Iran J Sci Technol Trans Electr Eng
DOI 10.1007/s40998-017-0016-6

RESEARCH PAPER

Developing a Gradient-Based Clustering Algorithm for Energy-Efficient Routing in Wireless Sensor Networks

Parvin Rahimi[1] · Yousef Darmani[1,2] · Abdorasoul Ghasemi[2]

Received: 22 June 2014 / Accepted: 19 February 2017

Abstract Appropriate clustering and routing algorithms in multi-hop wireless sensor networks considerably affect the energy consumption and prolong the network lifetime. Besides, the required inter-cluster communications in these networks may lead to imbalanced energy consumption among cluster-heads that in turn decreases the network lifetime. In this paper, a gradient-based clustering algorithm for energy-efficient routing (GCER) in wireless sensor networks is proposed. The main idea is based on partitioning the sensing region in such a way that the total energy consumption of the network is minimized. The algorithm uses unequal clustering structure which balances the energy consumption among the cluster-heads and lessens the effect of hotspot problem. Furthermore, a distributed protocol for choosing cluster-heads and routing is deployed to balance the energy among all sensor nodes. Simulation results show that the proposed scheme balances the energy consumption among the cluster-heads and increases the network lifetime compared to some recent reported clustering schemes in the literature.

Keywords Energy balancing · Hot spot problem · Network lifetime · Unequal clustering · Wireless sensor network

✉ Abdorasoul Ghasemi
arghasemi@kntu.ac.ir

Parvin Rahimi
Parvin.Rahimi@ee.kntu.ac.ir

Yousef Darmani
Darmani@kntu.ac.ir

1 Faculty of Electrical Engineering, K.N. Toosi University of Technology, Tehran, Iran

2 Faculty of Computer Engineering, K.N. Toosi University of Technology, Tehran, Iran

1 Introduction

In wireless sensor networks (WSNs), a large number of sensor nodes are densely deployed over a desired area to monitor environmental parameters or to sense specific data. The sensor nodes send their data to one or some data sinks which are located in the sensing field in a single-hop or multi-hop manner (Akyildiz et al. 2002). WSNs are usually application-based networks where the sensor nodes are typically equipped with low-cost batteries, limited memory, and low processing capabilities. In most applications, changing or recharging the batteries is not practical (Sendra et al. 2011), so many nodes may deplete their batteries and lose their connection to the rest of the network. Therefore, designing energy efficient protocols is crucial to have efficient and long-life networks.

In the past decade, several techniques have been proposed to increase the scalability and energy efficiency in data gathering of WSNs. It is shown that clustering significantly improves the energy consumption in data gathering, hence there are many researches on hierarchical clustering and routing. In this method, instead of directly communicating with the sink, each cluster member communicates with its short distant corresponding cluster-head (Heinzelman et al. 2002; Younis and Fahmy 2004).

Clustering technique increases the cluster-heads load and forces them to run out of their batteries faster than their cluster members. This imbalanced energy consumption can lead to shortening the lifespan of the cluster-heads; therefore the rotation of cluster-heads (Heinzelman et al. 2002) is used to balance the energy consumption among the cluster-heads and the other members.

Published online: 18 April 2017

A cluster-head forwards the data to the sink using either single-hop or multi-hop communication through other cluster-heads. In gradient-based model, all sensor nodes are categorized according to their gradients, i.e., their hop counts to the sink. The generated data by sensors must be delivered via a multi-hop path to the sink in the descending direction of the gradient (Schurgers and Srivastava 2001). Research findings (Mhatre and Rosenberg 2004) have shown that multi-hop routing is more energy-efficient than sensor-to-sink direct transmission over long-distance transmissions. However, multi-hop routing techniques force all nodes near the sink to relay more packets than the others. Consequently, those nodes deplete their batteries very fast, leading to what is known as *hot spots* problem (Li and Mohapatra 2007). When this problem emerges, no data can be delivered to the sink; therefore, the imbalanced energy consumption among different cluster-heads partitions the network.

In this paper, a gradient-based clustering algorithm for energy-efficient routing (GCER) in WSNs is proposed and evaluated. This method aims to balance the energy, decrease the total energy consumption, and prolong the lifetime of the network. The main contributions of this paper can be summarized as follows:

- In GCER, the WSN field is partitioned into multiple concentric rings. The sensor nodes are categorized according to their own individual gradients based on their hop counts to the sink. We obtain the proper value for the width of each ring that minimizes the total energy consumption of all nodes.
- In GCER unequal partitioning of the field for each clustering area is used to balance the energy consumption among cluster-heads. The algorithm computes the proper cluster radii and the number of cluster-heads for each ring.
- In GCER an energy-aware cluster-head selection method and gradient-based inter-communication routing protocol are used to balance the energy consumption and to mitigate the hot spots problem in the network.

The rest of this paper is organized as follows: Sect. 2 reviews some related works. We present the network model and problem statement in Sect. 3. Section 4 presents the GCER protocol and explains the proper value for the width of each ring and the corresponding cluster radii to minimize the total energy considering the balanced energy consumption constraints. Section 5 presents protocol operation and describes the energy-aware cluster-head rotation and data relay. Simulation results are provided in Sect. 6 before concluding the paper in Sect. 7.

2 Related Work

Recently, several clustering algorithms and cluster based routing protocols have been proposed to prolong the network lifetime in WSNs. These routing protocols offer more scalability, flexibility, robustness and energy efficiency compared to the ordinary flat routing techniques (Zhang et al. 2013; Peiravi et al. 2013; Wang et al. 2012; Yong and Pei 2012).

In Heinzelman et al. (2002), low-energy adaptive clustering hierarchy (LEACH), as a distributed clustering protocol for periodical data-gathering applications in WSNs is proposed. In LEACH, each node acts as a cluster-head or an ordinary node according to a certain probability in each round. Randomized rotation of cluster-heads is used to balance energy consumption over all sensor nodes in the network. LEACH is suitable when cluster-heads send their data directly to the sink; hence it is not an appropriate mechanism for a large-scale WSN.

For multi-hop transmission scenarios, hybrid, energy-efficient, distributed clustering (HEED) scheme is proposed in Younis and Fahmy (2004). In HEED, cluster-heads are selected periodically according to their residual energy and a secondary parameter like node proximity to its neighbors or node degree to minimize the communication cost taking into account the communication-range constraints and intra-cluster communication cost information. However, it does not consider the energy balancing issue among cluster-heads. As a result, the cluster-heads near the sink are burdened with much heavier relay traffic than the others which leads to the hot spots problem around the sink.

