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Multi-hop Cluster Based Cooperative Spectrum Sensing Approach for Cognitive Radio Networks

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Abstract—Spectrum sensing is a key function in cognitive radio networks to detect vacant frequency bands for secondary (unlicensed) users without causing any interference to the transmission of primary (licensed) users. Due to the destructive conditions of sensing channel such as multipath fading and shadowing, a local sensing may not be able to meet the requirements for reliable sensing. Therefore, cooperative spectrum sensing is introduced to detect the primary user more accurately. Clustering approach is considered as an effective method that used in cooperative spectrum sensing to tackle the degradation in the performance of spectrum sensing due to fading and shadowing of reporting channel, and also to reduce the control channel overhead when the number of cooperative users becomes very large. However, most existing cluster-based cooperative spectrum sensing approaches are based on one-hop communication between the cluster heads and the fusion centre, which are suitable for small-scale networks. In practice, the fusion centre is usually located far away from the primary networks in the case of large-scale cognitive radio networks, which leads to some cluster heads to be far from the fusion centre. Such a case, the distant cluster heads will need more power to report their cluster results to the fusion centre, also may deteriorate the overall sensing performance at the fusion center due to reporting errors. In this paper, we propose a multi-hop cluster-based cooperative spectrum sensing scheme using Centralised Low Energy Adaptive Clustering Hierarchy (LEACH-C) protocol in order to reduce the power consumption and prolong the network's lifetime, as well as improving the sensing performance. The simulation results show that our algorithm can achieve better energy gains as well as less delay than conventional cooperative spectrum sensing algorithms.

Index Terms—cognitive radio, cooperative spectrum sensing, clustering technique, multi-hop cognitive radio.

1 Introduction

The rapid deployment of new wireless devices and services has led to increasing demand for spectrum resources. However, recent radio spectrum measurements undertaken by the Office of communications (Ofcom) in the UK and the Spectrum Task Force (SPTF) in the USA have shown that most of the licensed spectrum bands are largely underutilized for significant periods of time in various geographical areas in the UK and the USA respectively [1], [2].

The telecommunication regulators around the world put forward the idea of exploiting unused spectrum to improve the flexibility and efficiency of spectrum access based on dynamic spectrum access (DSA). By enabling the secondary use of spectrum on an opportunistic basis, a powerful and flexible wireless systems can be achieved everywhere, that are able to provide further support for the traffic growth and changing demands in traffic. Cognitive radio (CR) is a key enabling technology of DSA, which provides the capability to share the licensed bands in an opportunistic manner. The cognitive terminals sense continuously the spectrum availability and serve its users without causing harmful interference to the primary users. Hence, spectrum sensing is the most important procedure of the cognitive radio technique.

The available spectrum bands can be determined by detecting the weak signal from a primary transmitter through the local sensing algorithms [3], [4], [5]. In practical applications, the received signal at each cognitive user may suffer from the hidden primary terminal problem and uncertainty due to fading and shadowing. In order to address the above issue, several research groups investigated in the last few years the possibility of introducing cooperation technique in sensing function [6], [7], [8].

Basically, the cooperation process between CR users in cooperative spectrum sensing (CSS) consists of three main phases: local sensing, reporting, and data fusion [8].The performance of centralized CSS depends largely on the performances offered in each phase. These performances are affected by many factors such as the accuracy of the local sensing, reliability of the reporting channel, data fusion techniques, network overhead, etc.

It is well known that the benefits of cooperative spectrum sensing comes at the cost of control channel overhead and more transmission data, requiring more power consumption and introducing additional transmission delay. In recent years, some studies have addressed the problem of power consumption in CSS. In [9] the authors proposed to reduce the communication overhead by replacing observation reports by hard decision reports. In [10], [11] the authors proposed to use a censorship strategy where only a user that has reliable information could report the sensing result to fusion centre (FC). Another method of network overhead reduction for CSS is to reduce the cooperative users, where the performance of sensing can be increased when cooperating a certain number of cognitive radios with the highest Signal to Noise Ratio (SNR) of sensing channel rather than participating all cooperative users in the network [12].

Clustering technique has been recently adopted in cooperative spectrum sensing for cognitive radio networks in order to overcome the problems exhibited by CSS. There are number of

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research works that focused on using clustering methods to improve the cooperative sensing performance under imperfect channel conditions [13], [14], [15], [16], [17], in which cognitive users are grouped into clusters and the user with highest reporting channel's SNR is chosen a cluster head (CH), which in turn sends the cluster decision to FC.

However, the above cluster-based spectrum sensing approaches focused mainly on the classical clustering methods, which are inefficient in terms of energy consumption. Furthermore, in reality, most of far clusters from the FC have reliable local sensing decisions, but may suffer from fading and shadowing due to low SNR of reporting channel, which may lead to further deterioration in sensing performance due to error reporting channel, and causing more energy consumption especially in wide cognitive radio networks (CRNs).

In this paper, we develop a multi-hop cluster based cooperative spectrum sensing algorithm using LEACH-C protocol. By dividing the total clusters into multi-levels based on the distance between the cluster heads (CH) and the FC, the above issues can be solved, more energy can be saved, and the performance of the spectrum detection and sensing delay can be also improved.

The rest of this paper is organized as follows. In section 2, the system model is presented. Section 3 describes in details the formation of multi-hop routing with LEACH-C based CSS approach. The energy model of our algorithm is described in section 4. In section 5, the performance of spectrum sensing and the sensing delay analyses of the multi-hop clustering approach are provided. The evaluation analyses and the simulation results are given in section 6. Finally, the conclusion is presented in section 7.

2 System Model

We consider a wireless cognitive radio network with M cognitive radio users (CRs), which act as local sensing devices, are assumed to be organized into clusters. Each cluster has a cluster head that makes a cluster decision based on the local decisions received from its cluster members and report the result to the cognitive base station that acts as a fusion centre FC. We also consider that the primary user signal at CRs is not initially known, therefore, we adopt an energy detector to conduct the local sensing, which is suitable for any signal type. In this detection algorithm, only the transmitted power of the primary system is known. Therefore, this power will be detected firstly, and then compared with a predefined threshold to determine whether the spectrum band is available or not [3]. When the energy of the received signal is greater than the detection thresholdλ, the detector will indicate that the primary user is present, which will depicted by exist hypothesis H1, otherwise, the primary user is absent, which will be represented by null hypothesis H_0.

The system structure of a cognitive radio network according to our clustering approach is illustrated in Fig. 1. First, all CRs are grouped into clusters using LEACH-C protocol [18]. In This protocol, the optimal number of cluster heads CHs is determined by the FC in centralized way, according to the best reporting channel gain, distance from the FC, and the energy level of the CRs. Based on multi-hop routing mechanism, the fusion centre will determine multi-level cluster heads according to their distances from the FC. For instance, the FC will determine a set of level 1 CHs whenever the distance of CRs is greater than a certain energy level predefined by the FC.

