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Exploring the Effect of Various Cluster Structures on Energy Consumption and End-to-End Delay in Cognitive Radio Wireless Sensor Networks

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ABSTRACT The growing demand and wide deployment of cost effective wireless communication networks, and the challenges related to its technical design and operations have necessitated the work on the more efficient use of the very limited radio frequency spectrum, limited energy resources and reduction of the end-to-end delay as an integral part of the next generation smart wireless networks. In this paper, we explore three different cognitive radio wireless sensor networks cluster structures; modified single-hop structure, multi-hop cluster structure, and hybrid cluster structure. We study the effect of the three structures in multiple setups in regards to varying the selected area. The evaluation results of the suggested three structures are compared with the single-hop cluster. Extensive simulation results carried out using MATLAB package showed that the end-to-end delay is minimum for the hybrid algorithm on the expense of a slight increase in energy consumption compared with the single-hop and the multi-hop cluster structures. On the other hand, the multi-hop cluster structure is more energy consuming than the single-hop, but it achieves a wider coverage area.

INDEX TERMS Cognitive radio, cognitive radio wireless sensor network, cluster structures.

I. INTRODUCTION

The RF spectrum medium that wireless communication operates on, is a concrete and finite resource divided into different licensed and unlicensed frequency bands. Each band has specific applications and limitations related to the bandwidth and quality. When considering the increasing deployment of next generation wireless communication networks which includes Cognitive Radio Wireless Sensor Networks (CRWSNs), energy efficiency is a fundamental factor affecting their development and performance. The swift proliferation of wireless communication applications on one side, and an accommodation of the accelerating demand for wireless users on the other side, calls for a more efficient use of the very limited RF spectrum resources and dictates the use of Cognitive Radio (CR) as a fundamental part of next generation smart wireless communication networks. This nature of CR improves the efficiency of Wireless Sensor Networks (WSNs) by increasing the communication reliability and improving the Sensors energy efficiency. When wireless sensor nodes with cognitive capabilities are introduced to an entire network, it gives exciting new opportunities to researchers and industry to develop algorithms, hardware and software that can overcome the limitations imposed by current wireless sensor design techniques [1]. The usage of optimal transmission strategy in CRWSN requires changes in the philosophy of spectrum management to balance, on one side, the amount of interference from dynamic multiple access, and optimum use of the spectrum, on the other. Spectrum sensing monitors the activities of Primary Users (PU) to detect which portions of the licensed spectrum band are not occupied by the PUs. However, propagation impairments such as receiver uncertainty, multipath fading, shadowing and interference in wireless channels degrade performance of spectrum sensing techniques [2]. The distinction between a primary user and a secondary user is the focus of spectrum sensing. In this work, we assume that spectrum sensing has been completed and users have been assigned portions of the spectrum. CRWSN strategy is involved in a wide range of application fields as follows: Health Information Systems; as medical information is critical and very delay sensitive. Intelligent Spectrum Access in Vehicular Networks and object tracking; where Vehicular wireless sensor networks are used for proactively auditing and collecting information in civilian environments, real-time surveillance; as CRWSN can aggregate multiple channels simultaneously to increase the channel bandwidth for bandwidth-hungry applications. CRWSNs are also used in the monitoring of outdoor and indoor environments for purposes such as factory automation and personal entertainment. Implementing these applications using CRWSN resolves jamming issues and restricted bandwidth problems, that often emerge in traditional WSNs. CRWSN may also serve military and public security applications in which it can handoff frequencies with different frequency bands with minimum channel access and communication delays [1].

Owing to the fact that the CR mobile users' devices are battery-powered, CRWSN nodes are power-restricted devices with a limited energy source. Power consumption is an important design factor and one of the main performance metrics that directly affects the network lifetime. Wireless sensor nodes need energy for spectrum sensing, channel negotiation, routing and forwarding and processing the data packets. Energy-Efficiency and transmission optimization become mandatory and beneficial in minimizing the consumed energy in sensing and registration process to save the limited energy resources.

