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Energy-efficient cluster-based dynamic routes adjustment approach for wireless sensor networks with mobile sinks

Jin Wang[1] · Jiayi Cao[1] · Sai Ji[2] · Jong Hyuk Park[3]

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Abstract In wireless sensor networks (WSNs), sensor nodes near static sink will have more traffic load to forward and the network lifetime will get largely reduced. This problem is referred to as the hotspot problem. Recently, adopting sink mobility has been considered as a good strategy to overcome the hotspot problem. Despite its many advantages, due to the dynamic network topology caused by sink mobility, data transmission to the mobile sink is a challenging task. To achieve efficient data dissemination, nodes need to reconstruct their routes toward the latest location of the mobile sink, which weakens the energy conservation aim. In this paper, we proposed an energy-efficient cluster-based dynamic routes adjustment approach (EECDRA) which aims to minimize the routes reconstruction cost of the sensor nodes while maintaining nearly optimal routes to the latest location of the mobile sinks. The network is divided into several equal clusters and cluster heads are selected within each cluster. We also set some communication rules that manage routes reconstruction process

✉ Jong Hyuk Park
parkjonghyuk1@hotmail.com; jhpark1@snut.ac.kr

Jin Wang
jinwang@yzu.edu.cn

Jiayi Cao
892198935@qq.com

Sai Ji
jisai@nuist.edu.cn

1 School of Information Engineering, Yangzhou University, Yangzhou, China

2 School of Computer and Software, Nanjing University of Information Science and Technology, Nanjing, China

3 Department of Computer Science and Engineering, Seoul National University of Science and Technology, Seoul, Korea

accordingly requiring only a limited number of nodes to readjust their data delivery routes toward the mobile sinks. Simulation results show that the mobile sinks for reducing reconstruction of route have improved the energy efficiency and prolonged lifetime of wireless sensor network.

Keywords Wireless sensor networks · Routes reconstruction · Energy efficient · Mobile sink · Clustering

1 Introduction

Cloud empowered computing and techniques are becoming more and more popular in recent years. Wireless sensor networks (WSNs) can be supported from bottom layer to the upper application layer by cloud computing techniques. WSNs are usually composed of hundreds or thousands of sensor nodes which can work cooperatively to monitor their surrounding sensor field. These sensor nodes have the data sensation, storage, transmission, and processing, etc. WSNs have various applications in many fields, such as military, agriculture, and healthcare, etc. [1]

Study on energy-efficient routing algorithms is an important and challenging research issue. Because of the limiting of battery capacity, compute capability, storage, and data process, and cannot be replaced, how to reduce the energy consumption, while prolonging the network lifetime is still the key problem in WSNs.

In the traditional routing scenarios, the sensor nodes transmit information to the sink node in a multi-hop manner. However, as the sink node is fixed, some sensor nodes near the sink need relay more date than others far away from the sink. This phenomenon is called as "energy hole". The sensor nodes near the sink node will consume energy too fast and dead too early, the corresponding sensor nodes are also referred to as "hot nodes".

Adopting the mobile sink helps to prolong the network lifetime accordingly alleviating energy-hole problem. However, it brings some new challenges for the data transmission process. It is different from the static sink scenarios, because the dynamic network topology caused by the moving sink, sensor nodes should keep track of the latest location of the mobile sink for efficient data delivery. Taking into consideration the scarce energy resource of nodes, frequent propagation of the location of sinks should be avoided as it greatly undermines the energy conservation goal.

How to enable sensor nodes to maintain fresh routes towards the mobile sink while suffering minimal communication cost? Overlaying-based virtual infrastructure over the physical network is considered as an efficient approach. In the virtual infrastructure-based data transmission schemes, only a set of designated nodes (such as cluster heads) are responsible to keep track of sink's location. These designated nodes gather the observed data from the nodes in their vicinity during the absence of the sink, and then, proactively or re-actively, report data to the mobile sinks.

In this paper, a new approach called energy-efficient cluster-based dynamic routes adjustment approach with mobile sinks is proposed. The proposed approach can make some cluster heads to maintain optimal routes with less number of hops to the latest location of sinks. The circular sensing field is divided into several equal sized clusters.