As shown in **Error! Reference source not found.**, we considered a three-hop clustering CSS scenario for cognitive radio network with three level of cluster heads CH_{Li}, where i=1,2,3. Here, there are two types of communication: intra-cluster communication, and inter-communication. During the intra-cluster communication, each cluster member sends its sensing results to related CH directly, assuming that a free error communication between them because they are close each to other. In inter-cluster communication, each higher level cluster head CH_{Li+1} sends its decision to the nearest next lower cluster head CH_{Li}, and this process will be repeated until reaching the FC. The number of clusters in each level may be varying, while the number of cluster members will be fixed. Therefore, in some cases, some of lower-level cluster heads will relay a signal for more than one higher-level cluster head.

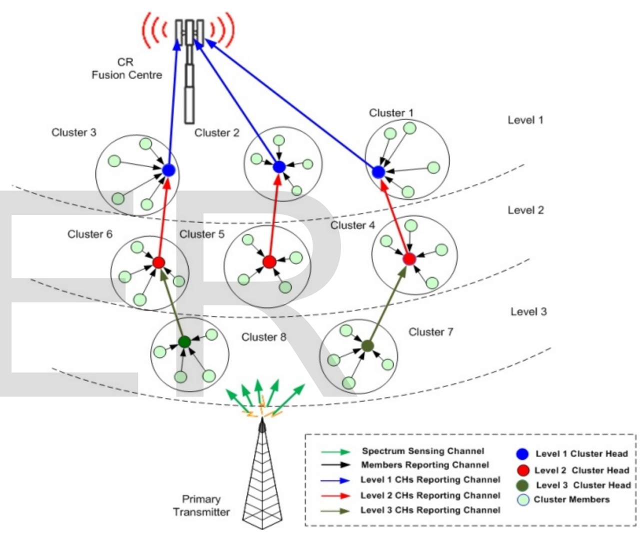

Fig. 1. Multi-hop cluster based cooperative spectrum sensing.

In this paper, we make the following assumptions:

1. We assume that a CRN topology is stable and consists of one fusion centre FC, one primary transmitter, and M of cognitive radio users CRs.
2. The cognitive users either are location aware, i.e., equipped with Global Positioning System (GPS), or location unaware. In such a case, the FC broadcasts an advertisement signal to all CRs at a certain power level, and each CR user computes its approximate distance to the FC according to the received signal strength.
3. CRs can use power control technique to adjust the transmission power to a level just enough for achieving a desirable performance.
4. The instantaneous channel state information of the reporting channel is available at the CRs.
5. The channel between any two CRs in the same cluster is perfect since they are close to each other.

The process of our proposed cluster-based CSS algorithm is conducted through the following steps:

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1. CR j in cluster i conducts spectrum sensing individually and makes a local decision Dij for i =1,…,K, j =1,…,Ni , where K is the number of clusters, Ni is the number of CR in cluster i and $M = \sum_{i=1}^{K} N_i$, where M is the total number of CRs in the network.
2. Then, each CRij will report its results to the CHi to make a cluster decision Ci based on Majority data fusion method.
3. Afterward, all CH_{Li+1} will send their results Ci to the FC via intermediate cluster heads CH_{Li} based on inter-cluster tree rooting at FC.

Finally, the fusion centre will collect all sensing results from cluster heads and make the final decision based on majority fusion rule, and then broadcasts it back to CRs via cluster heads.

3 Multi-hop Routing with Leach-c Protocol

The Multi-hop LEACH-C is a centralized clustering scheme, which operates in rounds, and each round consists of two phases: setup phase when the cluster heads and clusters are organized, followed by a steady state phase when cluster members begin send their data to CH and on to the FC, as shown in Fig. 2.

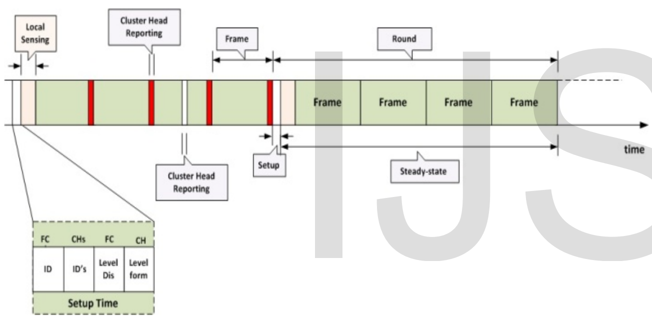

Fig. 2. Time line showing Leach-c operation.

3.1. Setup phase

During the setup phase of our clustering protocol, each CR user sends information about its current location or its distance from the FC, current energy level, and SNR of reporting channel to the FC. We assume that the FC can reach all CRs in one hop over a common control channel.

Firstly, the FC divides the CRs into different levels according to their distances from the FC. In order to reduce the energy consumption during reporting phase, a predefined distance threshold (dhop) will be determined according to default power level required for one hop communication. In multi-hop scenario, if we assume that there are L hops, i.e., there are (L-1) predefined distance thresholds ($dhop_1$,$dhop_2$,.,dhop L_{-1}), where $dhop_1$= dhop ; $dhop_2$= 2*$dhop_1$; $dhop_{U-1}$ = (L-1)*dhop. Any CR user that has a distance less than dhop will be set in level 1, otherwise, if it has a distance less than $dhop_2$ will be set in level 2, and so on. After discovering CRs at different levels, the FC sorts CRs in descending order according to the SNR of reporting channel and to their residual energy. Then, FC computes the average energy level of each CR user, and whichever CR users have energy above this average level will be listed under the list of candidates as a CH_L for current round, while the remaining CR users will act as cluster members. The FC determines the optimal number of clusters based on minimizing the energy consumed by cluster members to transmit their results to the CH_L, by minimizing the total sum of squared distances between the cluster members and the closest CH_L[19].