The prominence of efficient energy saving techniques has been the drive behind many research works to construct the wireless network that minimizes energy consumption for sensing operations. Mustapha *et al.* [1] proposed an energy-aware clustering algorithm for cooperative spectrum sensing to minimize spectrum sensing energy costs. Usman *et al.* [3] proposed a detailed comparison between multiple techniques in [4] and [5], which discussed different routing techniques in the sensor-assisted CR; namely SENDORA and LEACH protocols, and how these techniques suffer from high energy consumption. However, [3] did not offer a multi hop solution, but various scheduling approaches are compared. Nonetheless, these approaches did not correlate with mobile sensing. Darak *et al.* [6] proposed a Decision-Making Policy (DMP) for the opportunistic spectrum access based on Cognitive Radios with Radio Frequency Energy Harvesting (RFEH) capabilities. Deng *et al.* [7] proposed using energy detection and own-waveform-based sensing to perform spectrum sensing while the user is transmitting in parallel. However, [7] did not describe the sensor network topology. Kim *et al.* [8] proposed a novel cognitively inspired algorithm, namely the Artificial Bee Colony Clustering (ABCC) algorithm, for the optimal configuration of Cognitive Radio Wireless Sensor Networks (CRWSNs). Network configuration is specified via a binary decision variable assigned to each node to classify a node as either a cluster head or a sensor node. Joshi and Borde [9], described CRWSN where the conventional wireless sensor nodes are equipped with CR functionality. CRWSN requires highly complicated sensor nodes, so the high cost of a CRWSN makes it impractical. Emre *et al.* [5] modeled the energy-efficient channel access problem using reinforcement learning. However, [9] neither investigated the practical issues of exchanging the Q-values, nor discussed the problem of extending the coverage area. Elmahdy *et al.* [10] formulated two optimization problems to a common constraint on the maximum packet delay to minimize the SU average packet delay. However, this optimization is applicable under specific constraints and depends on how tight the applied constraints are.

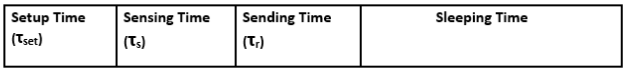
In this paper, we propose three different CRWSN cluster structures; modified single-hop cluster structure, multi-hop cluster structure, and Hybrid cluster structure to address the communication between CR mobile users in CRWSN. The proposed scenarios are discussed with regards to the communication coverage standards for WiFi and Mobile Applications. The proposed single-hop cluster structure is a modified version to the one in [3], where the number of registered nodes are conditionally controlled and restricted to be no more than three. On the other hand, we propose a multi-hop and a hybrid cluster structure, to enhance the energy efficiency and the end-to-end, with a wider coverage area which overcomes the short coming of a high concentration of a large number of nodes in [3]. This leads to an increase in the intensity of electromagnetic waves within the coverage area, which negatively affects human health.

In the multi-hop cluster structure, the system model is composed of multi-hop infrastructure sensor nodes formed in sets of overlapping clusters to ensure full coverage. Within multi-hop communication range, the CR mobile user is surrounded by one or more clusters of sensor nodes. In order to save energy, inactive clusters are kept in sleeping mode. In the hybrid structure, the CR mobile user establishes a connection using either the shared CRWSN or direct ad-hoc setup, based on the CR mobile sender and receiver location and Signal to Noise Ratio (SNR). The overall end-to-end delay and energy consumption are measured when sensor nodes are in single-hop cluster, in a modified single-hop cluster and in a multi-hop cluster model. Also, the probability of detection and false detection are evaluated.

The remainder of this paper is organized as follows; in section II we give a detailed system description, along with an explanation of how to form a cluster and subset division. In section III we explain the system model. In section IV the simulation results and detailed discussion and a through comparison with the other algorithms are introduced. Finally the paper is concluded in section V.

II. SINGLE-HOP SYSTEM DESCRIPTION

This work considers the sensor-assisted CRWSN with ad-hoc CR mobile users, where the users utilize the system in a time slotted manner as in Fig. 1, and the sensor node goes through quadruple S-stages (setup, sense, send and sleep) while active. The CR mobile user serving as a cluster head receives the sensing outcomes report from sensor nodes directly. A common control channel is used for exchanging the control parameters between the nodes and the mobile user. The location of each sensor node is either known from infrastructure information, or determined by the CR mobile user through a built-in GPS.



Setup Time **(τ_{set})**	**Sensing Time** **(τ_s)**	**Sending Time** **(τ_r)**	**Sleeping Time**

FIGURE 1. Time Slot Structure.

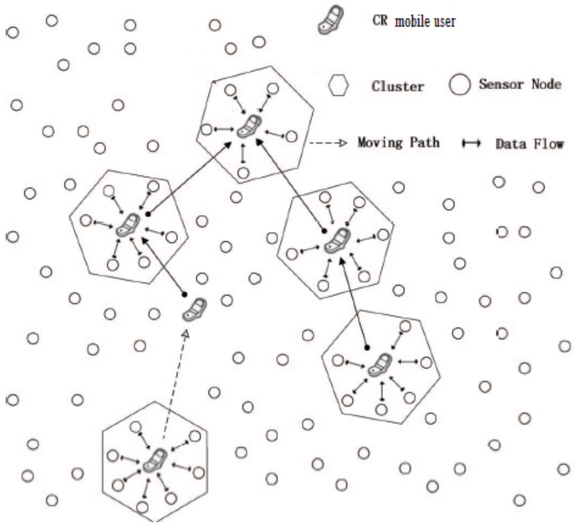


FIGURE 2. Cluster Formation.

