Pei *et al. EURASIP Journal on Wireless Communications and Networking* (2015) 2015:122
DOI 10.1186/s13638-015-0354-x

EURASIP Journal on Wireless Communications and Networking
a SpringerOpen Journal

RESEARCH Open Access

LEAUCH: low-energy adaptive uneven clustering hierarchy for cognitive radio sensor network

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Abstract

The integration of wireless sensor network (WSN) and cognitive radio (CR) technology enables a new paradigm of communication: cognitive radio sensor networks (CRSN). The existing WSN clustering algorithm cannot consider the advantage of channel resource brought by CR function in CRSN, and the CR network (CRN) clustering algorithm is designed based on the infinite energy nodes; thus both algorithms cannot operate with energy efficiency in CRSN. The paper proposes a low-energy adaptive uneven clustering hierarchy for CRSN, which can not only consider the advantage of the channel resource in reducing the energy consumption but also employ uneven clustering method for balancing the energy consumption among the cluster heads under multiple hops transmission means. Simulation results show that compared with the existing several typical clustering algorithms including WSN and CRSN clustering algorithms, low-energy adaptive clustering hierarchy (LEACH), HEED, energy-efficient unequal clustering (EEUC), cognitive LEACH (CogLEACH), and distributed spectrum-aware clustering (DSAC), the proposed algorithm can not only efficiently balance the energy consumption among cluster heads and network load in CRSN but also remarkably prolong the network lifetime.

Keywords: Cognitive radio sensor network; Channel resource; Uneven clustering; Energy consumption

1 Introduction

The existing wireless sensor network (WSN) operates in the public unlicensed spectrum band, which has become increasingly crowd because of the emergence of the vast wireless communication technologies. Meanwhile, the increasing serious mutual interference caused by the coexistence of heterogeneous wireless systems in the public unlicensed spectrum band has become a bottleneck problem which greatly limits the further development of WSN.

In order to solve the above both problems in WSN, the cognitive radio sensor networks (CRSN) is proposed, where implement dynamic spectrum access can be used [1-3]. Introducing cognitive radio (CR) technology into WSN makes the sensor nodes possess the ability of spectrum sensing. WSN can thus operate over the idle licensed spectrum band, which can not only reduce the collision probability of channels but also increase spectrum utilization and enlarge the operate spectrum band. The network throughput can further be increased, and the communication delay can also be shortened [4].

Since a large number of sensor nodes with limited energy may be randomly deployed in harsh environments and operate by forming a network in an *ad hoc* manner. Such a scenario requires an energy-efficient routing protocol that accounts for scalability. Clustering is shown to achieve such constraints and generally enlarges the network lifetime [5].

However, CRSN brings a new technical challenge in terms of its routing algorithm. On the one hand, the existing routing strategies in CR network (CRN) mainly focus on overcoming the spectrum scarcity and increasing the spectrum utilization by providing the combination scheme of the spectrum and route. However, they fail to consider the energy scarcity problem and hardware limitation problem inherited from the traditional WSN [6-9]. On the other hand, the existing clustering routing algorithms in non-CR WSN mainly focus on minimizing

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energy consumption in nodes. However, they do not consider the spectrum sensing and spectrum management problem [10-13]; thus, they cannot exploit the advantage of spectrum resource brought by CR function in reducing energy consumption, and further, they cannot efficiently operate in CRSN.