Generally, there are many scenarios of clustering method in multi-hop clustering strategy, which depend mainly on the number of CR users at each hop. For instance, one of these scenarios considers that the number of clusters is equal in each hop with variable number of cluster members, while the other scenario is that the number of cluster is variable with the equal number of cluster members. In this paper, we have adopted in the design of multi-hop routing algorithm on the equal clustering method, in which the number of cluster members is equal in all clusters, which is simple in implementation and more realistic. In order to discover clusters at different levels, the FC broadcasts its Identifier (ID) over the common control channel, and all cluster heads, which receive this broadcast, will record the FC ID. Then, all CHs send a message with their own ID's to the FC using their default power level (the required power for intra-cluster communication). Based on a single hop distance, CHs that are near to the FC will form level one hop CH_{L1}s. Afterward; FC will send a new control packet with all level one CH_{L1} ID's in it. As the same, all CHs will reply to this message at default low power level with their own ID's as well as ID's of level one CH_{L1} (CH_{L1} will not reply to this message, since their ID's are present in the control packet). In this case, CHs cannot be able to send their reply directly to the FC, where they will send at lower power level. Since CH_{L1} are at the distance of one hop from CH_{L2}, therefore, these replies will be received by level one CH_{L1} whose ID's are present in the reply message, which in turn relay them to the FC. Similarly, FC will repeat broadcast control message with ID's of all CHs that have discovered. This process continues until completing all CHs in the network.

3.2. Cluster formation

The cluster formation is done by CHs, where each CH broadcasts an advertisement message (ADV) using a carrier-sense multiple access (CSMA) MAC protocol, which instructs the CR users to select their CHs. After receiving the messages from all CHs, each CR user sorts the received power signal of each message and selects the largest one as its selected CH. Then, each CR user should inform the CH that it would be a member of the cluster by sending back a join-request message to the selected CH using CSMA MAC technique. This join message contains the cluster head's ID and the CR user's ID. Each CH compares its ID with received one, and if the cluster head's ID matches its own ID, the CH will accept the join request; otherwise, the request is rejected.

After completing the cluster formation, each CH knows which CRs are in its cluster and creates a TDMA schedule assigning each member a time slot to transmit its sensing result, and then informs all members in its cluster a CSMA code which is used for communication among them. After the TDMA schedule is known by all members in the cluster, the set-up phase is complete and the data transmission can start.

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3.2. Steady State Phase

In this phase, the CRs start to transmit its results to the CH during their allocated time slots. As shown in Fig. 2, this phase is divided into frames, which depend on the number of clusters. The time to send a frame of data is constant and depends on the number of cluster members. During each frame, all the cluster members send their results to the CH in respect to the TDMA schedule, and then the CH collects the local decisions, makes the cluster decision about the presence of the primary signal, and sends it to the FC via intermediate cluster heads within different levels in accordance to its time slot. Afterword, the FC combines the received clustering decision to make the final decision then broadcasts it back to all CHs, which in turn send it to its cluster members.

4 Energy Model of Multi-hop Cluster Based CSS

Typically, most of energy dissipation in each single wireless device is the result of transmitting energy dissipation to run the radio electronics, the power amplifier, and receiving energy dissipation to run the radio electronics. In our analysis, we use the same radio model described in [20], where the energy required to transmit or receive one message of size B bits over a transmission distance R, is given by:

$$E_{TX}(B,R) = \begin{cases} BE_{elec} + B\epsilon_{fs}R^2 & if \quad R \le R_O \\ BE_{elec} + B\epsilon_{mp}R^4 & if \quad R > R_O \end{cases} \quad (1)$$

$$E_{RX}(B,R) = B\,E_{elec} \quad (2)$$

Where B denotes the length of the message, R denotes the transmission distance between transmitter and receiver. E_{elec} is the electronic energy consumed to send or receive a message; E_{TX} represents the total energy consumed by the transmitter, while E_{RX} is energy consumed by the receiver. ϵ_{fs} and ϵ_{mp} denote the energy dissipated by the transmit power amplifier to maintain an acceptable SNR in order to transfer data reliably, and depend on the channel model, where R^2 is the free space path loss, while R^4 is the multipath fading loss, and $R_O = \sqrt{(\epsilon fs/\epsilon mp)}$ is the breakpoint or threshold distance [21]. Power control can be used to invert this loss by appropriately setting the power amplifier; if the distance R is less than a threshold R_O, the free space model ϵ_{fs} is used; otherwise the multipath model ϵ_{mp} is used.

4.1. Energy Model of Conventional CSS

In conventional cooperative spectrum sensing approaches, the fusion centre selects a sensing channel and instructs all CRs to individually perform local sensing, also sends the Time Division Multiple Access (TDMA) schedule for each CR user transmission. Therefore, every CR user will remain in sleep state with significantly less power and will not be on until its transmitting slot time. Using direct communication algorithm, each CR user sends local decision directly to the FC. Therefore, if the FC is far away from the CR user, direct reporting will consume more energy.

Fig. 3 shows a general sensing frame structure of conventional CSS. In general, the energy consumption of a conventional CSS during the sensing period may include the energy consumed in sensing the channel occupancy (Es); the energy consumed in the sleeping mode (Ep); the energy consumed in computing the observations and making a local decision (Ec); and the energy consumed in transmitting the local decision to the fusion centre (ER). In practice, Ep<Ec<<ER, then we can ignore Ep and Ec.

$$E_R = \begin{cases} BE_{elec} + B\epsilon_{fs}D^2 & if \quad D \le R_O \\ BE_{elec} + B\epsilon_{mp}D^4 & if \quad D > R_O \end{cases} \quad (3)$$

where D represents the transmission distance between CR user and the fusion centre.

$$E_{local} = E_s + E_R \quad (4)$$

$$E_{total} = ME_{local} \quad (5)$$

We can see from (5) that the power consumption is mainly depending on the number of CRs and the distance between the CR user and the FC.

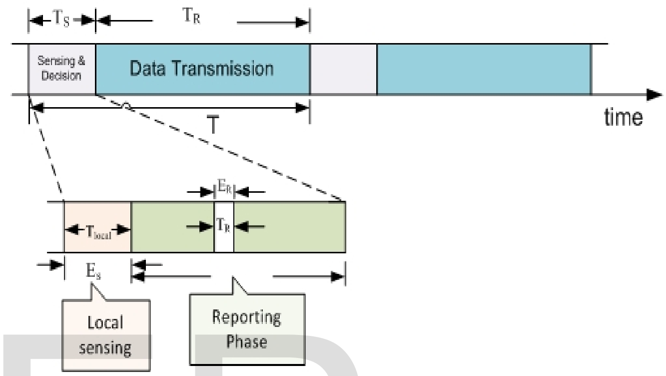

Fig. 3. Frame structure of conventional CSS.

4.2. Energy Model of One-hop Cluster Based CSS

In one hop clustering approaches, the data transmission begins when each cluster member sends its local sensing decision to the selected CH during each frame as shown in Fig. 4.