A. CLUSTER FORMATION AND SUBSET DIVISION

The CRWSN nodes are grouped into disjoint subsets to form overlapping clusters. Only active subsets are awake to perform the sensing task, and others remain in sleep mode to save energy as shown in Fig. 2. The formatted clusters are used to implement the communication coverage for the users. Clustering is considered one of the main power saving solutions for CRWSNs [1]. The communication roles are distributed between the sensor node and the CR mobile user. Each CR mobile user transmits Advertising (ADV) messages to all sensor nodes containing the ID of the CR mobile user, the position, the number of registered nodes by the CR mobile user and the header information. The header information field contains the type of message which is used to filter the received control messages into ones advertising the CR mobile user parameters or nodes control parameters.The control message from the nodes may contain the response from the nodes to the CR mobile user, the ID of the CR mobile user, the remaining energy, and the SNR. When a node receives many messages, the node will join the CR mobile user closest to it to save energy. If a node is equidistant from two or more CR mobile users, it will join the CR mobile user with the least number of registered nodes to minimize wait time.

B. CLUSTERING UPDATING PROCESS

The formatted clusters should start the updating process when there is a change in the CR mobile user position, a change in the number of nodes, or un-clustered nodes join. Subset Formation may be decomposed into one or more disjoint subsets, activating only one subset of the nodes rather than the entire cluster, which reduces the energy consumption by putting the inactivate nodes in sleep mode. To avoid failure, subset formation begins with the node that has the most remaining energy [3]. As the CR moves, the distance between the CR and registered node may increase. In which case, the node may unregister from the CR by sending a leave request. The CR should, then, remove this node from the registered nodes and send a join request to the nearest unregistered node.

C. SYSTEM MODEL PARAMETERS

The cluster formation setup stage requires the calculation of the number of nodes S, that satisfies the constraints on the probabilities and global probabilities of detection and false alarm. The overall energy consumption, and the overall end-to-end delay are used to monitor the performance of various setups. By iterating over different number of samples U and energy threshold for a local decision ϵ at variable SNR γ_j, the probabilities of detection P_{dj} and false alarm P_{fj} for the j-th node of a subset given in [3] and [12] are calculated by (1) and (2):

$$P_{dj} = Qu(\sqrt{2\gamma_j}, \sqrt{\epsilon}) \tag{1}$$

$$P_{fj} = \left[\frac{\Gamma(U, \epsilon/2)}{\Gamma(U)}\right] \tag{2}$$

Q_u is the generalized Marcum Q-function, $\Gamma(.)$ and $\Gamma(.,.)$ are the complete, incomplete gamma functions respectively. Where $Q_u(a,b) = \int_b^\infty (x) exp(\frac{(x^2+a^2)}{2}) I_0(ax)dx$, $\Gamma(x) = \int_0^\infty e^{-t} t^{x-1} dt$, and $\Gamma(a,b) = \int_b^\infty t^{a-1} e^{-t} dt$. Note that γ_j is reported to the CR as a part of the join process messages. The probabilities of no detection of a node j are independent on other nodes, hence the probabilities are multiplied. Global detection probability Q_d and global false alarm probability Q_f are given by (3) and (4);

$$Q_d = 1 - \prod_{j=1}^{S} (1 - P_{dj}) \tag{3}$$

$$Q_f = 1 - \prod_{j=1}^{S} (1 - P_{fj}) \tag{4}$$

subject to the following constraints (5) and (6);

$$Q_d \geqslant Q_d^{min} \tag{5}$$

$$Q_f \leqslant Q_f^{max} \tag{6}$$

where Q_d^{min} and Q_f^{max} represent minimum global detection probability and maximum global false alarm probability respectively.