Each cluster has only one cluster head which will be elected at the beginning. Cluster head rotation is done based on the residual energy. The mobile sinks are allowed to move in a clockwise or counter clockwise direction along the border of the sensing field to collect the data from the closest cluster head in single hop manner. When the sink moves from one cluster head to another cluster head, some rules will be used to find optimal routes to the new sink's location and we can reduce route reconstruction cost of the sensor nodes while prolongs the network lifetime.

The rest of the paper is organized as follows. Section 2 introduces some related work. In Sect. 3, we provide relevant network and energy models first. Then, we present the proposed approach in detail. Performance evaluation is given in Sect. 4 and Section 5 concludes this paper.

2 Related work

Low-energy adaptive clustering algorithm (LEACH) [2] is a famous clustering algorithm for WSNs which has become a benchmark for WSNs measurement. Only one cluster head in each cluster, the cluster heads are selected randomly. In the clusters, the member nodes send data to the cluster heads, and then, the cluster heads communicate with the sink node after date fusion. LEACH is superior to the traditional algorithms in aspect of extending network lifetime, but the cluster heads distribute unevenly in each round, and all cluster heads communicate with sink node directly, it does not apply to a lager network model.

Power-efficient gathering in sensor information (PEGASIS) [3] is an improved version over LEACH. PEGASIS routing algorithm can achieve good results in terms of energy-balancing and network lifetime. However, the shortcoming of PEAGSIS mainly includes the following three aspects. First, it will inevitably generate some long-chain between adjacent nodes, because the chain is based on nearest neighbor node algorithm. Second, the cluster head rotation mechanism will cause some nodes die earlier, especially those are far away from sink nodes, because of long distance transmission. Third, resection of the head of chain after each round will increase the communication overhead.

Energy-efficient mobile sink routing algorithm (EEMSRA) [4] is another clustered routing protocol based on LEACH. A key characteristic of EEMSRA is that the cluster heads create a TDMA (time division multiple access) schedule when the member nodes transmit data. Therefore, this algorithm is a cross-layer protocol which operates coordinated with the MAC layer, it might not be applicable to a wide range of devices. However, it is still a beneficial protocol in terms of energy efficiency, it also proposed a cluster head rotation mechanism to mitigate the hotspot problem.

Mobile sink-based routing protocol (MSRP) [5] employs cluster heads as data aggregation centers to collect the sensor data from the corresponding clusters. It is very similar to EEMSRA, but it has one key difference that the sensor data aggregated in the cluster heads may be obtained only when the sink comes closer than a distance threshold. Therefore, it is only suitable for delay-tolerant applications. Moreover, the protocol does not guarantee that the sink will visit all the cluster heads within a bounded time, so it is possible that some portions of the network may not be well served.

Unequal cluster-based routing algorithm has been proposed [6]. Sensor nodes are grouped into clusters with unequal sizes. The size of the cluster increases as the distance of its cluster head from the sink node increases. Therefore, cluster heads far away from sink node can preserve energy because of the fewer inter-cluster date forwarding. Unequal Cluster-based Routing algorithm also implements an energy-efficient multi-hop routing protocol for inter-cluster communication, which considers the trade-off between energy cost and the residual energy of sensor nodes.

MECA (Mobile sink-based energy-efficient clustering algorithm) [7] deploys a mobile sink node at the sensing area, the movement track is fixed and predictable, the entire network is divided into several equal parts as clusters, and only one cluster head in each cluster, so that the more uniform distribution of cluster heads will be achieved. Each cluster head collects information from the corresponding clusters and sends to the mobile sink node directly, and data fusion reduced the traffic load.

The authors in [8] proposed a low-energy consumption routing protocol for mobile sensor networks with a path-constrained mobile sink. They proposed to delay sending the data packet until the mobile sink approaches the position with the shortest path. It not only guarantees the shortest path but also exhibits robustness with dynamic node mobility. Xie and Pan [9] proposed an energy-efficient routing mechanism based on the cluster-based method for mobile sink in WSNs with obstacles. In addition, the authors presented a heuristic tour-planning algorithm for the mobile sink to find the obstacle-avoiding shortest route.

In [10], an energy-efficient distance-aware routing algorithm with multiple mobile sinks for WSNs has been proposed. The location of mobile sink node is determined by the transmission range of the sensor nodes and the boundary nodes. If the neighbor nodes of the sink within transmission range, it will communicate with sink node directly. Otherwise, it will communicate with sink by a relay node in a multi-hop manner, the relay node is determined by the distance and residual energy. In [11], the authors compared static sink strategy with mobility sink strategy. They found that nodes near the sink consume energy faster than others far away from the sink, because the sensor nodes that near the sink node will bear more traffic load. In the mobile sink scheme, the authors proposed three mobile strategies, which are random mobile strategy, fixed mobile strategy, and controlled mobile strategy.