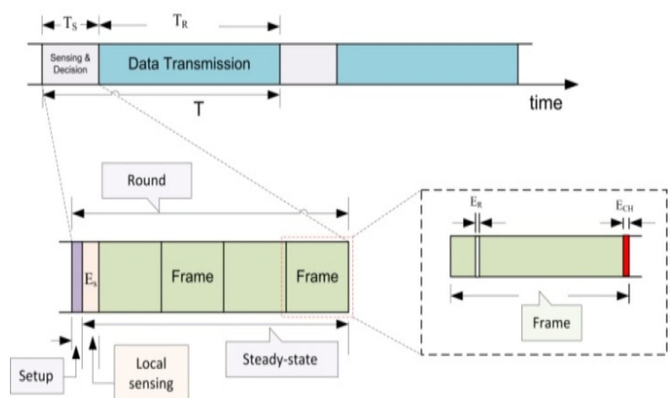

Fig. 4. Frame structure of cluster based CSS.

Presumably, the distance between each cluster member (non-CH) and the closest CH is small, so the free space model (R^2) is adopted in energy dissipation. Thus, the energy consumed by each cluster member is expressed by:

$$E_{non-CH} = E_S + B\,E_{elec} + B\,\epsilon_{fs}R^2 \quad (6)$$

Assuming that the CRs are uniformly distributed in Z x Z region, and based on the approximation in [18], we can approximate the area occupied by each cluster to (Z^2/K), thus,

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the expected (R^2) becomes:

$$R^2 = 0.159\frac{Z^2}{K} \quad (7)$$

where K is the number of clusters. Therefore, we can rewrite (6) as:

$$E_{non-CH} = E_S + B\,E_{elec} + 0.159B\,\epsilon_{fs}\frac{Z^2}{K} \quad (8)$$

Also in our system, we assume that some of CHs are far from the FC, thus the energy dissipation in each CH during a single frame follows the multipath model (R^4 power loss) and can be given as:

$$E_{CH} = E_{sensing} + E_{data\,receiving} + E_{data\,collection} + E_{data\,transmission} \quad (9)$$

$$E_{CH} = E_S + BE_{elec}\left(\frac{M}{K} - 1\right) + BE_{DC}\frac{M}{K} + BE_{elec} + B\epsilon_{mp}R^4 \quad (10)$$

Here R represents the distance between CH and the FC, and EDC denotes data collection. The energy dissipation in each cluster when $[(M/K) >> 1]$ can be approximated as

$$E_{Cluster} = E_{CH} + \left(\frac{M}{K} - 1\right)E_{non-CH} \approx E_{CH} + \left(\frac{M}{K}\right)E_{non-CH} \quad (11)$$

The total energy consumed by the network can be written as:

$$E_{total} = E_{setup} + KE_{Cluster} \quad (12)$$

By substituting (6-11) into (12), the total energy of cluster based CSS can be rewritten as:

$$E_{total} = E_{setup} + (K + M)E_S + 2MB\,E_{elec} + MB\,E_{DC} + KB\,\epsilon_{mp}R^4 + 0.159MB\,\epsilon_{fs}\frac{Z^2}{K} \quad (13)$$

By differentiating (13) with respect to K and equating the results to zero, the optimal number of K can be obtained as

$$K_{opt} = \sqrt{\frac{0.159MB\epsilon_{fs}}{E_S + B\epsilon_{mp}}}\frac{Z}{R^2_{to\,FC}} \quad (14)$$

4.3. Energy Model of Multi-hop Cluster based CSS

In multi-hop cluster based CSS algorithm, the FC sets the cluster heads, and issues a TDMA schedule for each level of cluster heads. Then, each cluster head will issue its own TDMA schedule for cluster members. Based on this schedule, cluster heads not only collect the local sensing results from their cluster members, but also act as relaying users for lower level cluster heads. Thus, the cluster heads that are far away from FC will send their sensing results to the FC through intermediate cluster heads, which lead to consume less energy compared to direct reporting.

Here, the energy consumption of each non-cluster head is the same as in one-hop clustering algorithm i.e., the same equation in (6) .But, the energy consumption of cluster heads will be different, because the cluster heads are divided into multi-level depending on their distance from the FC, and only the level one cluster heads will send their results directly to the FC, while other level cluster heads will send their results through next level cluster heads until reaching the FC. As a result, the energy consumption in each cluster head will be depending on the distance from other upper level cluster heads, as well as on the number of time that be receiving and relaying the results of lower level cluster heads.

The cluster head needs to fuse the all local sensing results and relay the other level cluster heads results, so its energy consumption is represented as

$$E_{CH}(i) = E_{sensing} + E_{data\,receiving}(i) + E_{data\,collection} + E_T(i) \quad (15)$$

$$E_{sensing} = Es \quad (16a)$$

$$E_{data\,receiving}(i) = B\,E_{elec}\left[\left(\frac{M}{K} - 1\right) + Relays(i)\right] \quad (16b)$$

$$E_{data\,collection} = B\,E_{DC}\frac{M}{K} \quad (16c)$$

$$E_T(i) = \begin{cases} BE_{elec} + B\epsilon_{fs}d^2_{Rely(i)} * (\mathrm{Relays(i)} + 1) & for\ d_{Rely(i)} \le d_O \\ BE_{elec} + B\epsilon_{mp}d^4_{Rely(i)} * (\mathrm{Relays(i)} + 1) & for\ d_{Rely(i)} > d_O \end{cases} \quad (16d)$$

Where Relays(i) is the times of relay, and $d_{Relays(i)}$ is the distance to its next hop CH. Finally, the total energy consumption can be written as:

$$E_{total} = E_{setup} + E_{non-CH} + K * E_{CH}(i) \quad (17)$$

5 Sensing Model of Multi-hop Cluster Based CSS

Cooperative spectrum sensing schemes are developed to improve the detection performance and shorten the sensing time. The performance of these approaches is measured mainly by two parameters: detection probability Pd, which indicates that the primary user exists, and false alarm probability Pf, which indicates that the primary user is present while in reality it is not. Another important parameter is misdetection probability Pm, which indicates that the primary user is absent while actually it is existing [22].

In our algorithm, each cluster member makes its own one bit hard decision: '0' or '1' which means absence or presence of primary activities, respectively. This one bit decision is reported independently to the FC via multiple intermediate CHs, which makes the final decision on the primary activity using one of the hard decision rules.

5.1. Local Sensing

Spectrum sensing is essentially a binary hypothesis testing problem, assuming that cognitive users are independent of each other, and each one conducting a local sensing using a simple energy detection algorithm (ED) [3], so the model can be described as follows:

$$x_i(t) = \begin{cases} n_i(t) & ,\ H_0 \\ h_i s(t) + n_i(t) & ,\ H_1 \end{cases} \quad (18)$$

xi(t) is received signal of the ith cognitive user; s(t) is transmitted signal of primary transmitter; $n_i(t)$ is zero mean additive white Gaussian noise; h_i is the channel gain; H_0 and H_1 represent that the primary signal is absent and present, respectively. The main function of energy detection is to make a decision between the two hypotheses.

