Energy-Efficient Cluster Head Selection for Cognitive Radio Sensor Networks

Emad Helal
National Research Institute of Astronomy and Geophysics
Helwan, Egypt
emadbadr2011@gmail.com

Ahmed Khattab
Cairo University
Giza, Egypt
akhattab@ieee.org

Yasmine A. Fahmy
Cairo University
Giza, Egypt
yfahmy@cws-cufe.org

***Abstract*—In this paper, we propose an Energy-Efficient Cluster Head Selection (ECHS) approach for Cognitive Radio Sensor Networks (CRSNs). ECHS achieves energy-efficient clustering while considering the dynamic channel access nature of CRSNs. ECHS is a distributed algorithm in which serving as a cluster head depends on two factors: the channel availability in the node's vicinity and the node's energy. To tackle the hot spot problem caused by the high traffic near the sink, ECHS forms many small clusters near the sink to share the forwarding load of the rest of the network. Dynamic channel assignment at the cluster heads is used to minimize the co-channel interference. Simulation results show that ECHS achieves a remarkable throughput increase while extending the network lifetime.**

***Index Terms*—cognitive radio sensor networks; energy efficiency; clustering; frequency assignment**

I. Introduction

Cognitive Radio Network (CRN) principles have recently been integrated with Wireless Sensor Networks (WSNs) to improve the spectrum requirements of WSNs. This results in a new paradigm called Cognitive Radio Sensor Networks (CRSNs) [1]. However, this integration poses simultaneous constraints: spectrum-awareness and energy efficiency which were inherited from CRNs and WSNs, respectively.

Clustering techniques for WSNs has received significant research [2-3]. However, the existing literature does not target dynamic channel selection in the clustering decisions as the case in CRSNs. Likewise, clustering techniques developed for CRNs do not take into account the limited energy resources of the sensor nodes in CRSNs. Hence, clustering techniques in CRSNs should be energy-efficient in organizing a large-scale network of sensors while being aware of the availability of channels, in order to prolong the network lifetime. One way to achieve this goal is through introducing new metrics to capture the tradeoff between energy-efficiency and opportunistic channel access in cluster head selection for CRSNs.

In this paper, we propose the Energy-efficient Cluster Head selection (ECHS) protocol for CRSNs. ECHS manages the clustering in an energy-efficient manner with awareness of the available free channels. In ECHS, the nodes which have a larger number of available free channels and more residual energy are selected to serve as Cluster Heads (CHs). ECHS also takes into account the CH node location which is an important factor to tackle the hot spot problem. The simulation results show that ECHS improves the throughput and network lifetime while maintaining high energy-efficiency.

The paper is outlined as follows. In Section II, we survey the related work. In Section III, the network model is described. The ECHS protocol is proposed in Section IV, and is evaluated in Section V. We conclude the paper in Section VI.

II. Related Work

Clustering is an efficient way to decrease the energy consumption and support scalability in WSNs. LEACH [4] is a popular distributed clustering protocol that was designed to improve the network lifetime. Each node in LEACH directly communicates with the sink in one hop. All nodes have an equal chance to become a CH to balance the load among nodes. In HEED [5], the selection of CH nodes is based on two parameters: the residual energy and the node's location with respect to its neighbors. However, both protocols do not tackle the hot spot problem. The hot spot problem is caused by the high traffic volume that is carried by the nodes near the sink which cause such nodes to drain their batteries quickly.

The hot spot problem has been addressed in [6-8]. The main idea is to reduce the intra-cluster communications to manage the high load from inter-cluster communications. The EC algorithm [8] divides the network into regions, and the number of network regions were adapted in order to minimize the multi-hop energy consumption. EC adjusts the probability of a node to become a CH in each region in order to maximize the network lifetime. However, all these WSN clustering techniques operate over a single frequency which are not applicable for CRSNs and their high speed applications.

Clustering in CRSNs adheres to the constraints of both WSNs and CRNs. The distributed spectrum-aware clustering (DSAC) scheme for CRSNs [9] forms clusters with low intra-cluster distance to reduce the communication energy. However, DSAC requires intensive message exchange for cluster merging which makes it energy inefficient. In [10], a spectrum-aware extension of LEACH (CogLEACH) is proposed. The basic idea is to exploit the number of sensed idle channels as a metric in choosing the CHs. However, CogLEACH consumes high energy in signaling for cluster formation.