To reduce the hot spots problem in multi-hop WSNs, unequal clustering mechanisms is adopted in more recent studies. Soro and Heinzelman (2005) study an unequal clustering model in multi-hop WSNs to balance the energy depletion among cluster-heads. This work concentrates on a heterogeneous network and assumes that cluster-heads are deterministically deployed at some pre-computed locations. The authors use both theoretical analysis and experimental investigation to show that unequal clustering mechanism is useful for heavy traffic applications. An energy-efficient unequal clustering mechanism (EEUC) was proposed in Li et al. (2005). EEUC suggests an energy-aware multi-hop routing protocol for inter-cluster communications. This algorithm presents an unequal-sized clustering mechanism in periodical data-gathering applications where the clusters closer to the sink have smaller size compared to those that are farther from the sink. This algorithm does not optimize the cluster-head radius to distribute energy consumption among different cluster-heads evenly. The directed diffusion data dissemination pattern is proposed in Intanagonwiwat et al. (2000). In this data centric routing scheme, the sink broadcasts an interest message. Considering the interest message, each node sends its data to the sink via the aggregation tree. Schurgers and Srivastava (2001) propose gradient-based routing (GBR) in which the number of hops taken from the sink is recorded in the interest message and the data packets are forwarded through the path with the largest gradient.

Han et al. (2004) introduced an improved version of the gradient-based routing protocol. In this scheme, every sensor node has a gradient value, which is defined as its minimum number of hops to the sink. The cluster-heads forward the data to the sink through a link with the descending direction of the gradient. Liu et al. (2012) propose an energy-balancing unequal clustering approach for gradient-based routing (EBCAG) with unequal-sized clusters for WSNs. Each sensor node has a gradient value, and the cluster size depends on the cluster-head's gradient value. The data are forwarded by cluster-heads to the sink via a path which is followed by the descending direction of the gradient. The EBCAG scheme assumes the same width for all rings. Also, EBCAG did not provide a way to select the next relay node in the next inner ring during the data dissemination phase. Also, each non-cluster-head node chooses its cluster-head according to the largest received signal strength. To minimize the total consumed energy in all nodes, Li et al. (2013) propose a scheme to construct optimal clustering structure. Also, distributed energy-aware cluster-head rotation and routing protocols are introduced to balance the energy depletion among all sensor nodes.

In this paper, a gradient-based clustering algorithm for energy-efficient routing (GCER) in wireless sensor networks has been proposed. In contrast to the EBCAG (Liu et al. 2012), our main idea is based on partitioning the sensing field unequally such that the total consumed energy in the network is minimized. The basic idea of GCER is to divide the network area into some concentric rings. The proper width of each ring and the corresponding cluster radii are derived to minimize the total required energy for intra- and inter-cluster communications. Moreover, GCER proposes a new scheme for inter-cluster multi-hop routing to balance the energy consumption among intervening cluster-head relays.

3 Network Model and Problem Statement

3.1 Network Model

We assume a wedge-shaped sensing filed W with radii R_{field} and angle φ in which n sensor nodes are uniformly distributed with density ρ. The sink is located at the convergence vertex of the wedge-shaped region. See Fig. 1).

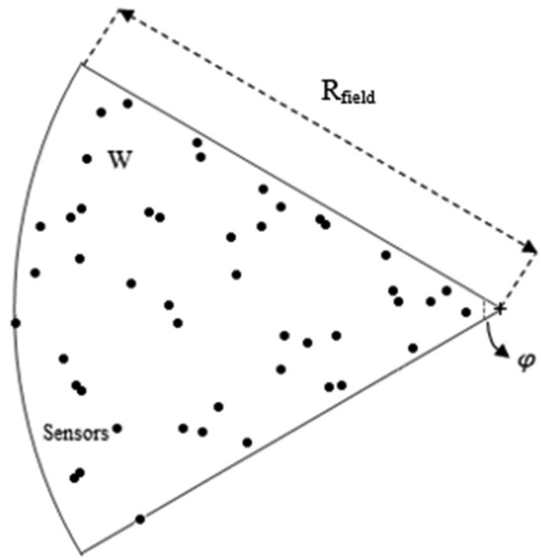

Fig. 1 Sensor nodes in a wedge-shaped region

The sensor nodes are deployed to transmit their data to the sink periodically and have similar capabilities and initial energy. Furthermore, it is assumed that the sensed data are correlated, so all cluster-heads can compress the received data from their cluster members into a single outgoing packet with fixed length. Let c denote the aggregation coefficient, i.e., the data from c sensors can be aggregated into a single packet. Also, it is assumed that the energy for data aggregation is E_{DA} (nJ/bit/signal). The energy consumption for receiving an l bit message is given by Heinzelman et al. (2002):

$$E_{\mathrm{Rx}}(l) = E_{\mathrm{Rx-elec}}(l) = lE_{\mathrm{elec}}, \tag{1}$$

And the consumed energy to transmit an l bit message over distance d is:

$$\begin{aligned} E_{\mathrm{Tx}}(l,d) &= E_{\mathrm{Tx-elec}}(l) + E_{\mathrm{Tx-amp}}(l,d) \\ &= \begin{cases} lE_{\mathrm{elec}} + l\varepsilon_{\mathrm{fs}}d^2 & d \le d_0 \\ lE_{\mathrm{elec}} + l\varepsilon_{\mathrm{amp}}d^4 & d > d_0 \end{cases}, \end{aligned} \tag{2}$$

where d_0 is the reference distance, E_{elec} is the electronics energy, $\varepsilon_{\mathrm{fs}}d^2$ and $\varepsilon_{\mathrm{amp}}d^4$ are the amplifier energies for free space and two-ray ground propagation models, respectively.

3.2 Problem Statement

As the transmission range of sensor nodes is limited, most nodes in a large-scale WSN send their data to the sink using multi-hop communication when clustering techniques are used. In multi-hop WSNs each cluster-head aggregates the received data from its cluster members and sends them to the next hop, moreover, it relays the traffic received from the other cluster-heads. Accordingly, in these networks the energy is consumed for intra-cluster and inter-cluster communications. The former corresponds to the energy spent by data communication and data processing within the cluster while the latter corresponds to the energy required for communicating with other cluster-heads and with the sink. Since the cluster-heads near the sink are burdened with much heavier relay traffic, they tend to die much faster than the other cluster-heads. Therefore, the hot spots problem will appear in the network and it shortens the network lifetime. Several unequal clustering mechanisms are proposed to mitigate the hot spots problem. In most of them, the nodes are grouped into unequal-sized clusters where the clusters near the sink have smaller size compared to those which are placed farther from the sink. As a result, the cluster-heads closer to the sink can save energy for relaying the traffic. Therefore, WSNs need a scalable and energy efficient multi-hop routing algorithm for periodical data dissemination applications. Hence, the main objectives of multi-hop routing include: energy balancing among the cluster-heads, low control overhead, fully decentralized and distributed mechanism. In this mechanism each relay node chooses the next hop based on its own information without requiring a central node to compute the proper links.