During local sensing process, each CR makes local sensing using energy detection algorithm and reports its local observation to the fusion centre FC individually. The false alarm probability Pf and the detection probability Pd at each CR can be calculated as:

$$Pf = Q\left[\frac{\lambda - \mu_0}{\sigma_0}\right] \quad (19)$$

$$Pd = Q\left[\frac{\lambda - \mu_1}{\sigma_1}\right] \quad (20)$$

where, Q represents cumulative distribution function and can be expressed as:

$$Q(\mathrm{x}) = \frac{1}{\sqrt{2\pi}}\int_{\mathrm{x}}^{\infty} \exp\left(-\frac{\mathrm{u}^2}{2}\right)du \quad (21)$$

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$\mu_0 = N\sigma_n^2$, $\mu_1 = N\sigma_n^2(\gamma + 1)$, $\sigma_0^2 = 2N\sigma_n^4$,$\sigma_1^2 = 2N\sigma_n^4(\gamma + 1)^2$, N: number of samples, σ_n^2: is the noise power, and $(\gamma = |h\_i\ (t)\ |\char`^2\ (\sigma s\char`^2)/(\sigma n\char`^2\ ))$ denotes to Signal to noise ratio SNR.

Using the strategy of constant false alarm rate (CFAR) and for a given desirable Pf, the value of threshold λ can be predefined from (19) as: $\lambda = N\sigma_n^2 + \sqrt{2N}\sigma_n^2 Q^{-1}(Pf)$, then this value will be used to determine the value of detection probability Pd using (20). In non-fading environments, where $h_i(t) = h$ is deterministic, the probability of false alarm and detection of each CR user are the same as expressed in (19) and (20) above. On the other hand, when each CR user receives the primary signal through the Rayleigh fading channel, the received signal energy and SNR at each user are location dependent. In such a case, the average probability of detection $\overline{Pd}$ may be derived by averaging (20) over the fading statistics as follows [23]:

$$\overline{Pd} = \int_x P_d f_\gamma(x)dx \quad (22)$$

where $f_\gamma(x)$ is the probability density function of the received SNR at each CR user under the Rayleigh fading channel.

5.2. Cooperative Sensing With Imperfect Reporting Channels

In practice, because of the imperfect reporting channel, errors can be occurring on the local decision bits which are transmitted by CR users to the FC. Thus, each reporting channel can be modeled as a binary symmetric channel with crossover probability pe which is equal to the bit error rate (BER) of the channel. Specifically, let pe = Pr(FC receives bit'1'| CR sends bit'0') and pe = Pr(FC receives bit'0'| CR sends bit'1'). Consider the ith CR user, and for binary phase shift keying modulation (BPSK) with Rayleigh fading channels, the average error probability $p_{e,i}$ can be given as [24]:

$$p_{e,i} = \frac{1}{2}\left(1 - \sqrt{\frac{\acute{\gamma}_i}{(\acute{\gamma}_i+1)}}\right) \quad (23)$$

where $\acute{\gamma}_i$ is the average SNR of the reporting channel between the CR user and the FC.

Under these conditions, the FC receives a bit '1' in two cases: when a CR user sends a bit '1' with probability $pd_i(1 - p_{e,i})$; or when a CR sends a bit '0' with probability $(1 -$ ity $(1 - pd_i)p_{e,i}$. On the other hand, the FC receives a bit '0' under two cases: when a CR user sends a bit '0' with probability $pf_i(1 - p_{e,i})$; or when a CR sends a bit '1' with ity $(1 - pf_i)p_{e,i}$. Thus, the detection and false alarm probability at the FC can be written, respectively, as follows.

$$Pd_i' = pd_i(1 - p_{e,i}) + (1 - pd_i)p_{e,i} \quad (24)$$

$$Pf_i' = pf_i(1 - p_{e,i}) + (1 - pf_i)p_{e,i} \quad (25)$$

5.3. Majority (k out of n) hard fusion rule

In general, there are three mean hard decision combination rules in wireless networks namely OR, AND, and Majority rules. If there are n cooperative users that have independent own decisions, when k=1, k=n, and k= [n/2], the k out of n rule represents OR rule, AND rule, and Majority rule, respectively. OR rule provides more protection to the primary system, because it allows the CRs to access the spectrum when all the reported decisions from CRs demonstrate that the primary user is absent, but it does not give us efficient spectrum utilization. On the other hand, in AND rule, the FC decides the primary user is present when all cooperative users reported that the primary user is present, thus, it gives a perfect spectrum utilization, but with poor protection to the primary system. Therefore, we adopted the majority rule in our system model, which provides a trade-off between the spectrum utilization and the interference protection.

If the reporting channels are free errors, then the detection and false alarm probabilities can be written as:

$$Qd = \sum_{j=k}^{M} \binom{M}{j} (pd_i)^j (1 - pd_i)^{M-j} \quad (26)$$

$$Qf = \sum_{j=k}^{M} \binom{M}{j} (pf_i)^j (1 - pf_i)^{M-j} \quad (27)$$

where M is the total number of cooperative users, and k =M/2.

Practically, most of reporting channels are imperfect; therefore, errors may be occurred during reporting the local sensing results to the FC. Here, we consider a BPSK signal in a CR network; error probability p_e can be calculated under multipath and shadowing effects as in (23). In our clustering approach, we assume that the cluster members are close to each other, therefore, the intra-cluster communication channels (channels between cluster member and the related cluster head) are perfect (free error). The total detection and false alarm probability at the CHs and the FC are given, respectively, as follows

$$PD = pd(1 - pe) + (1 - pd)pe \quad (28)$$

$$PF = pf(1 - pe) + (1 - pf)pe \quad (29)$$

$$Qd = \sum_{j=k}^{M} \binom{M}{j} (PD_J)^j (1 - PD_J)^{M-j} \quad (30)$$

$$Qf = \sum_{j=k}^{M} \binom{M}{j} (PF_J)^j (1 - PF_J)^{M-j} \quad (31)$$

5.4. Multi-hop Clustering CSS

Consider a multi-hop clustering cognitive radio network with both identical and non-identical channels. We assume that there are L hops between primary user and the FC. Each non identical cluster head CH_L forwards the cluster results to the next hop cluster head CH_{L-1} with probability error Pe given as [25]

$$p_{e,i} = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma_i'}{1+\gamma_i'}}\right) \quad (32)$$

$$P_e = \frac{1}{2}\left(1 - \prod_{i=1}^{L-1}(1 - 2p_{e,i})\right) \quad (33)$$

Where $p_{e,i}$ is the probability error of one hop cluster. In the event that the reporting channel is identical, (the SNR is the same for all cluster heads), the equivalent probability error will be given as

$$P_e = \frac{1}{2}(1 - (1 - 2 * p_e)^{L-1}) \quad (34)$$

then, the total QD&QF will be expressed as:

$$QD = pd(1 - Pe) + (1 - pd)Pe \quad (35)$$

$$QF = pf(1 - Pe) + (1 - pf)Pe \quad (36)$$

6 Sensing Delay of CSS

Another metric that is important for spectrum sensing is agility. In cooperative spectrum sensing, an additional time-delay will be introduced due to the cooperation between CRs and the FC. From Fig. 3 and Fig. 4, the total detection delay of the conventional and the cluster based cooperative spectrum sensing, respectively, can be derived as follows.