Substituting in the above equations generates the following (7) and (8):

$$1 - \prod_{j=1}^{S} (1 - P_{dj}) \geqslant Q_d^{min} \Leftrightarrow 1 - Q_d^{min} \geqslant \prod_{j=1}^{S} (1 - P_{dj}) \tag{7}$$

$$1 - \prod_{j=1}^{S} (1 - P_{fj}) \leqslant Q_f^{max} \Leftrightarrow 1 - Q_f^{max} \leqslant \prod_{j=1}^{S} (1 - P_{fj}) \tag{8}$$

P_d^{min} and P_f^{max} are the minimum detection probability and the maximum false alarm probability, respectively. Thus the following conditions should be satisfied; $P_{dj} \geqslant P_d^{min}$ and $P_{fj} \leqslant P_f^{max}$ for all the j values, where P_d^{min} is the minimum bound of P_{dj}, j = 1,..., C and P_f^{max} is the maximum bound of P_{fj}, j= 1,...,C, $P_{dj} \geqslant P_d^{min}$ and $P_{fj} \leqslant P_f^{max}$, j= 1,...,C [3]. Since P_d^{min} and P_f^{max} are constant, hence (9) and (10) should be satisfied for all nodes, as follows;

$$(1 - P_d^{min})^S \geqslant \prod_{j=1}^{S}(1 - P_{dj}) \tag{9}$$

$$(1 - P_f^{max})^S \leqslant \prod_{j=1}^{S}(1 - P_{fj}) \tag{10}$$

Substituting (7) and (8) into (9) and (10)

$$1 - Q_d^{min} \geqslant (1 - P_d^{min})^S \tag{11}$$

$$1 - Q_f^{max} \leqslant (1 - P_f^{max})^S \tag{12}$$

By taking the logarithm of both sides for equations (11) and (12):

$$\left\lceil \frac{\log(1 - Q_d^{min})}{\log(1 - P_d^{min})} \right\rceil \leqslant S \leqslant \left\lceil \frac{\log(1 - Q_f^{max})}{\log(1 - P_f^{max})} \right\rceil \tag{13}$$

Where S is the maximum number of sensor nodes in any subset from (13), S is given as

$$S = \left\lceil \frac{\log(1 - Q_f^{max})}{\log(1 - P_f^{max})} \right\rceil \tag{14}$$

The calculated energy is the average consumed energy for all nodes. The energy consumed in the cluster formation stage including the initial control signals exchange process is less than or equal 0.3 % of the overall energy consumption [3], thus, the initial setup energy is neglected and the sensing energy E_s is considered the main energy consumed.The overall energy consumed is calculated by (15):

$$E = E_{int} + E_s \tag{15}$$

Where E_{int} and E_s are the energy consumed in the setup phase (Cluster and the subset setup) and the sensing phase, respectively. The time duration for sensing, calculated by (16), depends on SNR, detection probability and false alarm probability.

$$\tau_{sj} = \left\lceil \frac{Q^{-1}(P_{fj}) - Q^{-1}(P_{dj})\sqrt{2\gamma_j + 1}}{\sqrt{f_s}\gamma_j} \right\rceil^2 \tag{16}$$

Where τ_{sj} and γ_j are the sensing time and the SNR, respectively, at the j-th node, f_s is the sampling frequency, and $Q(:)$ as in [3] is the complementary cumulative distribution of a standard Gaussian. τ_{sj} must satisfy the following constraints (17):

$$\tau_{sj} \leqslant \tau_{smax} \qquad j = 1, .., S \tag{17}$$

TABLE 1. List of parameters and their notations.

Parameters	Symbols
Total Number of sensor nodes	S
Actual number of active nodes	K
Energy consumption in Sensing	E_s
Power consumed in sensing	P_s
end-to-end Delay	D
Detection Probability of each node/ cluster	P_d
False alarm Probability of each node/cluster	P_f
CRs mobility coverage range	A_r
Energy threshold for a local decision	ϵ
Global detection probability	Q_d
Minimum global detection probability	Q_d^{min}
Global false alarm probability	Q_f
Maximum Global false alarm probability	Q_f^{max}
Time duration of sensing	τ
Maximum sensing duration	τ_{max}
Number of samples	U
SNR	γ

Where τ_{smax} is the maximum duration for sensing, which is set to an estimated value of 2 ms [3]. The energy consumed in the sensing phase is calculated using the following equation (18):

$$E_s = \sum_{j=1}^{S} P_s \tau_{sj} \tag{18}$$

where P_s is the average power of the sensing process and τ_{sj} is the sensing duration for node j from (16), in S number of sensor nodes.