978-1-5090-5721-4/16/$31.00 ©2016 IEEE

III. System Model

We consider a CRSN that is composed of N cognitive sensor nodes that are referred to as the secondary user (SU) nodes. The SUs are homogeneous, battery-operated energy-constrained, and uniformly distributed in the considered area. SU nodes are equipped with a single transceiver that switches between C traffic channels in an opportunistic manner. Each node is equipped with spectrum sensing capability and can correctly determine the vacant channels. We assume that the channels do not change during the clustering phase. The control information is exchanged via a common control channel (CCC). All nodes always have data to send. The initial transmission range of a SU node is r_i meters which varies from one region to another as in [8]. Nodes initial energy levels are unequal. We use the energy consumption model for the sensor nodes as in [4]. The CRSN has only one sink node that is located at the network edge. The nodes are randomly distributed in a rectangular area of length X and width W, and is divided into regions as shown in the example depicts by Fig. 1. Each region R_i has width a as calculated in [11].

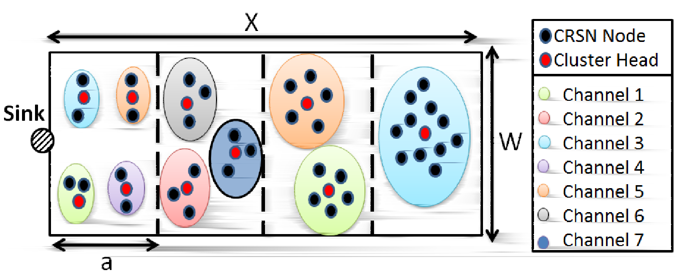


Fig. 1: Example ECHS network with 4 regions.

All the SUs are in range of P primary networks. The transmission activity of the primary users (PUs) follows a Semi-Markov ON-OFF process [12]. The probability that each channel in not utilized by the PU, i.e., free is P_{free}.

SU nodes are synchronized and time is divided into rounds. Each round consists of a setup phase for cluster formation, and a slotted steady-state phase in which intra-cluster communications are TDMA scheduled as shown in Fig. 2.

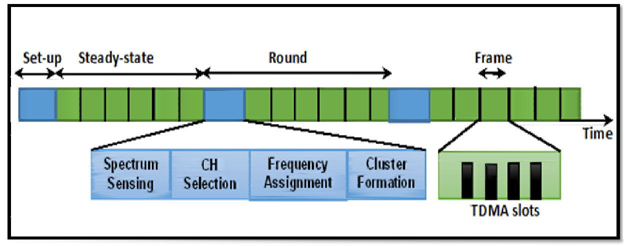


Fig. 2: ECHS Time line.

IV. Energy-Efficient Cluster Head Selection

In this section, we propose the Energy-Efficient Cluster Head Selection (ECHS) approach. In the setup phase of each round, all N nodes sense the available channels and determine the free channels. The proposed ECHS protocol is composed of three phases: (1) CH selection, (2) frequency assignment, and (3) cluster formation as explained next.

A. CH Selection

The CH selection phase is responsible for selecting which nodes to serve as CHs in the different network regions. The number of CHs varies from one region to another according to the distance from the sink. The number of CHs increases as we approach the sink. Typical WSN CH selection techniques [4-8] are based only on the residual energy without consideration of the dynamic spectrum nature in CRSN. Meanwhile, existing CRSN clustering techniques such CogLEACH [10] take into account the number of vacant channels in CH selection without regard to the energy aspects. In contrast, our idea is to select CHs that have higher residual energy and more vacant channels to simultaneously address both the energy and dynamic spectrum challenges. ESCH divides the CH selection phase in two steps: (1) initial CH selection, and (2) final CH selection.