In conventional mode, all cooperative users perform local sensing independently at the same time, and then each one will send it sensing decision according to its own TDMA schedule time. Thus, the total sensing time of the conventional cooperative spectrum sensing (Tcon.) can be given as:

$$Tcon. = T_{local} + M * T_R \quad (37)$$

where T_{local} is the local sensing time, M is the number of co-operative users, and T_R denotes the reporting time of one user.

As we know, the main goal of cluster-based algorithm is to reduce the communication overhead between the CRs and the FC, also to decrease the sensing time, thus increase the agility of the system. In cluster based CSS scheme, after the formation of all clusters is completed, all cluster members within each cluster will start to perform the local sensing individually at the same time, and then report their decision results to their CHs using their TDMA schedule time. Afterward, each CH will send its cluster result to the FC according to its TDMA schedule time. Back to **Error! Reference source not found.**, if we symbolize the setup time the (Tsetup), and the number of cluster is K, then, the total sensing time of the cluster based CSS (Tclus.), can be written as:

$$Tclus. = T_{setup} + T_{local} + \left((\frac{M}{K} - 1) + K \right) * T_R \quad (38)$$

Form above equations (37) and (38), we can observe that the cluster based CSS has smaller sensing time compared to conventional approach due to the advantages of clustering, and when K=M, Tclus. ≈ Tcon., which almost the same as that of the conventional scheme. When K<<M, the detection time can be decreased greatly with clustering algorithm.

In multi-hop clustering mechanism, relaying the cluster sensing results from far cluster heads to the FC via intermediate cluster heads introduces an additional delay, which depends on the number of all relaying signals in the network (Nrelay). Thus, the total sensing time of the multi-hop clustering CSS approach will be the same as in (38) but with adding relaying delay time (Trelay), and can be expressed as follows

$$T_{relay} = \sum_{i=1}^{L} \left(N_{hop,i}\right) * T_R \quad (39)$$

$$T_{multihop} = T_{setup} + T_{local} + \left(\left(\frac{M}{K} - 1\right) + K \right) * T_R + T_{relay} \quad (40)$$

By differentiating the (40) with respect to K and equating the results to zero, the optimal number of K can be obtained as

$$K_{opt} = \sqrt{M} \quad (41)$$

7 Simulation Results

In this section, we will evaluate our algorithm using a computer simulation and compared it to existing approaches. To do so, the simulation will focus on several topics, including spectrum sensing performance, energy consumption, and sensing agility, using MatlabR2010b simulator [26]. In our simulation, we will adopt the same energy model parameters are used in [18], and we will study the energy gain metric of our algorithm by finding the total energy consumed and comparing it to conventional clustering approaches.

In order to evaluate the sensing performance of our clustering algorithm, we analyze the whole probability of detection Qd at the FC as function of whole probability of false alarm for different numbers of cooperative users. In majority fusion rule, the final decision that a primary signal is present is made if at least half of cooperative users indicate the presence of the primary signal.

7.1. Energy Mode Simulation

For our experiments, we consider a cognitive radio network with100 nodes which are randomly generated and uniformly distributed between (x=0, y=0) and (x=200, y=200) with the BS at location (x=100, y=275) as shown in Fig. 5, and the reporting message is 1 bit long. Also we assume a simple model for the radio hardware energy dissipation and adopt the same communication energy parameters as in [18], and are given as: Eelec= 50 nJ/ bit; Efs=10 pJ/ bit/ m2; Emp=0.0013 pJ /bit/ m4; EDC=5 nJ /bit.

Fig. 5 shows the topology and the formation of our multi-hop clustering approach with 4-hops and 20 clusters, which we used in our simulation. Here, we consider that the FC can divide the CRs into 4 levels (Li), i = 1,2,3,4, based on their distances from the FC, assuming that the distance threshold of one hop communication($do = \sqrt{(\epsilon fs/\epsilon mp}$), which is here equal to (87.7 m). Thus, the FC will discover the different levels (L1, L2, L3, and L4) of CRs according to (do, d1, and d2), where d1=2do, and d2=3do, respectively. Here, for simplicity, we considered that the number of CRs at each level is same and equal to 5. In practice, this is not always true, because in some cases and depending on the distances between the CRs and the FC, the number of CRs in some levels will be greater than other levels, which leads to an unequal number of clusters in each level. However, there is no much impact on the evaluation of our energy mode under all assumptions, including equal number or unequal number of CHs at each level.

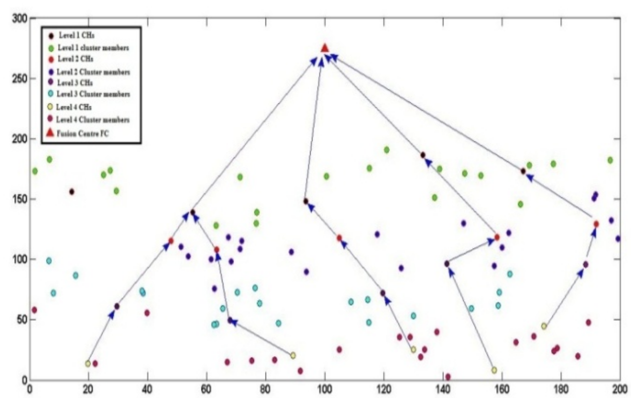

Fig. 5. CR network deployment with Cluster formation.

Fig. 6 illustrates the total energy dissipation in the network with different modes. We can show that the energy performance of the cluster based CSS scheme is better than the conventional mode. Furthermore, more energy reduction can be achieved when multi-hop clustering approach is used. It can also be shown that the energy consumption of conventional mode increases greatly with the increase of the number of CRs, while in other modes it increases slightly with the number of CRs, particularly in multi-hop clustering mode. The results also show that there is a slight saving in energy performance of 4-hop clustering mode compared with 2-hop mode. For instance, in the case of 100 CRs, the results show that there is a great reduction in energy dissipation and can be reached to 64% in one-hop clustering mode compared to the conventional cooperative mode, whereas the two-hop clustering mode has achieved 50% of energy savings compared with one-hop clustering approach. Furthermore, we will get a slight reduction in the energy consumed when the number of hops is increased. As shown in Fig. 6 the decline of the energy consumed in 4-hop will be 15% compared to 2-hop mode. In other words, multi-hop clustering CSS algorithm can provide a great energy efficient transmission, which is particularly true for a wide cognitive radio networks.