Recently, CRSN has attracted much attention of researches from the world, and some literatures including routing algorithms are also published [6,14-24]. Taking account of the shortcomings of the existing clustering routing algorithm in WSN and CRN, the paper proposes a low-energy adaptive uneven clustering hierarchy (LEAUCH) for CRSN, which can not only consider the advantage of channel resources brought by cognitive function in CRSN but also exploit the uneven clustering method based on the channel resources. More specially, in the proposed algorithm, the number of idle channels of each node is taken as its weight and the nodes with more idle channels are elected as candidate cluster head (CH) nodes. Based on the idea of the uneven clustering method, there are fewer members in the clusters near the sink. In this way, the energy of CHs near sink can be saved, and further more energy can be used for forwarding data, which can balance energy consumption among CHs under multiple hops transmission means in CRSN. In addition, when selecting the next hop node, the CHs consider not only its relative distance to the sink but also residual energy in the candidate nodes. Experimental results show that the proposed algorithm can not only be suitable for the CRSN, effectively balance the energy consumption in CHs under multiple hop transmission means, but also optimize the energy consumption of each node in the network, and further remarkably prolong the network lifetime.

The paper is organized as follows. Section 2 presents related work. Section 3 presents network model and LEAUCH algorithm. Section 4 is a performance analysis of LEAUCH. Section 5 is a simulation analysis of the proposed algorithm. The last section is a conclusion of the paper.

2 Related work

Low-energy adaptive clustering hierarchy (LEACH) [25] is regarded as the most representative traditional algorithms. However, it can be only suitable for WSN operating in the unlicensed spectrum band, and thus, it cannot operate with energy efficiency in CRSN.

The literature [14] proposed a distributed spectrum-aware clustering (DSAC) algorithm based on the traditional K-means clustering algorithm with group-wise constraint. The algorithm initially takes each node as CHs and then merges CHs in each iteration until the number of CHs reaches a theoretically optimal number. However, a large number of information is intensively exchanged between nodes and CHs, which lead to the great waste of the energy in the nodes.

The literature [15] proposed a cognitive LEACH (CogLEACH) for CRSN that uses the number of vacant channels as a weight in the probability of each node to become a CH and that can prolong the network lifetime compared with LEACH algorithm. However, the algorithm does not consider the balance of energy consumption among CHs under multiple hops transmission means, which may lead to the premature death of the nodes near the sink because of their excessive energy consumption (CHs near the sink need to frequently forward data to the sink).

The literature [22] proposed a spectrum-aware cluster-based energy-efficient multimedia (SCEEM) routing protocol for CRSNs, which can support the quality of service (QoS) and energy-efficient routing by limiting the participating nodes in route establishment. The proposed protocol in the literature is thus a cross layer routing protocol and only suitable for wireless multimedia sensor networks (WMSNs) application scenario, which comprised of sensor devices equipped with audio and visual information collection modules, can have the ability to retrieve multimedia data, store or process data in real-time, correlate and fuse multimedia data originated from heterogeneous sources, and wirelessly transmit collected data to desired destinations. Moreover, WMSNs are designed for those real-time applications which demand strict deadline, low delay, high throughput, and reliability as well as those non-real time applications which require high or medium bandwidth, loss intolerance, etc. However, most deployed WSNs measure physical phenomena like temperature, pressure, humidity, or location of objects. In general, most of those applications have low bandwidth demands and are usually delay tolerant. Therefore, the proposed protocol in the literature cannot be suitable for the CRSNs.

The literature [16] proposed an event-driven clustering algorithm. The qualified nodes are determined based on the distance from sensor nodes to the event occurrence point and the sink. CHs are selected among the qualified nodes according to node degree, available channels, and the distance to the sink in their neighborhood. The clusters in the scenario are immediately dismissed after finishing data transmission, and all nodes enter the sleeping state again in order to save the energy. Therefore, the proposed algorithm in the literature is only confined to event-driven CRSN, which cannot be suitable for other scenarios such as the time-triggered CRSN scenario.

In order to prolong the network lifetime, prior research works mainly focus on balancing energy consumption among nodes as cluster members (CMs). However, they neglect the problem of balancing energy consumption among CHs under multiple hops transmission means.

In energy-efficient unequal clustering (EEUC) algorithm [17], the authors proposed an uneven-sized clustering method to balance the energy consumption among CHs. However, the EEUC algorithm does not take into account the advantage brought by CR technology in CRSN, so its CHs selection method can only apply to WSN. Apparently, the algorithm cannot efficiently operate in CRSN.