1) Initial CH Selection: Each node calculates its probability to become CH, P_i. In ECHS, P_i is computed based on the initial energies of the nodes. Unlike [5] which uses the nodes' residual energies, using the initial node energies reduces the number of exchanged messages, and hence, saves more energy. Furthermore, the computation of $P_i(t)$ in ECHS uses the the channel availability in the region in which the nodes are located. In ECHS, the probability of a node to become cluster head inside region R_i is given by

$$P_i = K\left(\frac{c_i}{\sum_{k=1}^{N} c_k} * \frac{E_\circ(i)}{\overline{E_\circ}}\right) \tag{1}$$

where c_i denotes the number of idle channels available in R_i, K is a protocol parameter that represents the average number of nodes elected as cluster head nodes per round, $E_\circ(i)$ is the initial energy of the node and $\overline{E_\circ}$ is the average initial energy of the network. Each node can sense on average $\mu = P_{free} * m$ idle channels, where m is the total number of channels in the used band (i.e. $|C|$). Therefore, the $\frac{c_i}{\sum_{k=1}^{N} c_k}$ summation term can be approximated by $\sum_{k=1}^{N} c_k = N * \mu$ [10]. Each node i picks a random number in [0, 1], if the number is less than P_i, then the node is self-elected as an initial CH node.

The number of nodes in region R_i is $\sigma a W$ where σ is the node density. The number of CHs n_i in R_i is then equal to $n_i = P_i \cdot \sigma a W$. In order to solve the hot spot problem, we aim at having more CHs as we approach the sink node. This can be achieve by shrinking the transmission range r_i of the CH as we move closer to the sink node. Given the computed P_i and the desired n_i, we compute r_i as [8]

$$r_i = \sqrt{\frac{1}{\pi \sigma P_i}} = \sqrt{\frac{aW}{\pi n_i}} \tag{2}$$

2) Final CH Selection: The number of initial CHs might be more than necessary in a given region. In the final CH selection, only those initial CHs with high residual energy are selected. Each initial CH node in region R_i transmits a "CH-announcement" packet and advertises its residual energy level within range r_i. The other initial CHs observe the announcements and compare their residual energies with the received ones. The final CH node is the one that has the highest residual energy in a given place. If an initial CH node does not receive any announcement from any neighboring CH for a period of time, then it is elected as the final CH node.

B. Frequency Assignment

The available frequencies dynamically change according to the PU activities. The frequency assignment of the final CHs in the different regions of the network should be distributed and energy-efficient. Moreover, the co-channel interference should be minimized as much as possible. ECHS frequency assignment depends mainly on the coordination between CHs inside a given region and between neighboring regions via message exchange over the CCC. We assume that the number of available channels is not less than the number of CH nodes in any given region. Frequency assignment starts from the first region (nearest to the sink) to the last region (farthest from the sink), because the first region contains more CHs than other regions. In the first region, the CHs choose from the available frequencies via CCC communication until all the first region CHs are assigned channels. Then, they notify the CHs in the second region about their selected frequencies over the CCC. The CHs in the second region choose from the remaining set of unused frequencies. Consequently, the third region CHs will choose from the set of available frequencies except those used by the second region CHs. And so on, CHs in R_i cannot use the frequencies used by R_{i-1} CHs. Thus, ECHS frequency assignment ensures that neighboring regions uses different frequencies as possible in order to minimize the co-channel interference.

C. Cluster Formation

Non-CH nodes should select the appropriate CH such that intra-cluster communication occurs in an energy-efficient manner. In ECHS, each CH node transmits a "CH information" packet which contains its ID and the used frequency over the CCC. The transmission range of the CHs will be doubled ($2{*}r_i$) to ensure that each node receives at least one announcement packet. A non-CH node listens to the CCC waiting for "CH information" packets. A node will select the nearest CH that has a common frequency with it. Non-CH nodes associate with CHs by sending "CH-association" requests and then the CHs will confirm this request by "CH-confirmation" messages. Thus, nodes associate with CHs without consuming high energy in CH region-wide broadcasts. Finally, each cluster head node will organize a TDMA schedule and transmits this schedule to their member nodes.

V. Performance Evaluation

A. Simulation Parameters

The performance of the proposed ECHS is evaluated using MATLAB simulations. We randomly deploy 6 PUs and 200 CRSN nodes in a $100\ m \times 426\ m$ area with a node density of $\sigma = 0.0047\ \ nodes/m^2$ in a given region. We select the initial number of CHs as $K = 0.1{*}N$. The probability that a channel is free (P_{free}) is equal to 0.5. The nodes' initial energy levels are unequal and randomly chosen in the range $[2,\ \ 4]\ J$. The average initial energy level of the nodes is manually set to be $\overline{E_\circ} = 3$. The data packets size is 4000 bits, and the control packet size is 200 bits.