III. PROPOSED SYSTEM MODEL

This work consists of multiple setups in regards to the coverage area and the cluster formation, where each cluster consists of a group of subsets of K nodes. First, we propose a single-hop cluster structure where we modify the system in [3] by stopping the sensing stage when three nodes are discovered and registered. Whereas in [3] the CR continues sensing until it discovers all the nodes in the closest disjoint subset, more than six nodes may be discovered, while three nodes or less are enough to complete the registration process. This issue is modified by setting a maximum to the number of nodes to be registered by any CR mobile user. Second we propose a multi-hop cluster structure where the same number of the sensor nodes S in sets of clusters are distributed in multi-layer clusters to maximize the coverage area A_r. This multi-hop cluster Structure is simply a repetition or expansion of a single-hop coverage scenario. This results in a path with multiple short hops which is more power efficient than paths with fewer hops but with longer hop distance [11]. Third we propose a hybrid cluster structure, in which the CR will have the chance to select the optimum path using either the ad-hoc scenario or the infrastructure based scenario. In this work we explore the effect of the three proposed cluster structures on both the energy consumption and the end-to-end delay in CRWSN. The common simulation parameters are concisely listed in Table 1. For notation convenience,the same symbols used are as in [3].

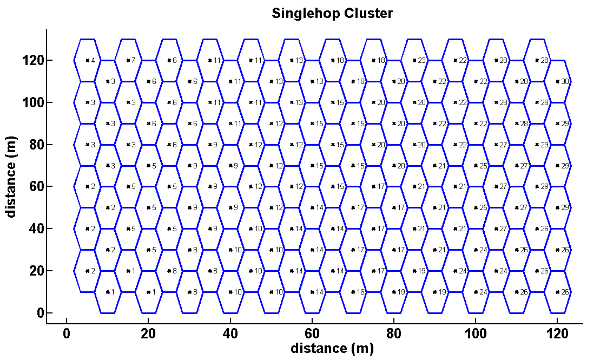


FIGURE 3. Modified Single-Hop Cluster Structure.

A. PROPOSED MODIFIED SINGLE-HOP CLUSTER STRUCTURE

In this cluster structure design, the wireless sensor nodes are in fully overlapped coverage to form single-hop cluster coverage as illustrated in Fig. 3. The sensor nodes within communication range r of each CR are grouped into clusters, and each cluster is divided into disjoint subsets with overlapped sensing coverage. One subset of the cluster is active and provides target detection and false alarm probabilities while the rest of the subsets are in a sleep mode. When simulating the single-hop structure in [3], it is observed that the CR has no limit to the number of sensing nodes where the CR starts to sense first node then continues sensing till all nodes are discovered. It is also observed that the distance between each sensor node is very short, and the overlapping is maximum; which increases the impact on human health because of the high effect of electromagnetic waves.

The number of nodes needed to form a cluster varies from 5 to 7 nodes as in [3]. However during the simulation the CR starts sensing nodes within the cluster, and registering with all nodes. Through simulations, we found that the CR does not need to register with all nodes in a cluster for successful communication, and that increasing the number of registered nodes beyond three does not improve performance. On the other hand, limiting the registered nodes to three minimizes end-to-end delay and energy consumption.

Thus, to overcome the aforementioned issue in [3], algorithm 1 is proposed which controls the number of registered nodes per CR. In this algorithm a number of sensor nodes S is formed in a modified single-hop cluster design structure, the global detection probability Q_d is assumed to be greater than the minimum global detection Q_{dmin}. For the number of rounds where the number of rounds represents how many times the CRs update their positions in the predefined area in each scenario, the energy consumed E_s and the end-to-end delay D are calculated. The CR takes τ sec to complete the registration steps but cannot exceed τ_{max}. The CR will stop sensing after reaching predefined K nodes.

B. PROPOSED MULTI-HOP CLUSTER STRUCTURE

The superlative number of clusters in the network plays an important role in the communication energy cost. After implementing the modified single-hop cluster structure, it is noticed that for registration and communication to be successfully completed, the CR should move within coverage of one or more overlapped clusters. From this perspective, the multi-hop cluster design is proposed and considered as repeated single-hop coverage scenario. In this model the same number of clusters as in the modified single-hop design is used to form a multi-hop cluster architecture with 120 % increase in the coverage area as presented in Fig. 4. Expanding the modified single-hop scenario leads to minimizing the effect of the electromagnetic waves on the human health, and reducing the carbon footprint [9]. The updates between the clusters are controlled via the central cluster to limit the update flooding messages. The update messages are sent when any new registration process starts. Moving between more than one shorter hop distance may be more efficient than moving between those fewer but longer hop distances [11]. Based on this result, the imbrication level is minimized thus adding more practicality to this design.The overlapping between the clusters is minimized, which in effect expands the same number of clusters in a larger area as in Fig. 5. Algorithm 2 provides the multi-hop scenario cluster shaping procedures in one of the predefined areas in conjunction with controlling the number of registered sensor nodes per CR as in the modified single-hop scenario.