Virtual circle combined straight routing (VCCSR) [12] is an efficient data collection in wireless sensor networks with mobile sink. It aims to reduce the path reconstruction cost by the moving sink. It constructs an adjustable routing tree to decreased energy consumption and thus helps in prolonging network lifetime. Virtual Grid-based Dynamic Routes Adjustment (VGDRA) [13] is an algorithm which aims to minimize the routes reconstruction cost of the sensor nodes when the optimal routes to the latest location of the mobile sink. This scheme proposed a set of communication rules pertaining to the route reconstruction process, thereby requiring only limited number of nodes to readjust their data delivery routes towards the mobile sink.

In [14], the authors proposed a clustering mechanism with multiple mobile relay nodes to prolong the network lifetime. First, the scheme partitions the network into several clusters. In each cluster, the relay nodes are used for data collection and coordination. These relay nodes have rich resources, and communicate with a static sink directly. The relay nodes will move to new locations within the formed clusters, such that the overall energy consumption is minimized. However, this scheme is not suitable for majority applications because of the extra cost incurred due to the use of multiple mobile relay nodes. In [15], the authors proposed an energy-aware sink relocation algorithm for mobile sinks. This scheme uses maximum capacity path protocol for routing. Mobile sinks start to move when two relocation conditions are met and find the next moving location which has the greatest weight value. However, the relocation conditions are met after a long time, and the protocol is not good at prolonging network lifetime.

In [16], the sensing field is divided into several regions by a novel partition algorithm. In each region, a mobile sink is adopted to visit every node of that region for data collection to balance the data collection latency. The shuffled frog leaping algorithm is adopted in the algorithm to calculate the optimal solution for the TSP and to reduce the traveling time of each mobile sink. In [17], the authors proposed an energy-efficient proactive data reporting protocols. This scheme establishes a logical coordinate system for routing and forwarding data packets. Sensor nodes update their coordinates according to the trail messages and the sojourn positions of the mobile sink, and establish routes by selecting next hop according to the shortest distance to the mobile sink. This algorithm can reduce control overheads.

In [18], the authors propose an approximation algorithm, which is called algorithm with the minimum number of child nodes when the depth is restricted (ADCMCST), to construct a tree network for homogeneous wireless sensor network, so as to reduce and balance the payload of each node, and consequently prolong the network lifetime. In [19], a novel routing protocol named location-aware routing protocol (LARP) for underwater sensor networks, where the location information of nodes is used to help the transmission of the message.

Zhang et al. [20] envisioned that home network will shift from machine-to-human to the machine-to-machine. Then, they presented the architecture of home M2M networks, standards, and QoS improvement. Liu et al. [21] proposed a role-dependent privacy preservation scheme (ROPS) for secure V2G (Vehicle-to-Grid) network in the smart grid. This paper identified a new security challenge and address different privacy issues.

In [22], the authors propose a new data gathering algorithm with the aim to leverage both unmanned aerial vehicle (UAV) and mobile agents (MAs) to autonomously collect and process data in wireless sensor networks.

3 Our proposed energy-efficient routing algorithm

3.1 Network model

We assume that the network is composed of N sensor nodes, denoted as: {N1, N2, N3…Nn}, respectively. They are uniformly dispersed in a circular field and monitor their surrounding environment continuously. We initially deploy two mobile sink nodes at the edge of the circular field. As shown in Fig. 1, we made the following assumptions:

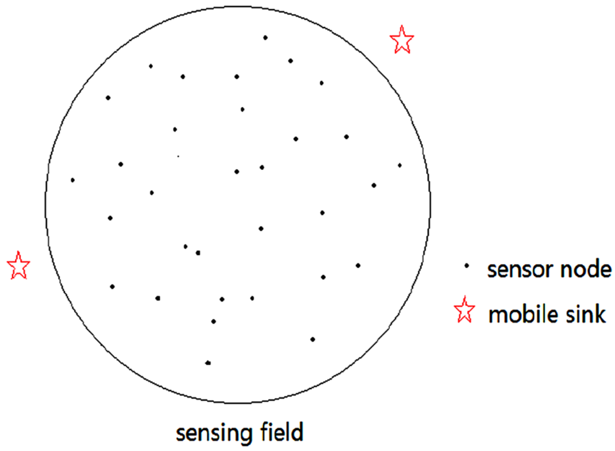

Fig. 1 Network model

1. All nodes are homogeneous and static.
2. Nodes can adjust their transmission power according to the relative distance to receiver.
3. Links are symmetric.
4. The two mobile sinks are highly powered and they do not have any resource constraints.
5. Both of the mobile sinks are allowed to move in counter clockwise direction for every half of the round to reduce the number of hops between the source nodes and sink.

