the number of channels scanned on an average by each node keeps decreasing. Though the reporting energy increases on an average, this increase is greatly offset by the decrease in the scanning energy since $E_{scan} \ll E_{srt}$ (or) E_{srd} .

4.2 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 9.

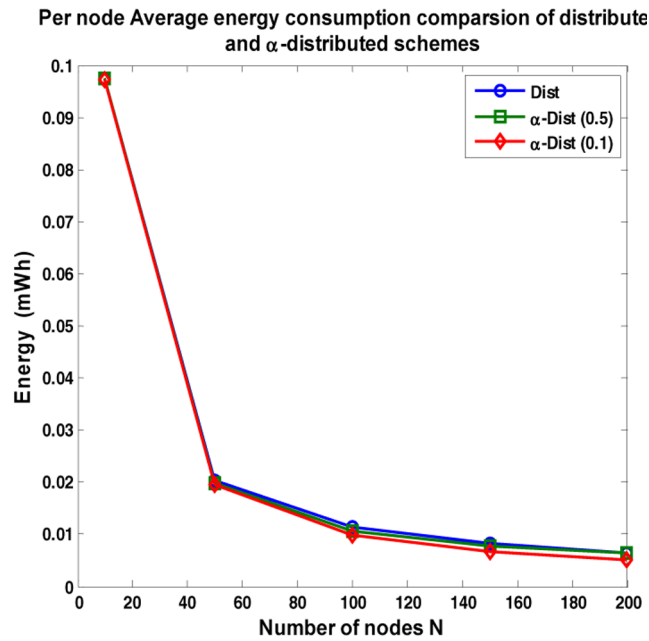


Figure 8 Average energy consumption of each node in distributed and α -distributed schemes.

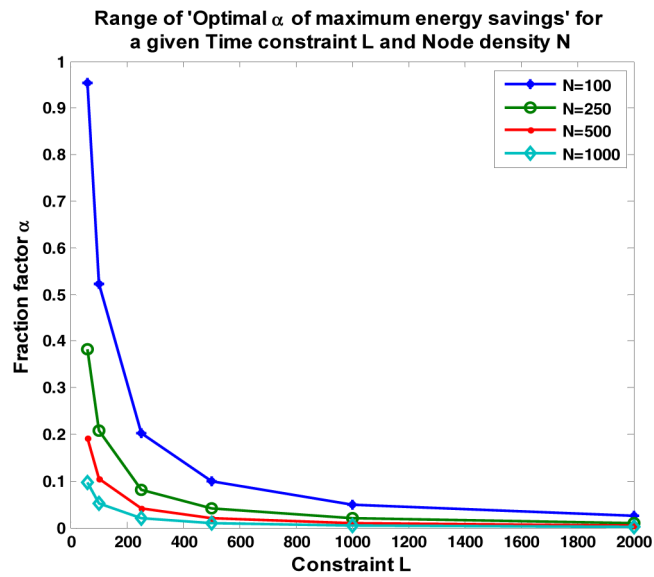


Figure 9 Optimal values of α where the energy savings of the α -distributed scheme over the distributed scheme are maximum, for a given N and L .

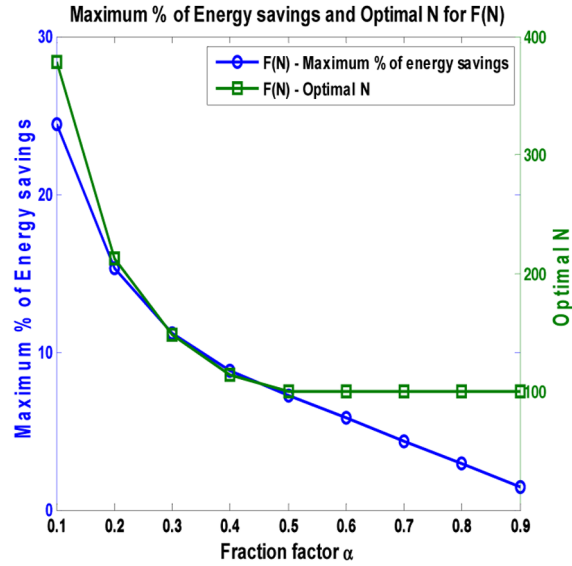


Figure 10 Percentage of energy savings and optimal N values where $F(N)$ is maximized.