3 Network model and algorithm description

3.1 Network model

In the paper, we consider the scenario where there are N randomly deployed CRSN nodes collecting data periodically and P primary users (PU). Let s_i denote the Ith node, and the corresponding set of nodes is denoted by $S = \{s_1, s_2, \cdots, s_N\}$. Let $C = \{1, 2, \cdots, m\}$ denote the available channels in the network and C_i the idle channels available to node s_i. We assume:

1. The sink is located outside the square observation area. Once deployed, CRSN node and the sink will no longer be moved;
2. All nodes are homogeneous and possess the function of information fusion. Each node has a unique identification (ID);
3. Each node has the ability of spectrum sensing and can correctly detect the available channels in the surroundings;
4. All nodes can adjust its transmit power to save energy based on its distance from the receiver;
5. The entire network has a network-wide common control channel (CCC) [26].

The CR technology is introduced into sensor nodes in CRSN, so the traditional LEACH algorithm must be improved to adapt the new scenario. For purpose of making the number of CMs near the sink relatively small, the CRSN is divided into many uneven clusters based on the determined CHs, as shown in Figure 1. In Figure 1, the circles of different sizes represent the different competitive ranges of the CHs and the lines with arrow represent multiple hop data transmission among CHs.

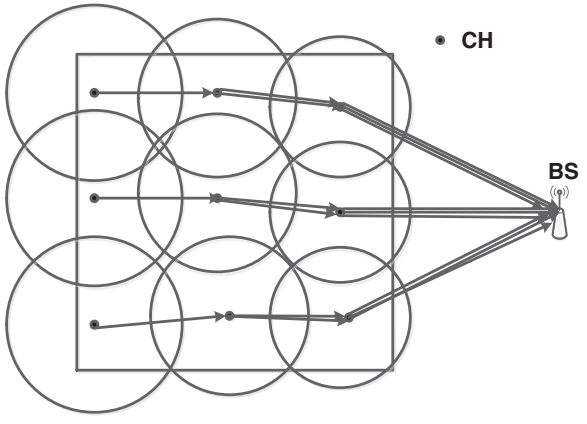

Figure 1 Uneven clustering routing algorithm.

3.2 Determination of the candidate CHs

In the regular LEACH, $P_{i(t)}$ is chosen such that $E\{\#CHs\} = k$, where [14]

$$P_{i(t)} = \begin{cases} \frac{k}{N - k*(r \mod \frac{N}{K})} & : C_i(t) = 1 \\ 0 & : C_i(t) = 0 \end{cases}$$

where N denotes the total number of nodes, k denotes the desired number of CHs (on average) per round, r denotes the current round number, and $C_i(t)$ is an indicator function determining whether or not node i has been a CH for the most recent $r \bmod (N/K)$ rounds. This formula of $P_{i(t)}$ maintains that each node is selected as a CH once per cycle of operation and thus balancing the load between nodes and extending time of the first node death.

The number of idle channels detected in each node is considered as an important factor in choosing CHs in the paper. If node i detects more idle channels than node j, it has more opportunity to find a common channel with nearby nodes, which may result in more opportunity to set up a cluster with a common channel.

A form of $P_{i(t)}$ should be constructed such that:

- $E\{\#CHs\} = k$.
- A node with more idle channels is more likely to become a CH.

According to the literature [10], the probability of a node to become CH is:

$$P_{i(t)} = \min\left(k\frac{c_i}{\sum_{j=1}^{N} c_j}, 1\right)$$

where c_i is the number of available channels. In the paper, the nodes with probability of $P_{i(t)} > 0.4$ is selected as candidate CHs.

3.3 Determination of CHs

The nodes with $P_{i(t)} > 0.4$ are selected as the candidate CHs and start to compete for CHs; other nodes enter sleeping mode until the end of the competition. Let s_i be one candidate CH, and its competition radius R_c can be calculated on the basis of the distance from the sink. During the competition, if s_i wins, then all other candidate nodes within its competition radius R_c quit the competition for CHs.