4 The Proposed Clustering Mechanism

4.1 Sensor Area Partitioning

In this section, the required relationship among different radii $R_1 < R_2 < \ldots < R_k = R_{\text{field}}$ is obtained such that the total consumed energy in the network is minimized. For this purpose, we partition the sensor arena into multiple concentric rings where the width of each ring is smaller than the reference distance, d_0. Assume that W is divided into k sectors C_1, C_2,…, C_k by its intersection with k concentric circles around the sink using monotonically increasing radius $R_1 < R_2 < \ldots < R_k = R_{\text{field}}$, where $R_k = R_{\text{field}}$ is a constant system parameter. C_0 is assumed as the sink and $R_0 = 0$. Let n_i denote the number of nodes deployed in sector C_i and A_i denote the area of sector C_i. Since all sensor nodes are uniformly distributed across W with density ρ for each i, $1 \le i \le k$, we have:

$$E(n_i) = \rho A_i = \rho \int_0^{\varphi} \int_{R_{i-1}}^{R_i} x \mathrm{d}x \mathrm{d}\varphi = \frac{\rho\varphi}{2}\left(R_i^2 - R_{i-1}^2\right). \quad (3)$$

where $E(n_i)$ is the expected number of nodes in sector C_i. Assume r_i and m_i are proper cluster radii and the number of cluster-heads in the ith ring, respectively.

$$E(m_i) = \frac{A_i}{\pi r_i^2} = \frac{R_i^2 - R_{i-1}^2}{r_i^2}, \quad 2 \le i \le k, \quad (4)$$

$E(m_i)$ is the expected number of cluster-heads in sector C_i. Also, assume B_i is the average rate of transmitted data by the cluster-heads in the ith ring, including both intra- and inter-cluster traffic. B_i can be calculated by:

$$B_i = c\lambda \frac{\sum_{j=i}^{k} E(n_j)}{E(m_i)} = c\pi r_i^2 \rho\lambda \frac{R_k^2 - R_{i-1}^2}{R_i^2 - R_{i-1}^2}, \quad 2 \le i \le k, \quad (5)$$

where c $(0 < c \le 1)$ and λ are the data aggregation coefficient and the average rate of generated traffic (bits/s) by each sensor node, respectively. Recall that c is the aggregation coefficient, i.e., the data from c sensors can be aggregated into a single packet. The expected transmission distance among cluster-heads in two adjacent rings C_i and C_{i-1} is shown with d_i and can be calculated using (6). In this equation, $\rho(i,r,\varphi)$ is the probability density function of nodes in the ith ring.

$$\begin{aligned} E(d_i) &= \int\int \rho(1, r, \varphi) r \times r \mathrm{d}r \mathrm{d}\varphi \\ &= \int_0^{\varphi}\int_{R_{i-1}}^{R_i} \rho(i, r, \varphi) r^2 \mathrm{d}r \mathrm{d}\varphi - \int_0^{\varphi}\int_{R_{i-2}}^{R_{i-1}} \rho((i-1), r, \varphi) r^2 \mathrm{d}r \mathrm{d}\varphi \\ \rho(i, r, \varphi) &= \frac{1}{A_i} = \frac{1}{\frac{\varphi}{2}\left(R_i^2 - R_{i-1}^2\right)} \\ E(d_i) &= \frac{2}{3}\left(\frac{\left(R_i^3 - R_{i-1}^3\right)}{\left(R_i^2 - R_{i-1}^2\right)} - \frac{\left(R_{i-1}^3 - R_{i-2}^3\right)}{\left(R_{i-1}^2 - R_{i-2}^2\right)}\right). \end{aligned} \quad (6)$$

Sensor nodes in ring C_1 can directly transmit their data to the sink, but all other sensor nodes should transmit their data through their own cluster-head. Using (6) we can find the expected transmission distance between each node and the sink as $2R_1/3$, where using (**5**) we have $B_1 = \pi r^2 c\lambda R_k^2/R_1^2$. According to the first condition in (2), the average energy consumption per second of cluster-heads in the inner ring C_1 is given by:

$$E_{\mathrm{Tx}_1}(B_1, d_1) = \frac{c\lambda R_k^2}{R_1^2} \times \left(E_{\text{elec}} + \varepsilon_{\text{fs}} \frac{4R_1^2}{9}\right). \quad (7)$$

Taking the derivative of (7), we have

$$\frac{\mathrm{d}E_{\mathrm{Tx}_1}(B_1, d_1)}{\mathrm{d}R_1} = -\frac{c\lambda R_k^2}{R_1^3} E_{\text{elec}} < 0. \quad (8)$$

Notice that (8) is a monotonically decreasing function of R_1, i.e., by increasing R_1, sensors in C_1 need less energy to transmit data to the sink. Assume R_1 takes its maximum possible value, i.e., $R_1 = d_0$. To find a relationship among different sectors' radii to minimize the average energy consumption per node, we first consider that energy for a node in the ith ring as:

$$E_{\mathrm{Tx}_i}(B_i, d_i) = B_i \times (E_{\mathrm{elec}} + \varepsilon_{\mathrm{fs}} d_i^2). \tag{9}$$

According to (9), the minimization of B_i reduces the average energy consumption. To minimize B_i, we use the Lagrange identity which is given in (10).

$$\sum_{1 \le p < q \le i} (a_p b_q - a_q b_p)^2 = \left(\sum_{p=1}^{i} a_p^2\right)\left(\sum_{p=1}^{i} b_p^2\right) - \left(\sum_{p=1}^{i} a_p b_p\right)^2. \tag{10}$$

For each j, $i \le j \le k$, let $a_j = (c\lambda n_j/m_i)^{1/2}$ and $b_j = 1$. Notice that

$$B_i = \sum_{p=i}^{k} a_p^2, \quad \sum_{p=i}^{k} b_p^2 = (k - i + 1). \tag{11}$$