The optimal values were computed in the Lingo optimization package using the formulations developed. It can be clearly noticed that the optimal α values decrease with increasing L . With higher L each node gets to scan more channels and so lesser scanning nodes are needed which results in a smaller α .

A further study of optimal values of N for a given α can be done using Figures 10 and 11. The ‘maximum % of energy savings’ line for both plots is for the corresponding energy savings at that optimal N for $F(N)$ and $G(N)$. The function $F(N)$ has the highest magnitude of energy savings at various values of N for varying α until $\alpha = 0.5$, after which the optimal N stays at 100 (value of C). 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 go down with increasing α values.

4.3 Centralized versus α -Centralized Schemes

Figure 12 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.

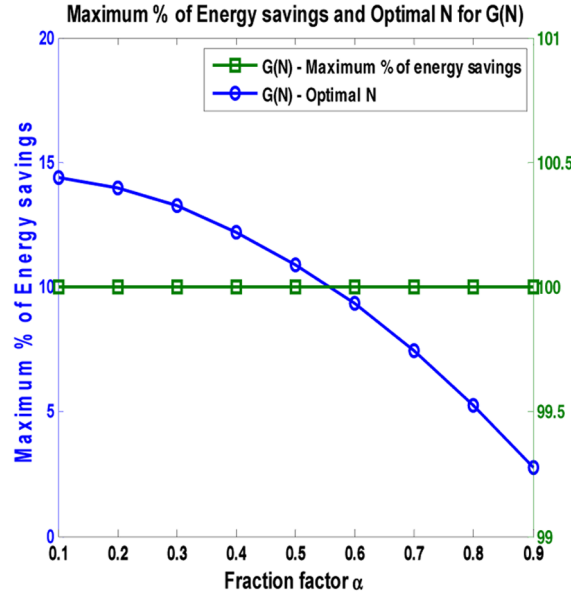


Figure 11 Percentage of energy savings and optimal N values where $G(N)$ is maximized.

The α -centralized schemes have lower energy costs with decreasing α and this can be attributed to the lesser control overheads both for the CH and the CMs. Also, the energy increase with increasing N is more linear in the centralized schemes while this increase is inclined towards being exponential in the distributed schemes. This clearly shows that centralized schemes in general are more energy efficient and hence 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, we use Figure 13 which shows that a higher K results in higher energy overhead.

4.4 Non-Cooperative versus Cooperative Schemes

Cooperative schemes not only reduce the bandwidth requirements to convey the scanning information but also the energy consumed to scan and share this information. Figure 14 proves this claim and it can be noticed 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 the cooperative schemes. The centralized schemes were plotted for $K = 1$ for a fair comparison.

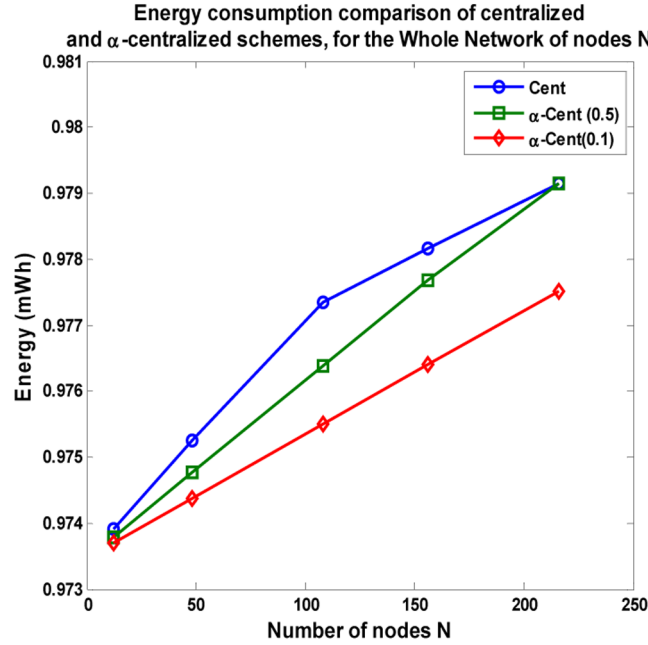


Figure 12 Total energy consumption for whole network of N nodes in centralized and α -centralized schemes.