Figure 2 is the topology structure of candidate CHs. In Figure 2, the circles with different sizes represent competition radius of candidate CHs. In accordance with the rule of determining CHs, s_1 and s_2 can become final CHs at the same time; however, s_3 and s_4 cannot become final

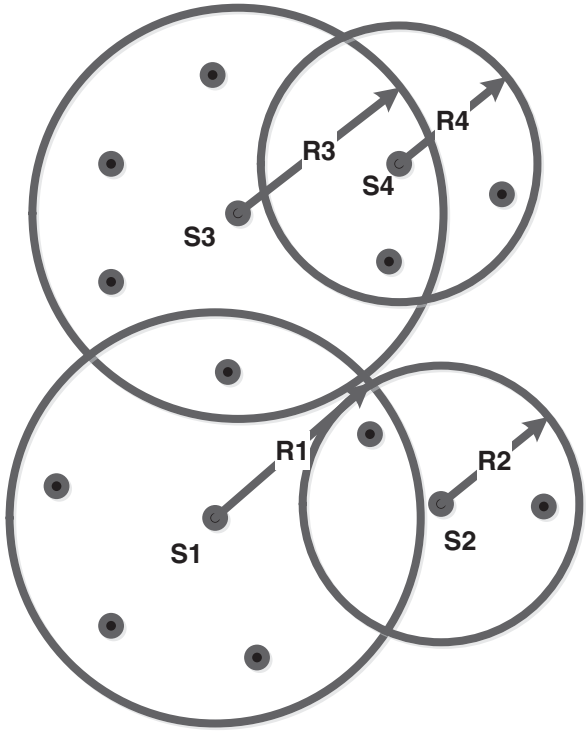

Figure 2 Competition radiuses of the candidate CHs.

CHs at the same time because s_4 falls in the range of the competition radius of s_3.

In the proposed algorithm, the clusters near the sink have short competition radius and fewer CMs, so that their CHs can use more energy to communicate among clusters and further balance the energy consumption among CHs.

Let R_c^0 be the maximum value of competition radius of candidate CHs, then the competition radius of the candidate CHs can be determined by $(1-c)\,R_c^0$, where c is the parameter used for controlling its value and $c \in [0,1]$. Therefore, the competition radius R_c of a candidate node S_i can be determined by [17]:

$$R_c = \left(1 - c\frac{d_{\max} - d\,(s_i, BS)}{d_{\max} - d_{\min}}\right) R_c^0$$

where $d_{\max}$ and $d_{\min}$ denote the maximum and minimum of the distance from the nodes to the sink respectively, and $d\,(s_i, BS)$ denotes the distance between the node s_i and sink. The competition radius decreases linearly with the distance from the nodes to the sink. For example, $c = 1/4$, the range of the competition radius is $3/4R_c^0 \sim R_c^0$.

Definition 1. In CHs competition algorithm of LEAUCH, the set of adjacent CHs of the candidate CH s_i is denoted by S_{s_i} and

$$S_{s_i} = \left\{ s_j \,|s_j \text{ is candidate CH}, d\left(s_i, s_j\right) < \max\left(R_{s_i}, R_{s_j}\right) \right\}$$

In the algorithm, each candidate node broadcasts their own competition message in the same power including node ID, competition radius R_c, and current residual energy, and the broadcast radius can be set to R_c^0 in order to save energy.

After receiving the broadcast message, each candidate CH forms its adjacent candidate CH set and then decides whether it becomes the CH or not. CHs can be decided according to the following step:

1. The node s_i with the highest residual energy in S_{s_i} become CH, then broadcast it;
2. If node s_i receives the winning message from s_j ($s_j \in S_{s_i}$), s_i quits the competition and broadcasts the quit message;
3. If node s_i receives the quit message from s_j ($s_j \in S_{s_i}$), then s_i will remove s_j from the set of its adjacent CHs.