3.2 Energy model

The first-order radio model of the MECA [7] has been adopted in this algorithm. Based on the distance between transmitter and receiver, a free space (d^2 power loss) or multi-path fading (d^4 power loss) channel models are used.

Each sensor node will consume the following E_{Tx} amount of energy to transmit one l-bit packet over distance d:

$$E_{Tx}(l,d) = \begin{Bmatrix} lE_{elec} + l\varepsilon_{fs}d^2, & d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4, & d \geq d_0 \end{Bmatrix} \tag{1}$$

where E_{elec} is the energy dissipated per bit to run the transmitter or receiver circuit, and ε_{fs} and ε_{mp} represent the transmitter amplifier's efficiency and channel conditions. The $d_0 = \sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ when the above two formulas are equal.

To receive one l-bit message, the following amount of energy will be consumed:

$$E_{Rx}(l) = lE_{elec}. \tag{2}$$

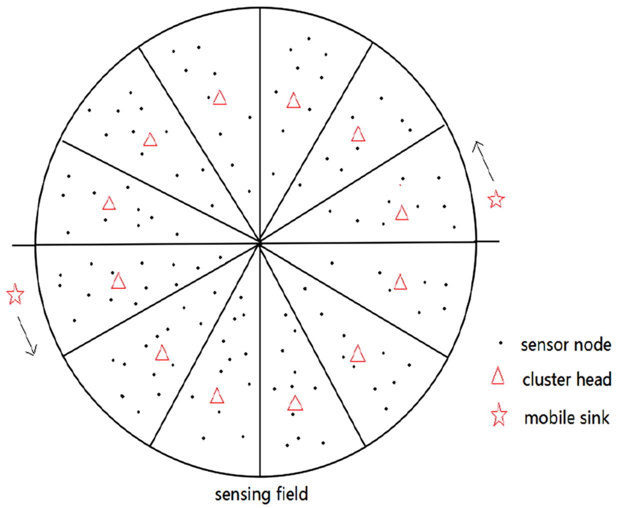

Fig. 2 Cluster formation

3.3 Clustering formation and cluster head selection

The entire network is divided into several equal clusters, so that the cluster formation is achieved first, as shown in Fig. 2.

Each cluster has only one sensor node which serves as a cluster head. The other nodes in the same cluster send data to the cluster head.

At the beginning of the selection, we first motivate the sensor node that is located in the center of each cluster like Si. It is viewed as the cluster head candidate. Then, it will compare with its neighbor nodes for their id and residual energy. If any node Sj has larger residual energy than Si, it becomes the new cluster head candidate and broadcasts its own information to its neighbor nodes. If Sj has equal residual energy with Si, the node with a smaller ID will become the new cluster head candidate. If Sj has smaller residual energy than Si, it still broadcasts its own message. In this way, the node with the largest residual energy will be chosen as the cluster head.

3.4 Inter-cluster routing procedure

After selecting a cluster head in each cluster, the node will broadcast a cluster head message to the member nodes. If the distance between the member nodes and the cluster head is less than the transmission radius, then the member nodes will communicate with cluster head directly. If the distance between the member nodes and the cluster head is larger than the transmission radius, they will find a relay node and communicate with cluster head in a multi-hop manner. In this way, member nodes will not communicate with cluster head directly in long distance, so that save the energy of the member nodes greatly and prolong the lifetime of the wireless sensor networks.