By substituting (11) in Lagrange's identity, we obtain

$$B_i(k - i + 1) = \sum_{i \le p < q \le k} (a_p - a_q)^2 + \left(\sum_{p=i}^{k} a_p\right)^2. \tag{12}$$

Clearly, B_i is minimized whenever

$$\sum_{i \le p < q \le k} (a_p - a_q)^2 = 0.$$

This occurs if and only if we have:

$$a_i = a_{i+1} = a_{i+2} = \cdots = a_k$$
$$n_i = n_{i+1} = n_{i+2} = \cdots = n_k, \quad 2 \le i \le k.$$

Since the node distribution in sensor arena is uniform, we have:

$$R_i = \sqrt{\frac{R_k^2 - R_1^2}{k - 1} + R_{i-1}^2} \quad R_1 = d_0, \quad R_k = R_{\mathrm{field}}. \tag{13}$$

Since the radius of the first ring is greater than the others, to avoid increasing the transmission distance of cluster-heads in the second ring, and to balance energy consumption among the nodes in the first ring, it should be divided into p subrings. In this case, the nodes located in the first subring send their data directly to the sink. However, to have balanced distributed traffic, the received data from outer rings cluster-heads are delivered to the sink through p steps.

Since the transmission energy dissipation is proportional to the distance between the transmitter and the receiver (Heinzelman et al. 2002), we use $B_{\mathrm{relay}1j} \times D_{1j}$ $(1 \le j \le p)$ as a cost function to calculate the average energy consumption by the nodes in the subrings for relaying the received data from the other cluster-heads. To balance the traffic load distribution, it is required to have:

$$B_{\mathrm{relay}1j} = \cdots = B_{\mathrm{relay}1p} = \frac{c\lambda(R_k^2 - R_1^2)}{R_1^2}. \tag{14}$$

Also, to balance the energy consumption among nodes located in the jth and $(j-1)$th subrings of the first ring, (15) should be satisfied.

$$B_{\mathrm{relay}1j} \times D_{1j} = B_{\mathrm{relay}1(j-1)} \times D_{1(j-1)}. \tag{15}$$

Using (14) and (15) we have:

$$D_{1j} = D_{1(j-1)} \rightarrow R_{1j} = \cdots = R_{1p} = \frac{R_1}{p}. \tag{16}$$

Using equal transmission range, the width of the subrings in the first ring should be equal.

4.2 Gradient Organization

In this paper, we use the gradient-based routing where each node records its minimum hop count (HC) to the sink as the gradient value (Han et al. 2004). At the beginning of the network partitioning stage, the initial HC values are set to zero. To establish the gradient at each node, the sink broadcasts a short control message to all its neighbors located in a circle with R_1 radii around it. The HC value of this control message is set to zero. When a node receives this message, increments the HC value of the control message and sets its HC to the new value of this message, and rebroadcasts the control message to its neighbors that are located at distance of radius $R_{(\mathrm{HC}+1)}$ far from it. This procedure keeps on until all nodes set their HC value based on the first received control message. Each node which receives duplicate control message simply discards it (Han et al. 2004). Therefore, nodes located in $(R_{i-1}, R_i]$ from the sink will have the same HC value, where $1 \le i \le K$ $(R_k = R_{\mathrm{field}})$, and the region W can be partitioned into K rings.

4.3 Calculation of Cluster Radius

At the end of previous stage, the network will partition into some unequal clusters that we use to balance the depleted energy among different cluster-heads. That is, clusters in the same ring have equal cluster size. To balance the cluster-heads energy consumption in the ith and $(i-1)$th ring, it is required to have:

$$E_{\mathrm{Tx}_i}(B_i, d_i) = E_{\mathrm{Tx}_{i-1}}(B_{i-1}, d_{i-1}) \tag{17}$$

Using (5) and (17), r_i can be calculated by (18).

$$r_i = r_k \sqrt{\frac{(E_{\mathrm{elec}} + \varepsilon_{\mathrm{fs}} d_k^2)}{(E_{\mathrm{elec}} + \varepsilon_{\mathrm{fs}} d_i^2)} \times \frac{R_i^2 - R_{i-1}^2}{R_k^2 - R_{i-1}^2}}, \quad 2 \le i \le k. \tag{18}$$

In the cluster-head selection phase, some tentative cluster-heads are randomly selected. Afterwards, these tentative cluster-heads start to compete within a competition range calculated by (18) to select final cluster-heads.

Until the end of this phase, other ordinary nodes will switch to the sleeping mode and keep sleeping. Section 5.1 describes this phase in detail.

4.4 Inter-Cluster Multi-Hop Routing

Using a certain transmission power, each cluster-head broadcasts a short control message called *ROUTING_CANDIDATE_MSG*; this consists of its node *ID*, residual energy (Re) and its gradient (HC). Receiving that message from other cluster-heads and based on (19), cluster-head forms a set of candidate relay nodes R_{CH} located in range *I* (Fig. 2).

$$R_{\mathrm{CH}}^{S_i} = \{s_j \in I | (d_i - \Delta x) \le d(s_i, s_j) \le (d_i + \Delta x),\ \mathrm{HC}(s_i) = \mathrm{HC}(s_j) + 1\}, \quad (19)$$

where $d(s_i,s_j)$ is the distance between node s_i and node s_j, $2\Delta x$ is the width of range *I*, A_I is the area of range *I* with angle θ. A_I is calculated as follows.

$$A_I = \frac{\theta}{2\pi}\left(\pi(d_i + \Delta x)^2 - \pi(d_i - \Delta x)^2\right) = 2\theta d_i \Delta x \quad (20)$$

When $d(s_i,Sink)$ is the distance between node s_i and the sink, θ is calculated as follows and is shown in Fig. 3.

$$(d(s_i, Sink) - d_i \cos\theta)^2 + (d_i \sin\theta)^2 = R_{i-1}^2$$
$$\theta = \cos^{-1}\left(\frac{d(s_i, Sink)^2 + d_i^2 - R_{i-1}^2}{2d(s_i, Sink)d_i}\right) \quad (21)$$

Δx is chosen so that $R_{CH}^{s_i}$ has $[E(m_{i-1})/E(m_i)]$ members at least. Thus (22) is obtained for Δx.