3.4 Clusters establishment

Nodes that have not participated in the election will wake up from sleep after the CHs are determined and join their own clusters according to the following steps.

1. Node s_i is one of the CHs in a round, and C_i is the idle channel detected by node s_i. Then, CH s_i broadcast their own message after winning the election, including ID and available channel lists;
2. Node C_j within the range of s_i has one or more same element with C_i . s_j sends messages including ID and available channel to request to join the cluster once it receives the CH information of s_i;
3. s_i records IDs and available channels of requesting nodes and selects the C_{iq}, a common channel that most requesting nodes and s_i share, then broadcast it;
4. Ordinary nodes decide to join the cluster in which the node spends the minimum energy in communicating with CH, then sends joining messages to inform the CH.

3.5 Stabilization phase

CMs in the cluster receive slot time which is distributed from CHs by TDMA and then transmits collected data to the CHs in turn. The CHs fuse the collected data from CMs and forward to the sink.

4 Experimental results and analysis

In the section, the simulation experiments on the proposed algorithm are conducted using MATLAB. The energy consumption model is derived from the literature [7]. This experiment makes a comparison between the proposed LEAUCH and the other four algorithms, LEACH [25], DSAC [14], cognitive LEACH (CogLEACH)

[15], and EEUC [17], in terms of CH energy consumption, network load balance, and network lifetime.

In the paper, we consider the scenario where 200 cognitive sensor nodes are randomly distributed in an 200 m × 200 m area, which share five available channels with five primary users. Some other simulation parameters are assumed as shown in Table 1.

E_{elec} denotes the energy consumption of the circuit board when the nodes receive or transmit wireless data, ε_{fs} denotes the energy amplification coefficient where $d \leq d_0$ in the free space, and ε_{mp} denotes the energy amplification coefficient where $d > d_0$ in multipath attenuation model. In addition, $P_{i(t)} \geq 0.4$, $R_c^0 = 90$, c = 0.5.

4.1 The comparison of total energy consumption of CHs

Generally speaking, CHs undertake more tasks than other nodes in communication, which lead to more energy consumption of CHs than other nodes. The performance of a clustering routing algorithm can thus be evaluated by CHs energy consumption, as shown in Figure 3. Note that the 15 rounds are taken randomly from simulations.

It can be observed from Figure 3 that the CH energy consumption in LEAUCH is lower than that of the other protocols. CHs in LEACH are selected randomly and inefficiently, which makes CHs energy consumption fluctuate dramatically. In addition, the communications in and between the clusters are processed through single hop and the data do not fused necessarily, which make CHs energy consumption in LEACH much higher than others.

Both DSAC and CogLEACH consider the residual energy of nodes, and the distance between nodes and their information is transmitted over idle channels. It can be seen from the Figure 3 that CHs energy consumptions in DSAC and CogLEACH are relatively lower. However, both algorithms are based on the uniform clustering method which leads to more energy consumption of CHs near the sink. At the same time, both algorithms easily produce the isolated nodes, which make them be inferior to LEAUCH.

EEUC protocol considers the distribution density of nodes and their residual energy as well as other factors when selecting CHs, which makes the selected CHs be relatively ideal and distribute in a relatively even manner. The CH energy consumption is thus relatively low.

The LEAUCH algorithm proposed in the paper can dynamically choose the best idle channels for communications, which can decrease the possibilities of the waiting and conflict caused by competing for channels among nodes, and the CHs energy consumption can thus be decreased. Furthermore, The LEAUCH also employs uneven clustering method, which can also contribute to balancing the energy consumption among CHs. Therefore, LEAUCH can obtain the most performance in the CHs energy consumption.