In some cases, it is observed that the distance between the CR users is shorter as shown in Fig. 6. However, in the multi-hop setup, the communication between these devices follows

Algorithm 1 Modified Single-Hop cluster Structure

```
Require: $K, S, Q_d, Q_d^{min}, \tau, \tau_{max}$
  For Rounds= 5000
  if $K < S,\ Q_d < Q_d^{min}$ then
      Check $P_d$ and $P_f$
      Check the number of registered nodes
      Stop registering when reaching specific $K$ nodes
      Calculate $E_s,\ D$
  else
      $K = K + 1$
      Calculate $E_s,\ D$
  end if
  end
```

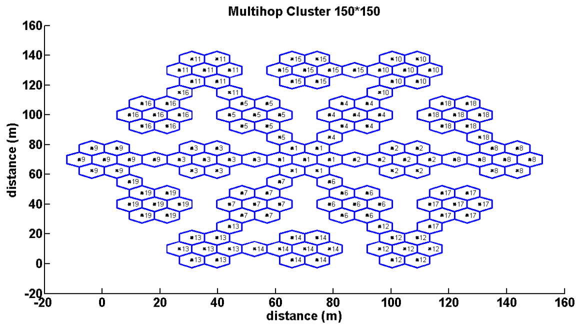


FIGURE 4. Multi-Hop cluster structure in 150 m X 150 m.

Algorithm 2 Multi-Hop Cluster Structure

```
Require: $K, S, Q_d, Q_d^{min}, \tau, \tau_{max}$
  For Rounds= 5000
  if $K < S, Q_d < Q_d^{min}$ then
    Check $P_d$ and $P_f$
    Shape the clusters into one of the predefined areas
    Calculate $E_s, D$
  else
    $K = K+1$
    Calculate $E_s, D$
  end if
  end
```

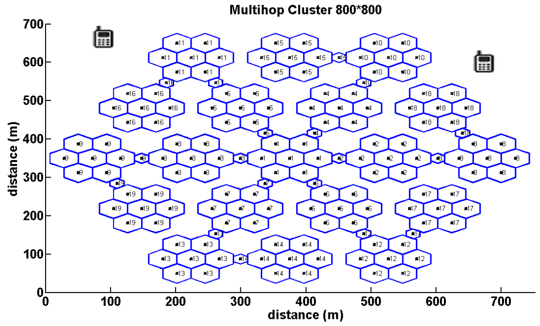


FIGURE 5. Multi-Hop cluster structure in 800 m X 800 m.

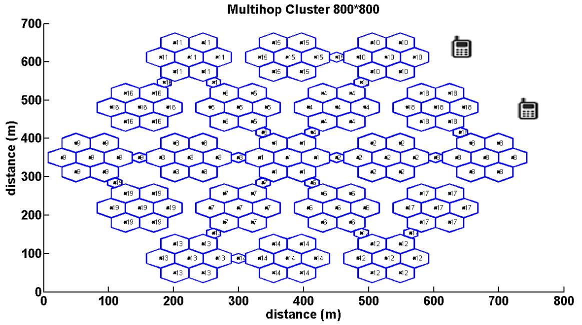


FIGURE 6. Two CRs communicating with hybrid model .

the path provided by the infrastructure-based sensor node, which results in suboptimal routing, as the provided route may not be the best route between them. This concern can be solved by giving CR the chance to select the optimum path considering the direct distance between the source and the destination which has a tremendous effect on decreasing the consumed energy.

C. PROPOSED HYBRID MODEL (AD-HOC ENHANCE)

In the hybrid model, in order to provide the optimum energy-efficient path, the source CR receives the infrastructure path metrics information via the control channel of the joined CRWSN and compares it to the calculated path metric information to reach the destination CR mobile user directly, then the CR mobile user determines the optimal transmission technique (ad-hoc scenario or Infrastructure based scenario).

Algorithm 3 Hybrid-Model Cluster Structure

```
Require: $K, S, Q_d, Q_d^{min}, \tau, \tau_{max}$
  For Rounds= 5000
  if $K < S, Q_d < Q_d^{min}$ then
    Check $P_d$ and $P_f$
    Shape the clusters into one of the predefined areas
    Choose to continue Infrastructure or ad-hoc based on SNR and distance
    Calculate $E_s, D$
  else
    $K = K+1$
    Calculate $E_s, D$
  end if
  end
```

In order to enhance the CR mobile user performance, the CR mobile user is configured with dual transmission technique as in algorithm 3.