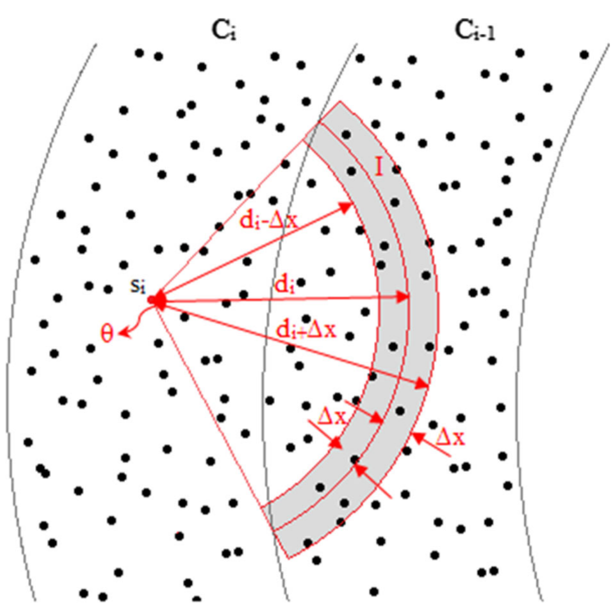

Fig. 2 The selection range of the candidate relay in the next ring by a cluster-head in the *i*th ring

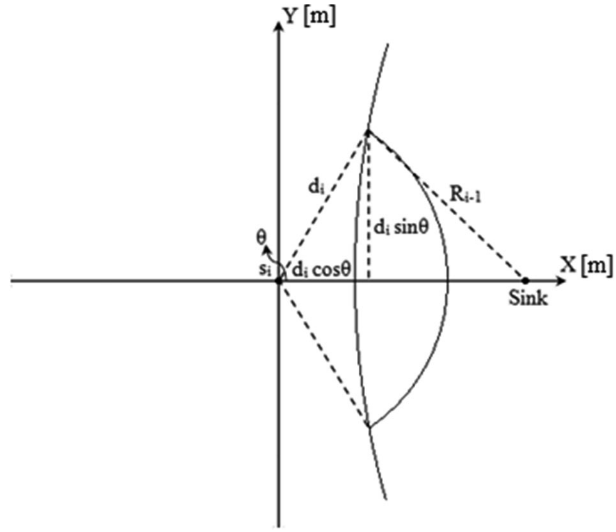

Fig. 3 Computation of angle θ

$$\rho A_I \ge \left[\frac{E(m_{i-1})}{E(m_i)}\right] \rightarrow \Delta x \ge \left[\frac{A_{i-1} r_i^2}{A_i r_{i-1}^2}\right] \times \frac{1}{\rho 2\theta d_i}. \quad (22)$$

Consequently, node s_i compares the residual energy of R_{CH} set members, and selects the relay node which has the most residual energy.

5 Protocol Operation

After network partitioning and gradient organizing stage, unequal clusters are constructed in the network. To balance the energy consumption in the network, responsibility of being the cluster-head is rotated among other sensor nodes in each ring. Each round consists of three phases: *cluster-head selection* phase, *cluster formation* phase, and *relay node candidate determination in next ring and data dissemination* phase.

5.1 Cluster-Head Selection Phase

In this phase, the remaining energy of each node acts as a main factor. At first, some tentative cluster-heads are randomly selected according to the probability T_i which is a predefined threshold determined using (23).

$$T_i = \frac{E(m_i)}{E(n_i)},\ E(m_i) = \frac{A_i}{\pi r_i^2} \quad (23)$$

Subsequently, a competition among tentative cluster-heads begins to select final cluster-heads. Other ordinary nodes should switch to the sleeping mode until the cluster-head selection phase terminates. In this stage, the competition range R_{comp} for each tentative cluster-head is equal to its cluster radii and it is calculated using Eq. (18).

Consequently, each tentative cluster-head broadcasts a message named *COMPETITION_CH_MSG* which contains its *ID*, gradient value (HC) and also its remaining energy (Re). In this phase, d_i is the broadcast radii of each control message. When a tentative cluster-head s_i receives *COMPETITION_CH_MSG* from node s_j, it compares the corresponding distance with the competition range of s_i. If they both are in the same ring and s_j is within the competition range of s_i, s_j will be added to the set of S_{CH}, which is the adjacent tentative cluster-heads of s_i. As soon as S_{CH} as a set of adjacent tentative cluster-heads of s_i is ready, tentative cluster-heads start to compete. A tentative cluster-head which does not have any adjacent tentative cluster-head will be chosen as a final cluster-head. Other tentative cluster-heads compare their remaining energy with their adjacent tentative cluster-heads energy. If the remaining energy of one tentative cluster-head is higher than all other node's energy in its S_{CH} set, it becomes a cluster-head and it broadcasts a *FINAL_CH_MSG*. If a tentative cluster-head receives *FINAL_CH_MSG* from an adjacent tentative cluster-head in its S_{CH}, it will quit the competition and broadcast a *QUIT_COMPETITION_MSG*. If a tentative cluster-head receives a *QUIT_COMPETITION_MSG* from an adjacent tentative cluster-head in its S_{CH}, it will remove this node from its S_{CH}. When a tentative cluster-head becomes a final cluster-head, there will not be another final cluster-head within its competition range R_{comp}. Once all cluster-heads have been selected, this process terminates. The cluster-head selection pseudo code for an arbitrary node s_i is given in Fig. 4.

$\alpha \leftarrow rand(0,1)$
if $\alpha < T_i$ **then**
  $Situation^{s_i} \leftarrow TentativeCH$
  computation of $R^{s_i}_{comp}$ using (18)
  broadcast a $COMPETITION\_CH\_MSG(ID^{s_i}, HC^{s_i}, Re^{s_i})$
else
  $Situation^{s_i} \leftarrow OrdinaryNode$
  switch to sleeping mode
  EXIT
end if
upon reception a $COMPETITION\_CH\_MSG$ from node s_j
if $d(s_i, s_j) < r^{s_i}_{comp}$ AND $HC^{s_i} = HC^{s_j}$ **then**
  Add s_j to $S^{s_i}_{CH}$
end if
While $Situation^{s_i} = TentativeCH$ **do**
  if $S^{s_i}_{CH} =$ NULL **then**
    $Situation^{s_i} \leftarrow FinalCH$
    EXIT
  end if
  if $RE^{s_i} > RE^{s_j}, \quad \forall s_j \in S^{s_i}_{CH}$ **then**
    $Situation^{s_i} \leftarrow FinalCH$
    broadcast a $FINAL\_CH\_MSG(ID^{s_i})$
    EXIT
  end if
  upon reception a $FINAL\_CH\_MSG$ from node s_j
  if $s_j \in S^{s_i}_{CH}$ **then**
    $Situation^{s_i} \leftarrow OrdinaryNode$
    broadcast a $QUIT\_COMPETITION\_MSG(ID^{s_i})$
    EXIT
  end if
  upon reception a $QUIT\_COMPETITION\_MSG$ from node s_j
  if $s_j \in S^{s_i}_{CH}$ **then**
    Remove t from $S^{s_i}_{CH}$
  end if
end While