Table 1 Simulation parameter setting

Parameter	Value
Parameter scene range	200 m × 200 m
Position of sink	(250, 100)
CRSN node number	200
Primary user	5
Available channel	5
Initial energy of	
Cognitive sensor node	0.5 J
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
ε_{mp}	0.0013 pJ/bit/m^2
d_0	87 m
Data package size	2,000 bits

4.2 The comparison of network load balance

For the purpose of improving the energy efficiency and prolonging the network lifetime, the energy consumption among CHs should be kept relatively balanced. Figure 4 shows the comparison of network load balance among several algorithms.

It can be seen from Figure 4 that LEAUCH and EEUC algorithms are better in load balance, LEACH protocol is the worst, and the DSAC and CogLEACH algorithms are medium.

The selection of CHs in LEACH is random, which makes its CH energy consumption in each round extremely unsteady. Also, CHs communicate with the sink directly in LEACH, which make the network load more unbalance.

In DSAC protocol, all nodes are initialized to CHs. During the merging of CHs, the energy consumption of information interaction between nodes and CHs is relatively high. Besides, node isolation problem can easily be caused. However, by introducing the cognitive function, information interaction in DSAC can operate in other available channels, which makes its network load be in medium.

The size of the clusters in CogLEACH is uniform, which may lead to the premature death of CH near the sink because CHs near the sink need to not only process data in the cluster but also forward data from other clusters. At the same time, the problem of the isolated nodes is not considered in the algorithm. Therefore, the CogLEACH obtains relatively poor performance in network load balance.

Both LEAUCH and EEUC consider the density of nodes and the distance between CHs and sink, which make the both algorithms have better performance in network load balance. Furthermore, considering the advantage brought

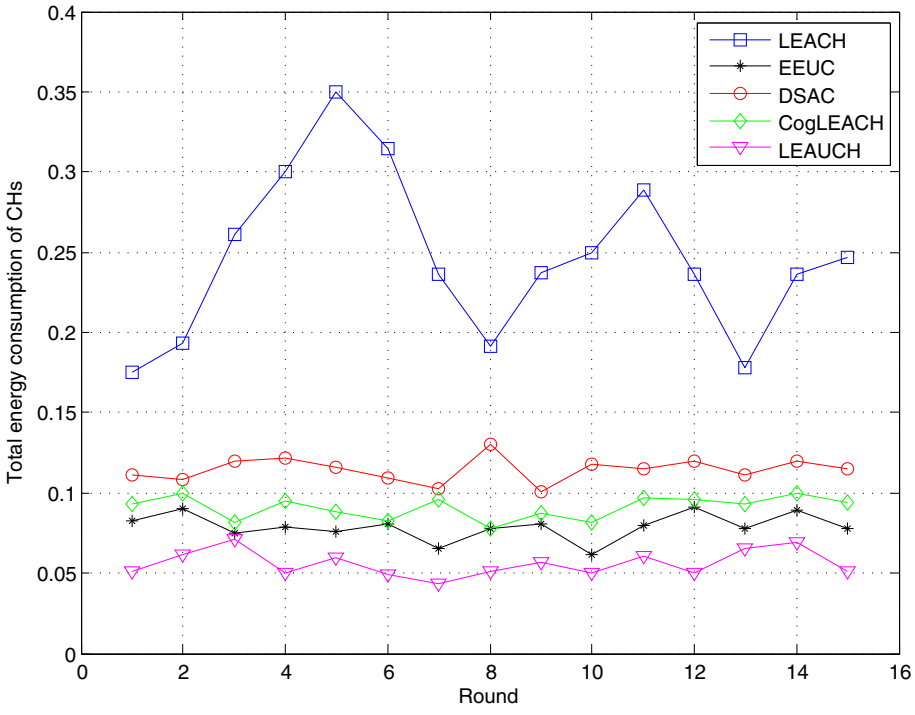

Figure 3 The comparison of total energy consumption of CHs.