B. Benchmark Protocols

We compare the performance of the ECHS protocol against the EC and the CogEC protocols. Nodes in EC select a single channel (out of the C channels) to use for their transmissions [8]. The CogEC operation is similar to the CogLEACH protocol [10] except we change its single-hop communication to multi-hop for fairness in comparison with ECHS and EC. The multi-hop routing technique in [8] is used in all 3 protocols.

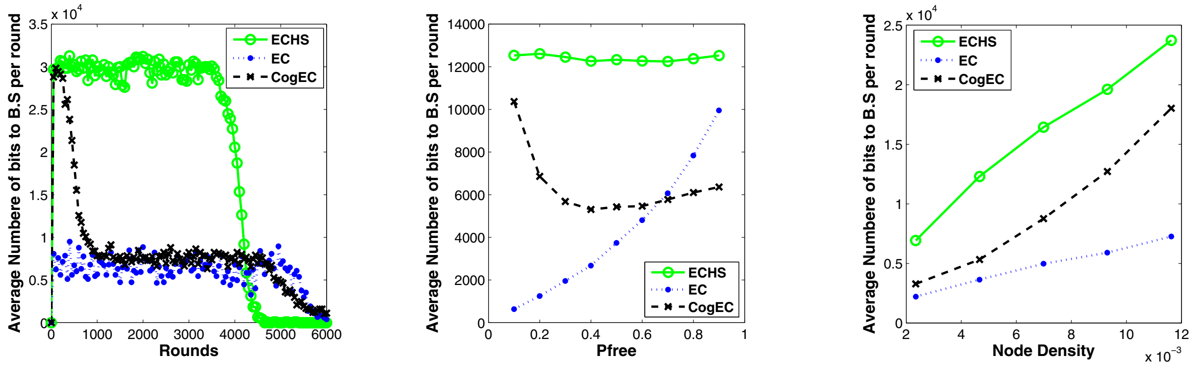
C. Throughput

Fig. 3 depicts the total network throughput for $P_{free} = 0.5$. Fig. 3(a) describes the variation of throughput versus simulation rounds. The ECHS throughput is three times the throughput of CogEC and EC protocols. This is due to ECHS awareness of the available spectrum. EC low throughput is caused by the nodes being blocked by the active PUs and stoping transmissions. Meanwhile, ECHS achieves higher throughput than the CogEC protocol because of the number of CHs participating in data routing in ECHS protocol is more than the CogEC protocol as shown in Fig. 4(a).

The remarkable throughput performance of our ECHS is obtained for different values of P_{free} as shown in Fig. 3(b). We next change the node density from 0.00235 to 0.01174. The increase in node density results in an increase in the number of CHs per unit area, leading to a better sharing of CH-roles and increase in the network throughput. Yet, our ECHS achieves the highest throughput as shown in Fig. 3(c).