Fig. 4 Cluster-head selection pseudo code

5.2 Cluster Formation Phase

All ordinary nodes which were switched to sleep mode in the previous phase, switch to wake-up mode in this phase. Then, final cluster-heads broadcast a message named *CH_ANNOUNCEMENT_MSG* within their own cluster radii. When a non-cluster-head node s receives *CH_ANNOUNCEMENT_MSG* from a final cluster-head t, and if s and t are in the same ring, s will add t to S_{FinalCH} as a set of its adjacent cluster-heads. Next, each non cluster-head node selects its own cluster-head from its S_{FinalCH} based on the highest communication cost, i.e., *joint weight*, which can be obtained from (24).

$$\text{Joint weight}(t) = \alpha \times \left[\frac{E_{\mathrm{res}}(t)}{E_0}\right] + \beta \times \left[\frac{1}{\frac{d(s,t)}{r_i}}\right] - \gamma \times \left[\frac{n_{\mathrm{member}}(t)}{n_i}\right]$$
$$t \in S^{s}_{\mathrm{FinalCH}}, \quad 0 \le \alpha, \beta, \gamma \le 1, \quad \gamma < \alpha + \beta < 1. \tag{24}$$

Where t belongs to S_{FinalCH} of node s, $E_{\mathrm{res}}(t)$ is the residual energy of t and $n_{\mathrm{member}}(t)$ is the number of cluster members, t. Assume α, β and γ are the adjustment coefficients. Node s sends a *JOIN_CLUSTER_MSG* to inform its cluster-head. The cluster formation pseudo code for an arbitrary node s is given in Fig. 5.

5.3 Relay Candidate Determination and Data Dissemination Phase

When clusters are formed, non-cluster-head nodes periodically transmit their data to their own cluster-head. Selecting the next relay node in the subsequent ring, a cluster-head aggregates its received data into a fixed length outgoing packet and sends it toward its neighboring cluster-head in the next inner ring. The packet is forwarded on descending gradient direction path. The relay candidate determination pseudo code for an arbitrary node s_i is given in Fig. 6.

if $Situation^{s} = FinalCH$ **then**
  broadcast a $CH\_ANNOUNCEMENT\_MSG(ID^{s})$
  EXIT
end if
upon reception a $CH\_ANNOUNCEMENT\_MSG$ from node t
if $HC^{s} = HC^{t}$ **then**
  Add t to $S^{s}_{FinalCH}$
end if
if $S^{s}_{FinalCH}$!= NULL **then**
  $myCH^{s} \leftarrow highest\_joint\ weight(S^{s}_{FinalCH})$
  broadcast a $JOIN\_CLUSTER\_MSG(ID^{s})$ to $myCH^{s}$
end if

Fig. 5 Cluster formation pseudo code

if $Situation^{s_i} = FinalCH$ **then**
  broadcast a $ROUTING\_CANDIDATE\_MSG(ID^{s_i}, HC^{s_i}, Re^{s_i})$
  compute d_i of s_i as its average transmission distance using (6)
  compute Δx of s_i as its relay candidate region using (22)
  EXIT
end if
upon reception a $ROUTING\_CANDIDATE\_MSG$ from node s_j
if $(d_i^{s_i} - \Delta x^{s_i}) \le d(s_i, s_j) \le (d_i^{s_i} + \Delta x^{s_i})$ AND $HC^{s_i} = (HC^{s_j} + 1)$ **then**
  Add s_j to $R^{s_i}_{CH}$
end if
if $R^{s_i}_{CH}$!= NULL
  $S^{s_i}_{relay} \leftarrow biggest\ residual\ energy(R^{s_i}_{CH})$
end if

Fig. 6 Relay candidate determination pseudo code

In the following, we demonstrate that the communication complexity of GCER for selecting cluster-heads and forming clusters in the network is $O(n)$, where n is the total number of nodes in the network. During initial cluster-head selection phase, $(n \times T)$ tentative cluster-heads are selected where each broadcasts a *COMPETITION_CH_MSG*. Consequently, each decides to be either a final cluster-head by broadcasting a *FINAL_CH_MSG*, or an ordinary node by broadcasting a *QUIT_COMPETITION_MSG*. Suppose k cluster-heads are selected, so, they send k *CH_ANNOUNCEMENT_MSG*, and $(n - k)$ ordinary nodes transmit $(n - k)$ *JOIN_CLUSTER_MSG*. Therefore, the messages add up to $2n \times T + k + n - k = (2T + 1) \times n$ in the cluster-head selection and cluster formation phases per round, where T is a constant. So, the communication complexity for cluster-head selection and cluster formation in the whole network is $O(n)$.

It illustrates that GCER as a distributed and scalable protocol in which cluster-head selection, cluster formation, and routing decisions are work-based on local energy information, has small communication complexity. In comparison with EBCAG (Liu et al. 2012), HEED (Younis and Fahmy 2004) and LEACH (Heinzelman et al. 2002), the control message overhead in GCER is the same as what is in EBCAG. In HEED the upper-bound of message complexity is $(N_{\text{iter}} \times n)$ where N_{iter} is the number of its iterations. In LEACH the message complexity is at least $O(n^2)$. Since we have avoided message iteration in the cluster-head selection algorithm, the control message overhead in GCER is much smaller than what is it in HEED and LEACH.

6 Algorithm Evaluation

In this section, we present the results of the simulation to evaluate the proposed scheme. At first, the energy balancing in different cluster-heads is considered. Afterwards, energy efficiency of the proposed method in comparison with the HEED, EBCAG and LEACH methods is investigated. To validate the performance of the proposed method, we simulate a homogeneous WSN consisting of n sensor nodes which are uniformly distributed in a circular area, i.e., $\varphi = 2\pi$. The simulation parameters are given in Table 1. Figure 7 shows unequal clustering regions based on GCER in a round. Simulations were performed 30 times and the averaged results are reported.