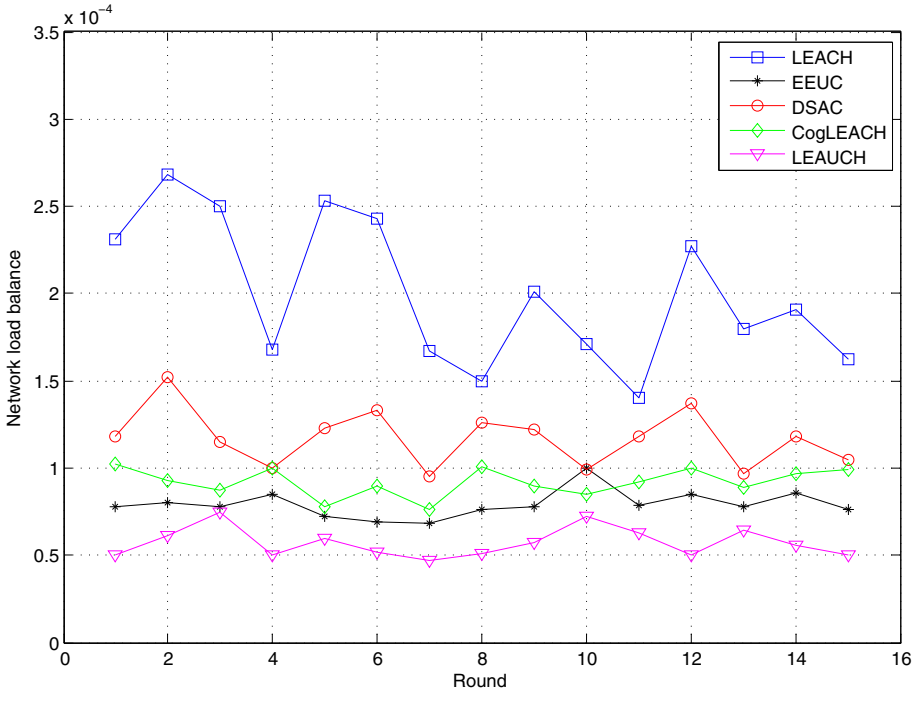

Figure 4 The comparison of network load balance.

by CR technology in CRSN makes LEAUCH superior to EEUC.

4.3 The comparison of network lifetime

Figure 5 is a comparison of the number of residual living nodes among the five algorithms. It can be seen from Figure 5 that the nodes in LEAUCH remain to have longer living time than the other four algorithms. The time span between the time of the first dead node and that of the last dead node is a reflection of the energy balance among nodes. The shorter the time span is, the better the performance of energy balance among nodes is and thus the more efficient the use of the energy is. Therefore, it can be seen from Figure 5 that LEAUCH can not only prolong the network lifetime but also remain the most performance of energy consumption among all nodes. It can also be seen from the figure that the network lifetime in DSAC and CogLEACH is longer than other protocols due to its cognitive function.

4.4 Performance analysis of throughput and delay

Most deployed WSNs measure physical phenomena like temperature, pressure, humidity, or location of objects. In general, most of those applications have low bandwidth demands and are usually delay tolerant. Therefore, the proposed routing protocol in the paper mainly focuses on the improvement of energy efficiency (energy consumption of nodes and the network lifecycle), while the performance of throughput and delay can be theoretically analyzed as follows:

Throughput: Apparently, LEAUCH has a significant improvement in the obtained throughput due to the spectrum-awareness property compared with other non-CR clustering routing protocols as CogLEACH in literature [9]. Nodes in non-CR WSNs may suffer from severe packet drop due to the competition for channels and interference with other systems operating on the same spectrum band, which results in a severe throughput degradation. Both of the proposed LEAUCH in the paper and CogLEACH are cluster-based routing protocols for CRSN; however, they have the similar data transmission process and almost same throughput.