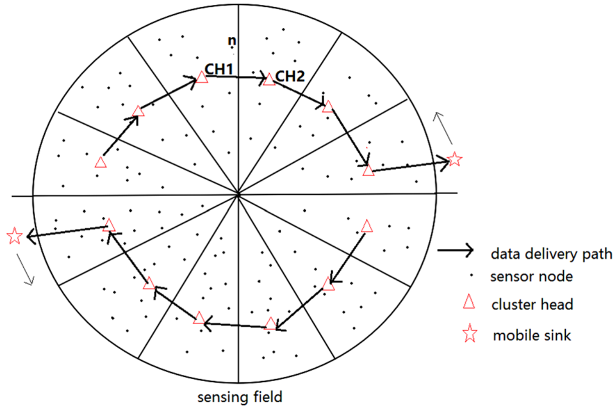

Fig. 3 Initial routes

3.5 Initial routes setup

During the inter-cluster routing procedure, some nodes that are slightly beyond the cluster boundary, these nodes might receive cluster head notifications from more than one cluster head and associate themselves to the closest one. These nodes that receive cluster head notifications from multiple cluster heads also share the information of the secondary cluster head with their primary cluster head. Such as node n, it will receive cluster head notifications from cluster head CH1 and cluster head CH2. Then, the node n will communicate with cluster head CH1 and share the information of the cluster head CH2 with cluster head CH1. In this way, each cluster head can communication with neighboring cluster heads. According to the initial location of the mobile sinks, all cluster heads adjust their routes to the position of the mobile sinks, as shown in the Fig. 3.

3.6 Dynamic routes adjustment

For solving dynamic network topology cause by sink mobility, nodes need to set up their data delivery routes in line with the latest location of the mobile sinks. Flooding the sink's latest location to the entire sensor field is most naive approach and greatly undermines the energy conservation goal. The approach proposed by us that only the set of cluster heads are responsible for maintaining new routes to the latest location of mobile sinks. For periodic collection of data from the cluster head, the mobile sinks are allowed to move in counter clockwise direction around the boundary of sensing field. The cluster head closer to the mobile sink transfers the information of the location of the mobile sinks to the remaining cluster heads in a controlled manner. We use some propagation rules for making the set of cluster heads to take part in route readjustment, as follows:

Rule 1: we treat the cluster head that is the closest to the sink as originating cluster head. The originating cluster head has to know whether the mobile sink is its next hop node or not. If the mobile sink was previously being set up as next hop of originating

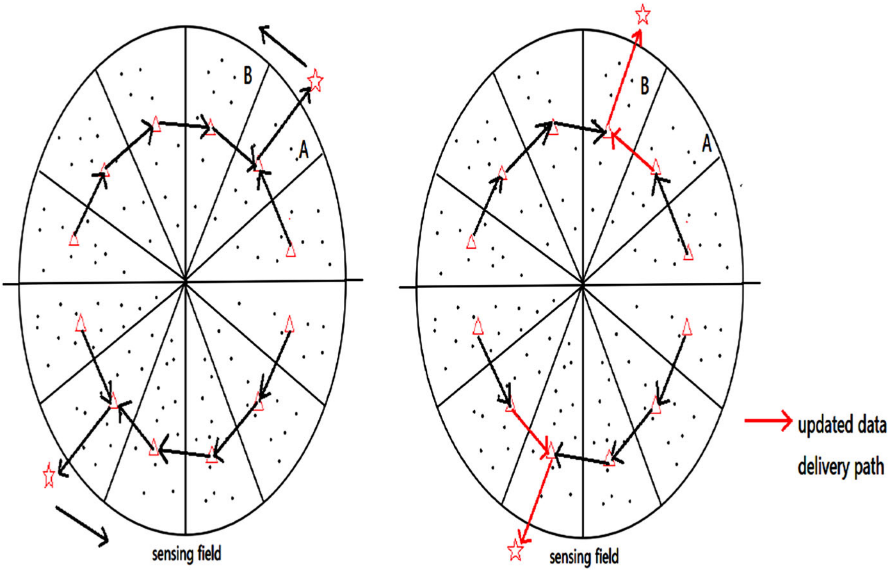

Fig. 4 Example of routes readjustments when sink moves from cluster A to cluster B

cluster head, it need not propagate the latest location of the sink. If the next hop is other than mobile sink, it executes rule 2.

Rule 2: the originating cluster head being one hop from the mobile sink sets the mobile sink as its next hop and propagates the update information to the previous originating cluster head.

Rule 3: the previous originating cluster head on the basis of receiving the update information of the sink's location from the current originating cluster head, it will set the current originating cluster head as next hop towards the mobile sink.