6.1 Energy Balancing

Figure 8 shows the average energy consumption of cluster-heads (CH) in each ring, which are consumed in a data gathering round. It justifies that GCER can balance the energy consumption among cluster-heads. As can be seen, EBCAG roughly consumes equivalent energy in the second to the fifth ring, but the node energy consumption in the first ring is greater than what is consumed in the other rings. The reason is that the number of relay nodes in the

Table 1 Simulation parameters

Parameter	Value
Sink location	(0,0) m
n	600
R_{field}	200 m
Initial energy	4 J
E_{elec}	50 nJ/bit
ε_{fs}	10 pJ/bit/m^2
E_{DA}	50 nJ/bit/signal
d_0	87 m
k	5
p	3
c	0.8
Data packet size	2000 bits
Packet number per round	50

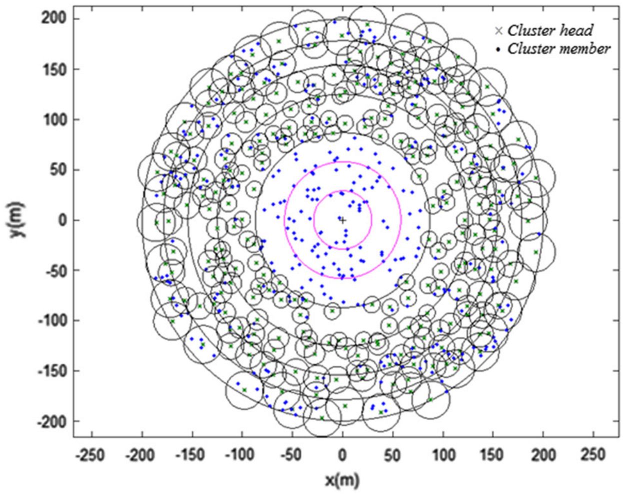

Fig. 7 Unequal clustering regions

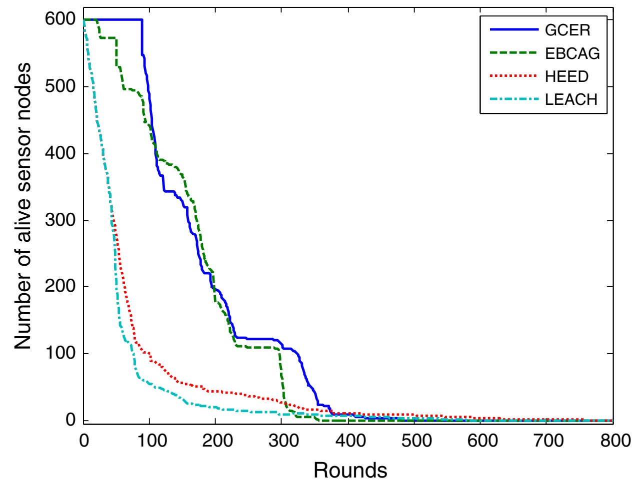

Fig. 9 Number of live sensor nodes over the time

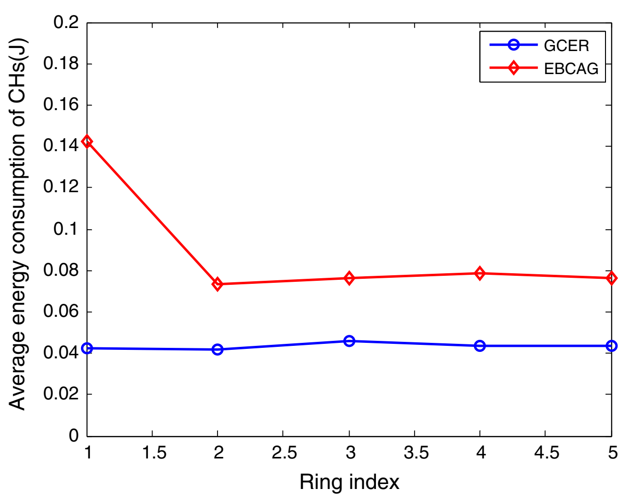

Fig. 8 Average energy consumption of CHs in each ring

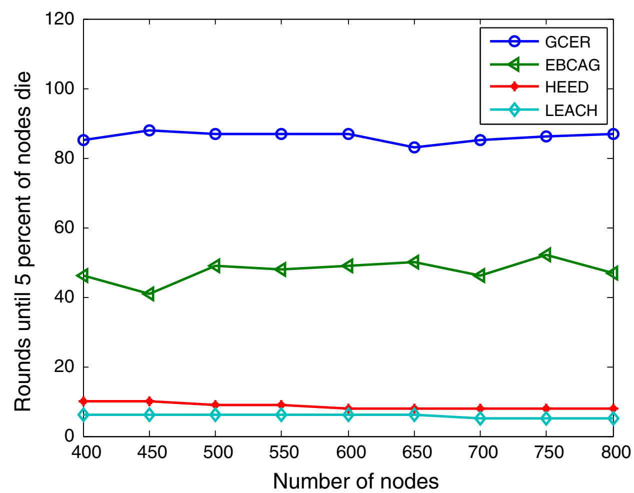

Fig. 10 Network lifetime vs. number of nodes (n)

first ring is less than what is needed to handle the amount of received traffic in this ring. As a result, nodes located near the data sink lose their energy faster than the other nodes. Moreover, it can be seen that the energy consumption of cluster-heads in GCER is 50% less than what is in the EBCAG.

6.2 Energy Efficiency

Figure 9 shows more alive sensor nodes in GCER compared with those in HEED, LEACH and EBCAG over the time. The reason is that the energy consumed by all nodes in GCER is much lower than what is in EBCAG, HEED and LEACH. Figure 10 shows the network lifetime vs. the total number of nodes in four schemes. We define the network lifetime as the number of rounds until 5% of the nodes deplete their batteries in the network. As shown, GCER improves up to 50% of lifetime over EBCAG, HEED, and LEACH. This is because GCER distributes the energy consumption among cluster-heads and minimizes the total energy consumption of the network. Figure 11 shows the comparison of the lifetime performance in four schemes when the sensing region radius is increased. Based on the results and under different radii of sensing regions, GCER performs better than the other three schemes.