Delay: Non-CR clustering routing algorithms operate in traditional WSN, and SNs transmit data using public spectrum band. There may exist huge amount of concurrent data transmission in public spectrum band and results in collisions, which may cause great transmission delay. The CR-based clustering routing algorithm (for example, CogLEACH and the proposed LEAUCH) in CRSN introduces cognitive function, and thus, the SNs in the CRSN can transmit data in the distributed idle channel to avoid data collision. Therefore, generally speaking, the spectrum-awareness clustering routing protocols including CogLEACH and the proposed LEAUCH in the paper have less delay relative to traditional clustering routing protocols, and obviously, CogLEACH and the proposed LEAUCH have almost same time delay.

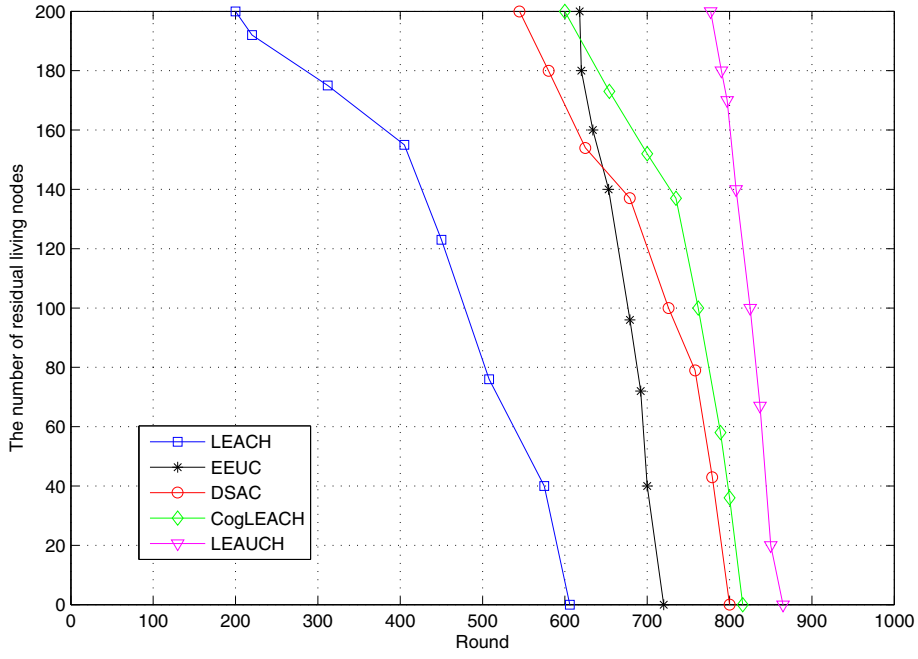

Figure 5 The comparison of the number of residual living nodes in the network.

5 Future works

The proposed routing protocol in this paper mainly focuses on the improvement of energy efficiency of sensor nodes and further increase the lifetime of WSN where the sensors are triggered periodically to measure physical phenomena like temperature, pressure, humidity, or location of objects. In general, most of those applications have low bandwidth demands and are usually delay tolerant. In future works, some application scenarios which require less delay, packets loss rate, and more throughput will also be considered, and thus, more complicated network topology is further considered to evaluate their performance.

6 Conclusions

The paper proposed the LEAUCH algorithm CRSN, which takes the number of idle channels of each node as its weight and chooses the nodes with more idle channels as candidates CHs. In addition, the proposed algorithm employs the uneven clustering method, which can balance energy consumption among CHs under multiple hops means. Experimental results show that the proposed algorithm can obtain the best performance in terms of network lifetime, the energy consumption of CHs, and network load balance.

Competing interests

The authors declare that they have no competing interests.

Acknowledgements

This work is partially supported by NSFC (61379159, 61201205, 61371164), Chongqing Education Commission Science and Technology Research Project (KJ130513), Chongqing Basic and Cutting-edge Project (CSTC2013jcyjA40020, CSTC2011jjjq40002), Chongqing Graduate Research and Innovation Project (CYS14149).

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Received: 14 January 2015 Accepted: 8 April 2015
Published online: 30 April 2015

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