IV. SIMULATION RESULTS AND DISCUSSION

In this section, the overall energy consumed and end-to-end delay are discussed as follows: energy consumption of the sensor network is iteratively measured against the number of rounds; and the overall end-to-end delay when the delay is defined as the time taken starting from the sensing process till the end of the reporting process from the registered CR. The network performance is evaluated by comparing the overall energy consumption and the overall delay with the results in [3].

A. SIMULATION RESULTS

All simulations were performed using MATLAB 2010 release (a) over an intel i7 quad-core 2.9 GHZ processor. The simulation is executed over 5000 rounds and the typical number of S nodes is calculated from (14), using algorithm 1, the number of registered nodes is controlled not only in the modified single-hop scenario but also in all proposed scenarios to minimize the sensing energy which is considered the main energy consumed. The energy consumed in the setup stage may be ignored as it does not exceed 0.3 % of the energy consumed in sensing [3]. The consumed energy per sensor nodes evaluated by (15) and (18), is plotted against the number of rounds for different communication ranges. The overall end-to-end delay is measured by (16) and (17) and plotted against the number of rounds. P_d and P_f are calculated using (1) and (2), respectively. From the simulation, it is found that P_d saturates with increasing number of samples U to a value near 0.5. However, P_f value decreases with increasing of the number of samples U, where γ varies between -25dB to -5dB. The initial energy E_{int}, the power consumed in sensing P_s within a subset, the number of nodes S and the sampling frequency are set, as in [3], to 5J, 100mW, 100 and 300 kHz, respectively.

The CR users move randomly in any direction between the multi-hop clusters structure within the predefined area

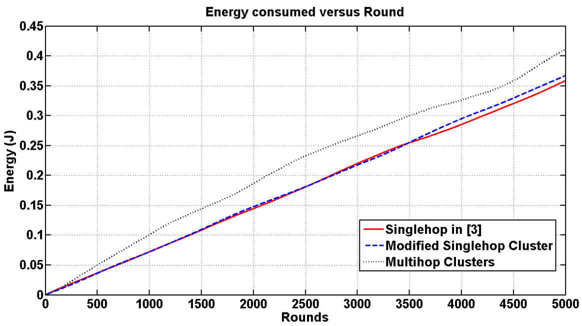


FIGURE 7. Overall energy consumption comparison in 150 m X 150 m coverage area.

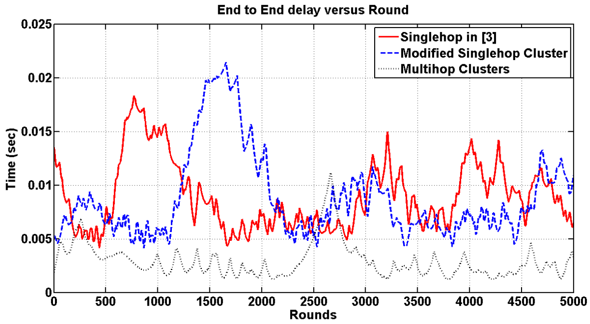


FIGURE 8. Overall end-to-end delay comparison in 150 m X 150 m coverage area.

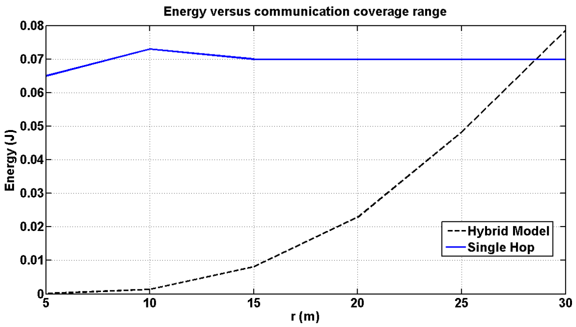


FIGURE 9. The consumed energy over different communication coverage ranges .

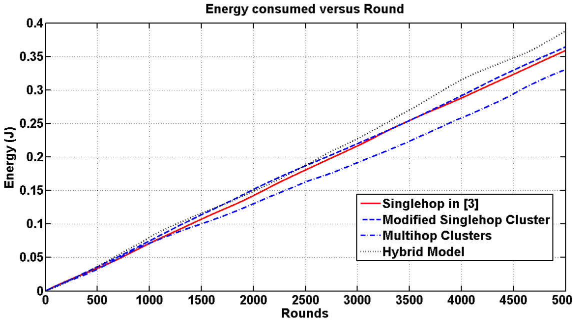


FIGURE 10. Overall energy consumption comparison in 800 m X 800 m coverage area.