Figure 4 shows an example of the data delivery paths when the sink moves from cluster A to cluster B. The cluster head in cluster B executes rule 2. It will set the mobile sink as its next hop and propagate the update information to the cluster head in the cluster A. The cluster head in cluster A executes rule 3. It will set the cluster head in cluster B as its next hop, when receiving the update information of the location of the mobile sink. In this way, only a limited number of cluster heads participate in the routes readjustment process, thereby reducing the overall routes readjustment cost of the network.

Figure 5 shows an example of routes status when sink moves within the same cluster. The cluster head executes rule 1 and does not propagate sink's location update. The cluster head in cluster A will still communicate with the mobile sink; the cluster head in cluster B will still set it as next hop. This strategy helps to minimize the routes reconstruction cost to a great extent and thus improves the network lifetime.

3.7 Rotation of cluster head

We set up an energy threshold, the residual energy of each cluster head will be compared with the energy threshold after each round. The cluster head selection will be

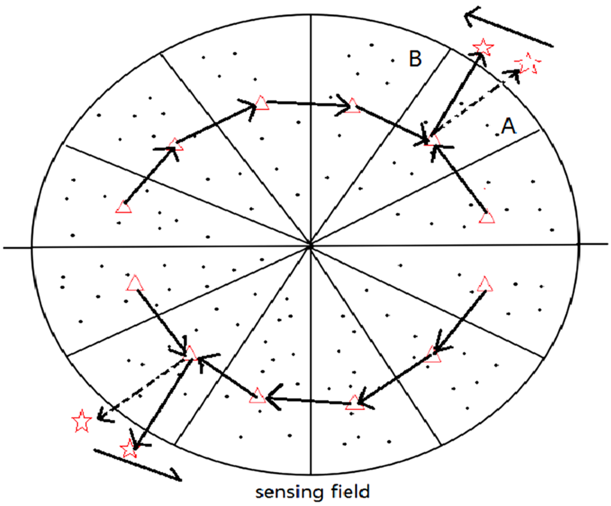

Fig. 5 Example of routes status when sink moves within the same cluster

carried out only for that particular cluster which the cluster head's residual energy falls below the minimum energy threshold. This scheme can avoid frequent re-clustering or cluster head election process, so that energy consumption of the network becomes less. Introduction of the two mobile sinks reduces the traffic load on the each cluster head as well as the number of hops to reach the sinks.

4 Performance evaluation

4.1 Simulation environment

We evaluate the performance of our algorithm via simulations in MATLAB. Our algorithm is compared with the common algorithm from the literature, namely VGDRA algorithm. The simulation environment is set up with the parameters listed in Table 1. We assume that all the senor nodes and the sink nodes are uniformly deployed in a circular sensing area.

4.2 Simulation results

Our algorithm is compared with VGDRA algorithm in aspect of the network lifetime in a circular network, because lifetime is an important metric to evaluate network performance, as shown in Fig. 6. The network lifetime is defined as the time elapsed since the nodes deployment till the first node dies due to energy depletion. It is clear that our algorithm has the best performance in prolonging network lifetime than the other one. When the mobile sink moves to a new location, our algorithm has less energy consumption in the routes reconstruction.

Table 1 Simulation parameters

Parameter name	Value
Network size (R)	400 m
Number of nodes (N)	200
Transmission radius (R_0)	50 m
Packet length (l)	2000 bits
Initial energy (E_0)	0.5 J
Energy consumption on circuit (E_{elec})	50nJ/bit
Free-space channel parameter (ε_{fs})	$10pJ/bit/m^2$
Multi-path channel parameter (ε_{mp})	$0.0013pJ/bit/m^4$
Distance threshold (d_0)	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ m