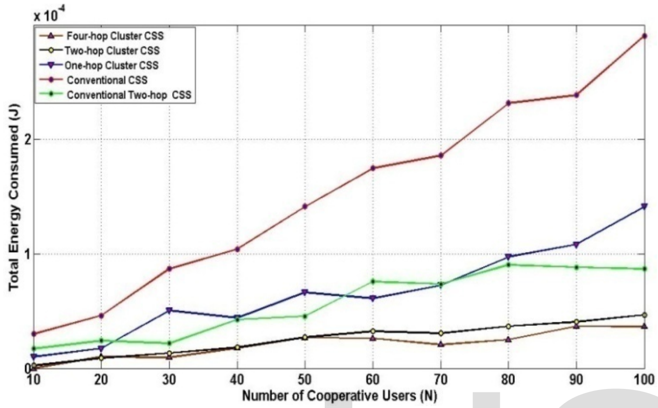

Fig. 6. Average Energy Dissipation versus number of users with different CSS modes.

The optimum number of clusters that minimizes energy dissipation in cognitive radio network is studied here. According to (14), we can analytically determine the optimal number of clusters K. Using our experimental parameters, and when ($75m \leq R_{\text{to FC}} \leq 295m$), the value of K will be (($1 \leq K \leq 5$). We verified this analytical result using simulations by varying K between 2 and 50.

Fig.7,which shows the energy dissipation as a function of K for two models (one-hop and two-hop), shows that the optimal number of clusters is around 4 for 100 cooperative users, which is agree well with our analysis. As illustrative in figure, when there is only few clusters (less than optimal number), the cluster members need more energy to report the results to their cluster head over far distance, and when there is more clusters (greater than optimal number), The dissipative energy will increase as a result of long distance between them and the fusion centre.

Another improvement that can be achieved by using our algorithm is the sensing agility.

Fig.**8** gives the normalized sensing delay $(TX/T(con.))$ in terms of number of clusters K in different number of hops L. As we can see in this figure, the normalized sensing time of single hop and multi-hop clustering approaches have a steep decline with the increase in the number of clusters K, and then begin to increase gradually at different rates according to the number of hops L. More specifically, although the multi-hop clustering scheme reduces the sensing time significantly within the range($2 \leq K \leq 5$), it adds further delay time within the range($K \geq 5$), but it stills much less than conventional mode (direct reporting).This is because more hops leads to more relaying needed to send the results to the FC, and thus, add further delay time, according to (41) and(42). According to (43), we can analytically determine the value of optimal number of clusters (K_{opt}) that gives a minimum sensing delay, which will be 10 when M = 100.

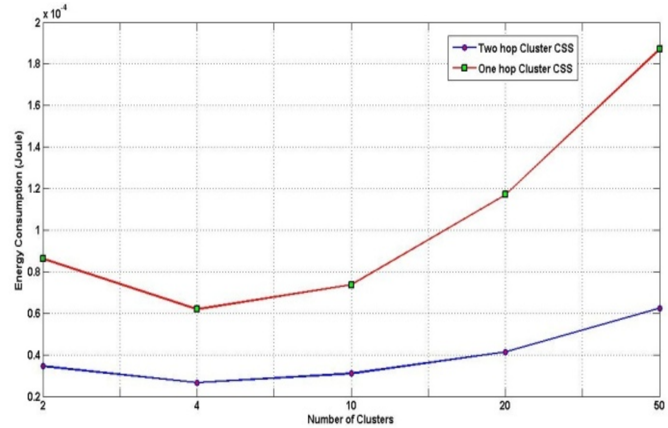

Fig.7. Energy dissipation versus number of clusters.

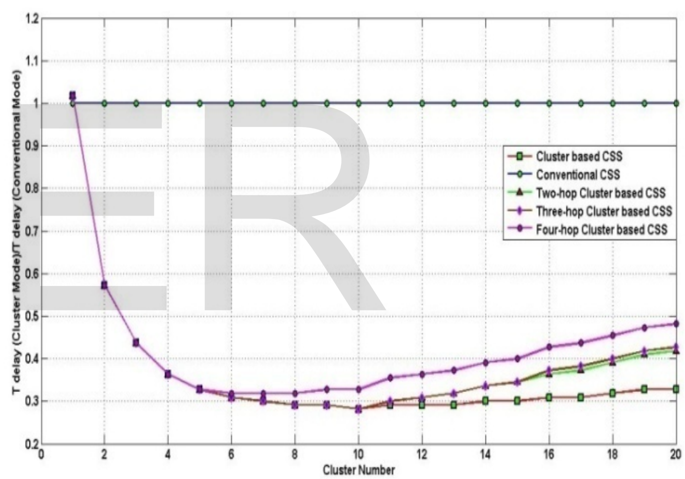

Fig.8. Sensing delay time performance in different cooperative modes.

7.2. Sensing Model of Multi-hop Cluster Based CSS

In this section, the sensing performance of multi-hop cluster-based CSS scheme is investigated under the perfect and imperfect reporting channels. The numerical results of our proposed algorithm are given to verify the analytical framework that is presented in the previous section.

First, the sensing performance of the conventional CSS is presented, where CRs are reported their local sensing results directly to the FC. Fig.9 shows the resulting receiver operating characteristic (ROC) curve for the decision fusion rules with the case of an Additive White Gaussian Noise (AWGN) for both sensing and reporting channels.

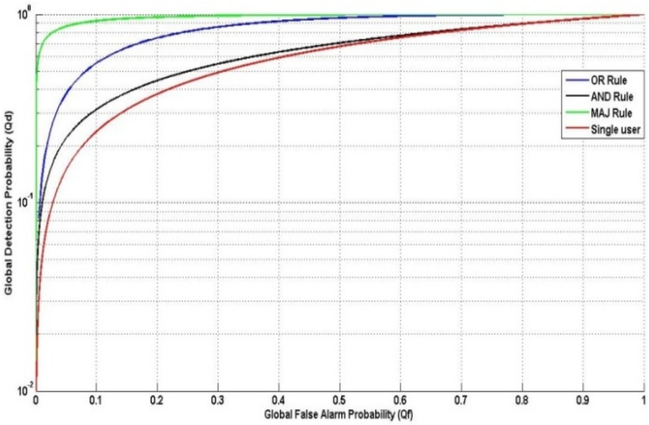

Fig.9. ROC curve of cooperative spectrum sensing with different fusion rules.