A_r, keeping the registered clusters only active to reduce the consumed energy. The proposed area A_r has different values, These values vary between 150 m X 150 m and 800 m X 800 m. Adding the modification to the single-hop model in [3] causes the CR mobile user to stop the sensing process after discovering the nearest nodes and start the registration process. The overall energy consumed in the proposed model is slightly lower than the single-hop in [3].

Fig. 7 and 8 represent the Overall energy consumption and end-to-end delay versus Rounds in the proposed multi-hop design, the proposed modified single-hop and single-hop in [3]. The overall energy consumption of the two moving CR mobile users in the first predefined area 150 m x 150 m, ranges between 0 to 0.12 J. The minimum values occur when the CR mobile users are closest to the clusters.

From the overall consumed energy and the overall end-to-end delay in the multi-hop design for A_r 800m X 800m, between the two moving CRs, it is noticed that the values are at their minimum when the CR is closest to the cluster. These values are slightly higher than the measured values in the first predefined area. The delay D is found between 5 ms and 30 ms. These results are considered superior to the large area covered by the clusters. Despite the fact that the consumed energy has increased with increasing the coverage area, the overall energy consumption is acceptable given the larger coverage area, which makes this setup feasible for outdoor implementation. As discussed in the hybrid model, due to the short distance between the CRs, they can communicate directly instead of communicating through cluster nodes. The CRs will use the ad-hoc technique to communicate in this scenario. The overall end-to-end delay varies in different formations as presented in Fig. 8, setting up the sensor nodes in multi-hop architecture decreases the delay to around 6 ms.

Fig. 9 represents the overall energy consumed over different communication coverage ranges r, in which the energy consumed is about 0.07 J with r between 0 to 30 m. However in hybrid model the shorter the distance the lower the energy consumed, where the value is near 0.01 J in the first 10 m then reaches 0.02 J in the second 10 m then increases gradually in the third 10 m to about 0.08 J. Comparing these values, the hybrid model is considered the most energy-efficient mechanism with a maximum value of 0.08 J in a 30 m communication coverage.

B. PERFORMANCE EVALUATION

The energy consumed for sensing and reporting local decisions is the main energy cost for spectrum sensing in cognitive radio networks. However, the energy consumed in communication is taken into consideration and added to the overall energy consumed. Fig. 10 shows a comparison between single-hop in [3], modified single-hop cluster, multi-hop cluster and hybrid cluster structures in overall energy consumption. The energy consumed in the hybrid cluster structure is slightly higher than the other setups. On the other hand, the hybrid design achieves minimum overall end-to-end delay (less than 5ms) as shown in Fig. 11. The complexity of the three proposed algorithms as well as the single hop

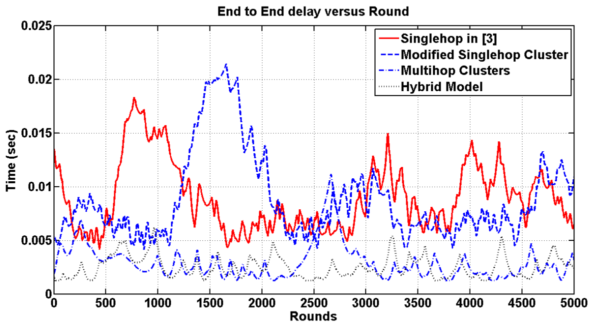


FIGURE 11. **Overall end-to-end delay comparison in 800 m X 800 m coverage area.**

in [3] is O(S*R), where S is the number of sensor nodes in the network and R is the number of rounds that represents how many times the cognitive radio mobile users update their positions.

V. CONCLUSION

In this paper, the energy consumption and overall end-to-end delay of various cluster structure for CRWSN has been investigated. First, an enhancement to the single-hop structure is introduced by controlling the number of registered nodes per cluster in each round. This modification results in slightly reducing the energy consumption compared to the unmodified single-hop structure. In order to increase energy efficiency, the multi-hop cluster structure is proposed. Simulation results show that the multi-hop cluster structure reduces energy consumption while simultaneously expanding the coverage area. The expansion in the coverage area is a consequence of minimizing the overlap between clusters. In the last configuration, a hybrid selection criterion is added to the mobile devices, which allows the mobile device to establish a connection using either the shared CRWSN or direct ad-hoc setup. While the ad-hoc setup introduces a slight increase in energy consumption, it minimizes the overall end-to-end delay. The end-to-end delay decreases from 30 ms in the multi-hop structure to less than 5 ms in the ad-hoc structure. By choosing the shortest direct path in the ad-hoc setup, the end-to-end delay is minimized on the expense of an increase in energy consumption. On the other hand, the multi-hop structure outperforms the single-hop and hybrid structures in terms of energy consumption and coverage area.

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