5 Discussion and Conclusions

The energy model of sensing developed in this work gives a platform for energy accountability, quantification and comparison of the non-cooperative sensing schemes and the generic cooperative sensing schemes – distributed and centralized, along with our proposed new α -schemes. Our investigation on their energy costs shows that the cooperative schemes outperform the non-cooperative scheme under the simplifying assumptions made and further the α -schemes are significantly 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 the relative energy savings.

Our results make some idealized and simplifying assumptions to make the analysis tractable in taking the first step of comparing cooperative and non-cooperative schemes for CRs. The current network scenario is considered to be a clique; a non-clique network would require additional work for cooperation relying on multi-hop communication which will increase the energy cost for cooperative schemes. We further make the assumption of perfect

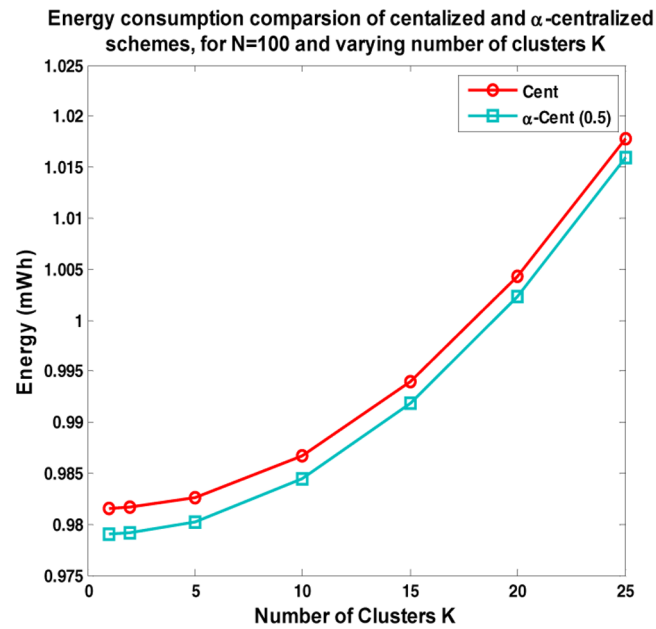


Figure 13 Impact of K on the total energy consumption for whole network of N nodes in centralized and α -centralized schemes.

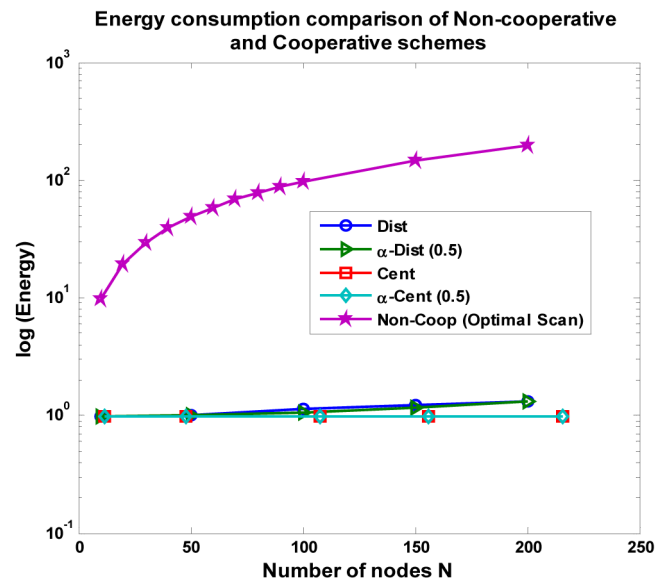


Figure 14 Energy consumption comparison of the non-cooperative and cooperative schemes.

scheduling in the sensing model; this assumption is feasible in networks that are tightly time-synchronized which is relatively easy to achieve in static networks with nodes within range of each other. The impact of achieving synchronization will have to be considered for networks that have mobile nodes, or require multi-hop communications. Finally, we do not consider power management issues in this paper. Our results are complementary to energy savings possible by such schemes. The results presented in this paper are based only on the energy to scan and energy to communicate. A useful next step will be to tie in the impact of various power management schemes and deal with synchronizing communication schedules and factor in energy costs.

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Biographies

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