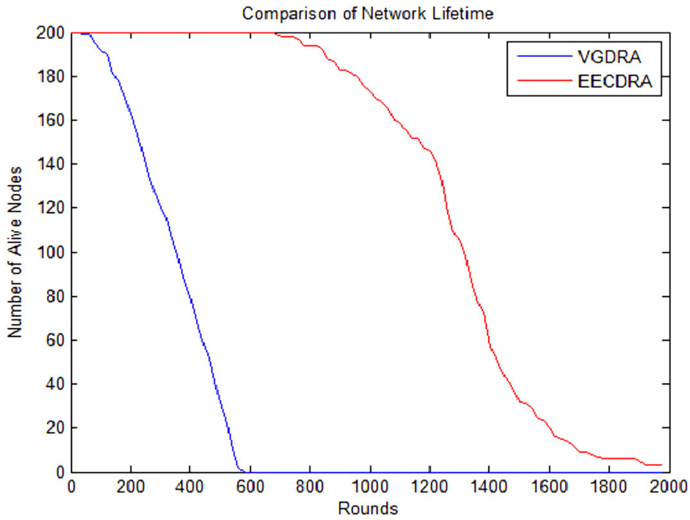

Fig. 6 Network lifetime

In this proposed algorithm, there are two mobile sinks which collect data from the sensing area, they are allowed to move in a counter clockwise direction along the border of the sensing field to collect the data from the closest cluster head in single hop manner. The two mobile sinks can reduce the traffic load on the each cluster head as well as the number of hops to reach the sinks, so that this mechanism can reduce the energy consumption in data transmission. We can see from Fig. 7, our algorithm has a good performance in energy consumption.

We also consider that the influence of the different number of mobile sinks in network performance, as shown in Fig. 8. Obviously, the network with multiple mobile sinks has good performance than the network with a single mobile sink, because the network with a single mobile sink, some cluster heads that far away from mobile sink will transmit data in a multi-hop manner, it is not good for energy conservation. However, that is not to say mobile sink the more the better. We should consider the cost of the network, so our algorithm has two mobile sinks.

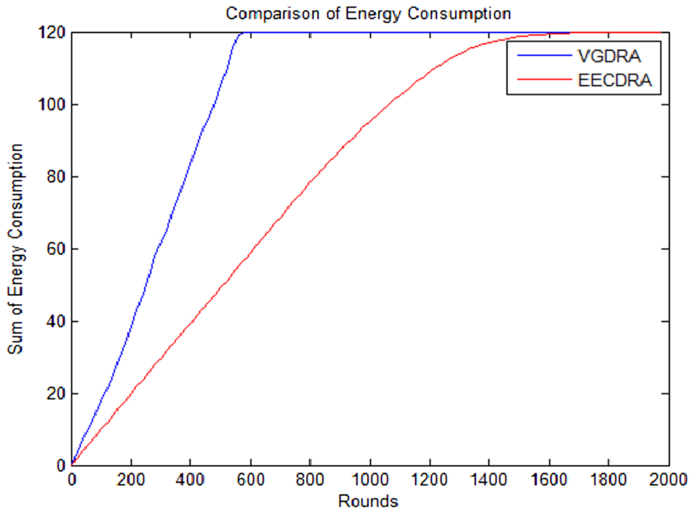

Fig. 7 Energy consumption

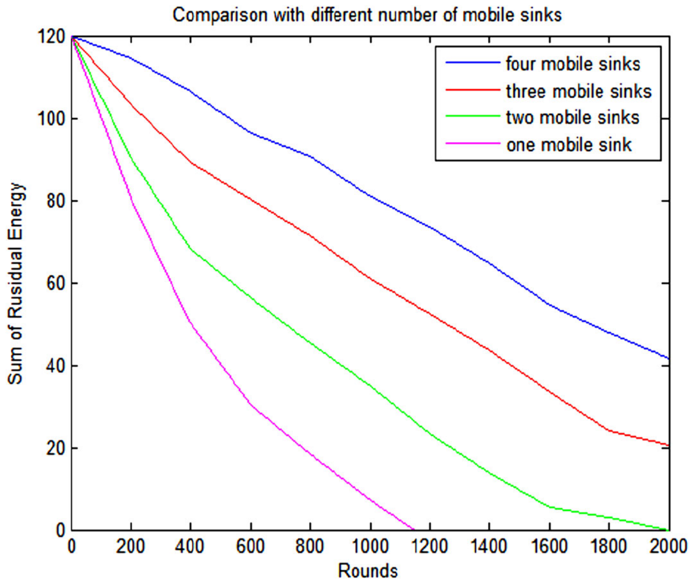

Fig. 8 Different Number of mobile sinks

5 Conclusions

In this paper, an energy-efficient cluster-based dynamic routes adjustment approach with mobile sinks for wireless sensor networks is proposed. Cluster heads are selected based on the residual energy of each node. The wireless sensor network lifetime is prolonged with optimal routes and limited flooding of update message to the limited number of cluster heads. The cluster head rotation mechanism alleviated the hotspot problem efficiently. The simulation results show that the proposed approach performs well in the wireless sensor network lifetime.

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