6.3 Average and Maximum Hop Count to the Sink

The hop count refers to the number of intermediate relay nodes that each data packet must pass from the source node to the sink. Due to store, aggregation and forward, and other latencies in each hop, a large hop count implies to have low real-time performance. Figure 12 shows the average and maximum hop count of the investigated schemes. In LEACH, cluster-heads directly transmit their

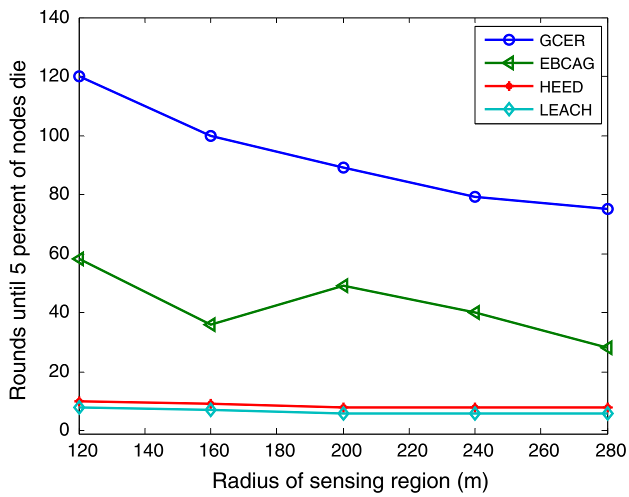

Fig. 11 Network lifetime vs. radius of sensing region

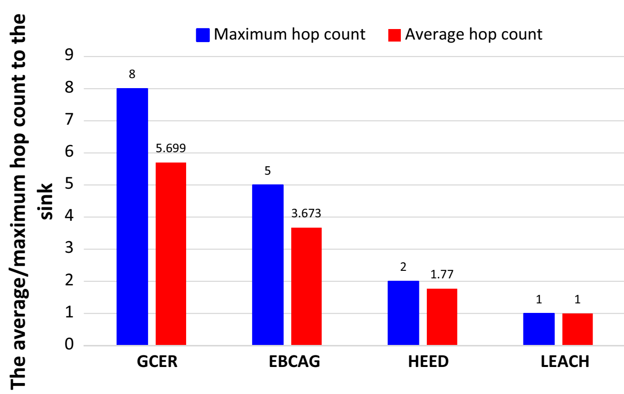

Fig. 12 The average and maximum hop count of sensor nodes to the sink

data to the sink. In EBCAG the gradient value of the cluster-head is set to its minimum hop count; consequently the packets are delivered in the shortest path to the sink. In the proposed algorithm, the sensing field is divided and the number of hops that traverses from each node to the sink has increased in comparison with the EBCAG method. Thus, in the proposed algorithm the maximum hop count has increased 37.5% compared to the EBCAG, 75% compared to HEED and 87.5% compared to the LEACH.

7 Conclusions

We address the unequal clustering techniques in homogeneous wireless sensor networks with uniform distribution of nodes. Then, a gradient-based clustering algorithm for energy-efficient routing (GCER) in wireless sensor networks was proposed and evaluated. We discussed energy balancing issue in unequal clustering and communication cost in multi-hop routing to prolong the network lifetime and mitigate the hot spots problem. The proposed unequal clustering mechanism and multi-hop routing protocol are gradient-based and are adjusted to minimize the total energy consumption of network considering the energy balancing constraints. The simulation results show that the proposed algorithm evenly distributed the energy depletion among cluster-heads and significantly increased the network lifetime compared to some recent schemes. We use the simple radio propagation model which takes into account the path loss and disregards fading, multi-path and other signal propagation effects. The next step of this research in the future is to extend the work to deal with more accurate models for signal propagation.

References

Akyildiz IF, Su W, Sankarasubramaniam Y, Cayirci E (2002) Wireless sensor networks: a survey. Comput Netw 38:393–422

Han K-H, Ko Y-B, Kim J-H (2004) A novel gradient approach for efficient data dissemination in wireless sensor networks. In: Vehicular technology conference IEEE 60th, vol. 4. pp. 2979–2983

Heinzelman W, Chandrakasan H, Balakrishnan A (2002) An application-specific protocol architecture for wireless micro sensor networks. IEEE Trans Wireless Commun 1:660–670

Intanagonwiwat C, Govindan R, Estrin D (2000) Directed diffusion: a scalable and robust communication paradigm for sensor networks. In: Proceedings of ACM mobile computing and networking (MOBICOM). pp. 56–67

Li J, Mohapatra P (2007) Analytical modeling and mitigation techniques for the energy hole problem in sensor networks. Pervasive Mobile Comput 3:233–254

Li C, Ye M, Chen G, Wu J (2005) An energy-efficient unequal clustering mechanism for wireless sensor networks. In: IEEE international mobile adhoc and sensor systems conference. pp. 604–611

Li H, Liu Y, Chen W, Jia W, Li B, Xiong J (2013) COCA: constructing optimal clustering architecture to maximize sensor network lifetime. Comput Commun 36:256–268

Liu T, Li Q, Liang P (2012) An energy-balancing clustering approach for gradient-based routing in wireless sensor networks. Comput Commun 35:2150–2161

Mhatre V, Rosenberg C (2004) Design guidelines for wireless sensor networks: communication, clustering and aggregation. Ad Hoc Netw 2:45–63

Peiravi A, Mashhadi HR, Javadi SH (2013) An optimal energy-efficient clustering method in wireless sensor networks using multi-objective genetic algorithm. Int J Commun Syst 26:114–126

Schurgers C, Srivastava MB (2001) Energy efficient routing in wireless sensor networks. In: Proceedings of IEEE military communications conference (MILCOM), vol. 1, pp. 357–361

Sendra S, Lloret J, Garcia M, Toledo JF (2011) Power saving and energy optimization techniques for wireless sensor networks. J Commun 6:439–459

Soro S, Heinzelman W (2005) Prolonging the lifetime of wireless sensor networks via unequal clustering. In: Proceedings of the 19th IEEE international parallel and distributed processing symposium (IPDPS). pp. 1–8

Wang A, Yang D, Sun D (2012) A clustering algorithm based on energy information and cluster-heads expectation for wireless sensor networks. Comput Electr Eng 38:662–671

Yong Z, Pei Q (2012) An energy-efficient clustering routing algorithm based on distance and residual energy for wireless sensor networks. Proc Eng 29:1882–1888

Younis O, Fahmy S (2004) HEED: a hybrid, energy-efficient, distributed clustering approach for ad hoc sensor networks. IEEE Trans Mob Comput 3:660–669

Zhang D, Yang Z, Raychoudhury V, Chen Z, Lloret J (2013) An energy-efficient routing protocol using movement trends in vehicular ad hoc networks. Comput J 56:938–946