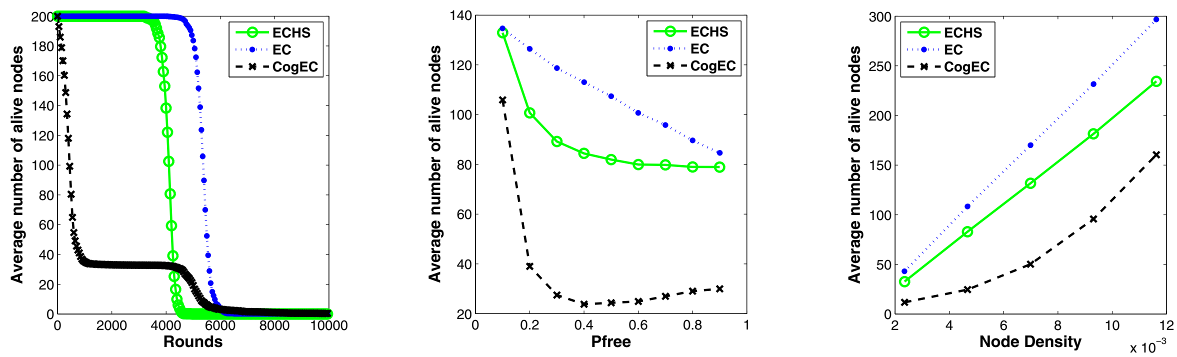
D. Network Lifetime

The network lifetime reflected by the number of alive nodes is shown in Fig. 4. The EC protocol maintains a higher number of alive nodes compared to other protocols. As shown in Fig. 4(a), nodes in EC are still alive up to 4500 rounds compared to 3500 and 1000 rounds in ECHS and CogEC, respectively. ECHS efficient clustering does not waste the nodes' energy in intra-cluser negotiations during cluster formation compared to CogEC. Both the ECHS and EC preserve 100% of the nodes alive for longer time rather



(a) Throughput versus rounds. (b) Throughput versus P_{free}. (c) Throughput versus node density.

Fig. 3: Total throughput in bits.



(a) Lifetime versus rounds. (b) Lifetime versus P_{free}. (c) Lifetime versus node density.

Fig. 4: Average nodes lifetime.

than only 20% of the nodes as in CogEC during most of the stable operation period before the first node in the network dies. Fig. 4(b) and 4(c) show the effect of P_{free} and the node density on the network lifetime, respectively. The lifetime of the EC is slightly higher than the ECHS but this is misleading since the EC throughput is significantly less than ECHS.

VI. Conclusion

In this paper, we have introduced the Energy-efficient Cluster Head Selection (ECHS) protocol for cognitive sensor networks. ECHS selects CHs with higher channels availability and residual energy. ECHS achieves higher throughput while extending the network lifetime by keeping 100% of the nodes alive during most of the operation period. This makes the ECHS protocol desirable for high data rate applications.

References

[1] O. Akan, O. Karli, O.Ergul, and M. Haardt, “Cognitive radio sensor networks,” IEEE Network, vol.23, no.4, pp.34-40, 2009.

[2] O. Younis, M. Krunz, and S. Ramasubramanian, “Node clustering in wireless sensor networks: recent developments and deployment challenges,” IEEE Network, vol. 20, no. 3, pp. 20-25, 2006.

[3] A. A. Abbasi, and M. Younis, “A survey on clustering algorithms for wireless sensor networks,” Computer communications, vol. 30, no. 14, pp. 2826-2841, 2007.

[4] W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “An application-specific protocol architecture for wireless microsensor networks,” IEEE Transactions on Wireless Communications, vol. 1, no. 4, pp. 660–670, 2002.

[5] O. Younis and S. Fahmy, “HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks,” IEEE Transactions on Mobile Computing, vol. 3, no. 4, pp. 366–379, 2004.

[6] S. Soro and W. B. Heinzelman, “Prolonging the lifetime of wireless sensor networks via unequal clustering,” in Proc. of IEEE International Parallel and Distributed Processing Symposium, 2005.

[7] S. Lee, J. Lee, H. Sin, S. Yoo, S. Lee, J. Lee, Y. Lee, and S. Kim, “An energy-efficient distributed unequal clustering protocol for wireless sensor networks,” in Proc. of the World Academy of Science, Engineering and Technology, 2008.

[8] D. Wei, Y. Jin, S. Vural, K. Moessner, and R. Tafazolli, “An Energy-Efficient Clustering Solution for Wireless Sensor Networks,” IEEE Trans. on Wireless Comm., vol. 10, no. 11, pp. 3973- 3983, 2011.

[9] H. Zhang, Z. Zhang, H. Dai, R. Yin, and X. Chen, “Distributed spectrum-aware clustering in cognitive radio sensor networks,” in Proc. of the IEEE GLOBECOM, 2011.

[10] R. M. Eletreby, H.M. ElSayed, and M. M. Khairy, “CogLEACH: A spectrum aware clustering protocol for cognitive radio sensor networks,” in Proc. of the IEEE CROWNCOM, 2014.

[11] D. Wei, Y. Jin, S. Vural, K. Moessner, and R. Tafazolli, “EC supporting materials,” http://info.ee.surrey.ac.uk/CCSR/EC/.

[12] A. Motamedi and A. Bahai, “MAC protocol design for spectrum-agile wireless networks: Stochastic control approach,” in Proc. of the IEEE DySPAN, 2007.