In this simulation, we assumed that a cognitive radio network with M=50 cooperative users operating at an average SNR of sensing channel $SNR_{local} = -10$ dB using N=50 samples. It can be seen from this figure that, for the same Qf, the Majority rule always outperforms OR rule and AND rules, and OR has better detection capability than AND fusion rule.

Second, the effective of error reporting under Rayleigh fading channels are considered, as shown in Fig.10. Here, we assumed that the number of samples N=10, and the average SNR of sensing link (between the primary transmitter and the CRs) is -10 dB. As we can see from this figure, when the number of CRs M increases from 50 to 100, and using the majority rule as a decision fusion rule at the FC, the detection performance will improve significantly. On the other hand, with the erroneous reporting channels, and when the average SNR of the reporting channel between each CR user and the FC is -5dB, the detection capability will be degraded due to the fading phenomena.

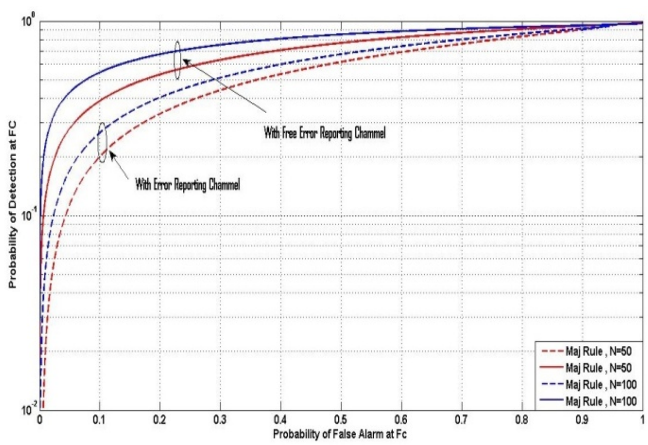

Fig.10. ROC curves of cooperative spectrum sensing over Rayleigh fading channels with and without error.

In Fig.11, the ROC performance of multi-hop clustering CSS scheme over Rayleigh fading is given. In this simulation, we consider a 100 CRs are deployed randomly with different average SNR of sensing and reporting channels within the ranges of (-10, -5) dB and (-25, 25) dB, respectively. For simplicity, we assume that the noise power at each CR user is equal to 1, and also the majority fusion rule at both the cluster heads and the FC is used. The results of conventional mode are also given for a comparison.

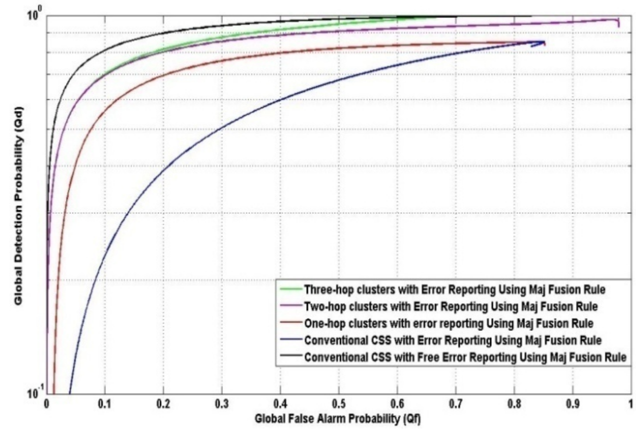

Fig.11. ROC curves for multi-hop Clustering CSS using Majority fusion rule.

As can be seen from this figure, the detection accuracy deteriorates as the number of error reports increases due to low SNR of reporting channel. However, the sensing performance can be enhanced using clustering approach. By using the clustering mechanism, the local sensing will be sent to the FC via intermediate CR user (CH) that has the largest SNR of reporting channel. In this simulation, we set the number of clusters K = 5, and the reporting SNR of CHs are (25, 8, 3, 0, -1) dB. Simulation results indicate a clear improvement in sensing performance compared to traditional detection mode even with some CHs that suffer from poor SNR, especially the far CHs.

Fig.11 also illustrates the advantage of detection capability of multi-hop clustering algorithm when the SNR of multi-hop is better than one-hop. Here, we assume that the clusters (k = 5) are formed at the FC based on the CR users' distances to the FC and divided into multi-hop levels. For instance, for two levels hop scenario, 2 in level-1 and 3 in level-2. In three levels hop scenario, 2 clusters in hop level-1, 2 in hop level-2, and 1 in hop level-3. Therefore, we can exploit the channel conditions between successive hops, which are much better than between far clusters and the FC. In our simulation, the SNR of the successive three levels hop communication are chosen randomly as (25, 8, 12, 14, 15) dB, respectively. In other words, 25 dB represents the SNR of reporting channel between the first CH_{L1} and the FC, 8 dB denotes to the SNR of reporting channel between the second CH_{L1} and the FC, and so on, while 15 dB is the SNR of reporting channel between the CH_{L3} and the first or second CH_{L2}. As shown, the sensing performance of multi-hop clustering scheme outperforms the one-hop mode, which basically depends on the channel conditions of the successive multi-hop. Although, the sensing performance of multi-hop algorithm has not reached to the ideal case (Free error case), it can be seen that there is a great improvement in the sensing performance for 3-hop approach compared to 2-hop, resulting from good reporting channels and the short distances between CHs.

8 Conclusion

In this paper, we have proposed a new multi-hop clustering approach for cooperative spectrum sensing. Based on our simulation results, the performance of the proposed algorithm has been evaluated through three assessment points, including sensing performance, sensing agility, and the energy consumption. The transmission energy consumption of our proposed scheme has been derived and compared with that of the conventional one. The simulation results have shown significant decrease in transmission energy consumption compared to the conventional schemes. The parameters of sensing performance and sensing delay time have also been derived and analyzed, and the obtained results have shown that the sensing performance of the multi-hop CSS is more accurate than one hop approach but incurs a slight increase in the sensing time due to successive data reporting. From these results, we can conclude that by increasing the number of hops we can improve the performance and efficiency of spectrum sensing. However, this improvement will be on the expense of the power consumption needed to report the decision results. Therefore, tradeoffs between these parameters (sensing accuracy, sensing delay, and energy consumption) need to be considered while designing spectrum sensing algorithms using CSS, in order to satisfy the requirement of the application.

In future, we plan to treat the tradeoffs issue as an optimization issue using some professional evolutionary techniques such as multi-objective optimization, where the optimal solution can be obtained in the presence of tradeoffs between above conflicting performance parameters.

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