GEERM: An Improved Grid-based Energy-Efficient Routing Method for WSN with Single Controlled Mobile Sink

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***Abstract*—Different from the previous cluster-based structure, in this paper, we present a grid-based energy-efficient routing method (GEERM) that aims to balance energy dissipation in a non-uniform distributed network. The GEERM employs a controlled mobile sink with two antennas to collect sensing data, which enable two cluster heads to upload data in each time by utilizing multi-user multiple-input and multiple-output (MU-MIMO) technique. Cluster-head election of each grid is based on three parameters, i.e. the number of data packets that nodes need to relay, the Euclidean distance to the mid-point of cells and residual energy of each node, respectively. The GEERM also considers other factors that waste battery power, such as packet collision and latency. Simulation results demonstrate that our routing method has shown better performance when compared with existing work.**

***Keyword*—Wireless Sensor Network, Energy Efficiency, Sink Mobility, GEERM, MU-MIMO**

I. INTRODUCTION

Recently, more and more people are aware that the networked micro-sensor technology will be a promising technology and start to engage in the research of the wireless sensor technology. Wireless sensor networks (WSNs), which are composed of a large number of low-cost, low-power, multifunctional sensor nodes randomly deployed to obtain data from the physical environment in a self-organized manner via wireless communication, brings a significant change for information perception. Up to now, the wireless sensor technology has been applied to different application domains, such as health care, military surveillance and tracking, and environmental monitoring. However, the battery capacity of micro-sensors is limited and batteries are unable to be replaced by humans in an unreachable environment. Hence, energy efficiency is always considered as a key problem full of challenges which hinders the development of the wireless sensor technology.

Traditional static node deployment [4] shows n-to-1 communication. This makes that sensor nodes in the vicinity of sink consume more battery power than other regular nodes and also leads to the hotspot phenomenon more easily. For this purpose, sink mobility is proposed to alleviate the hotspot problem which prevents local nodes from suffering more workload. The hotspots will be changed as the sink moves, which extends the network lifetime significantly.

Sink mobility also has security benefits [5] where mobile sinks are more difficult to track than static sinks. Previous static sinks are placed in a fixed position. An attack to static sinks, e.g., destroying sinks and stealing sensitive information [6], would come very easily. However, if sinks have mobility, the adversary has to track and locate the mobile sink before attacking the sink carrier, which makes mobile sinks more resistant than static sinks. Moreover, mobile sinks can link the isolated network segment by accessing the portions of the network to improve the network connectivity, which is impossible for static sinks to realize.

Despite a lot of benefits, sink mobility also brings a series of new problems, such as data dissemination, routes adjustment and energy dissipation. Locating the sink is a primary problem for data dissemination that source nodes have to know the destination location. Unlike static sink

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scenarios, the network topology becomes dynamic as the sink changes its own position. Frequent location updates give rise to frequent unpredictable topology change. Once the sink gets to a new position, it must broadcast its latest location to the whole network thereby causing significant overhead.

To copy with these problems, in this paper, we propose a routing method, which is called Grid-based Energy-Efficient Routing Method (GEERM), to determine the tour of a mobile-sink node in a WSN. We highlight some key features and the contributions of the GEERM as follows:

1) We consider three parameters for cluster-head election, which makes more reasonable distribution of cluster heads in a non-uniform distributed grid area. Each grid communicates with each other via gateway nodes.
2) The GEERM employs a controlled mobile sink equipped with two antennas by utilizing MU-MIMO technique [7] to move along a straight-line trajectory at a constant speed to collect data from two sides.
3) The GEERM maintains the optimal routes to the latest location of mobile sinks by using a dynamic routes adjustment scheme.
4) Sensor nodes can adjust the transmission range based on their residual energy.

The remainder of this paper is organized as follows: Section II gives a brief introduction of related work. Section III introduces the system model. In Section IV, the GLRM algorithm is described in detail. Section V shows simulation results and performance evaluation. Finally, we conclude this paper in section VI.

II. Related Work

A. Mobile-Sink based Routing Methods

Many people focus on hierarchical routing methods. These methods all construct a virtual hierarchical structure and determine a multi-tier hierarchy of roles among the nodes. A successful network with a hierarchical structure can access to the high-layer nodes easily and has a corresponding strategy for the hotspot problem.

A modified stable election protocol (MSE) [8] was proposed to predetermine the sink's trajectory which is a straight line through the network. In Fig. 1(a), the whole network is divided into clusters and MSE forwards the sensing data aggregated to the mobile sink via cluster-head nodes. MSE establishes a node failure maintenance mechanism for the whole network. The failed cluster-head nodes will be removed from the network automatically and MSE will select a new cluster-head node for data forwarding. However, after several node deletion operations, the network will become sparse and the distance between cluster-head nodes will be increased, which will result in significant transmission power consumption and shorten the network lifetime.

In [9], Two-Tier Data Dissemination (TTDD) is one of the hierarchical approaches which have been put forward long ago. As shown in Fig. 1(b), TTDD is a virtual grid-based approach, which provides scalable and efficient data delivery to multiple mobile sinks. Each source node with the sensor data proactively constructs a rectangular grid and becomes a crossing point of this grid. Sinks receive data on the move continuously by flooding queries within a local cell only whenever needed. Location-aware sensor nodes are also needed. In general, overhead for constructing grids in TTDD is immense for periodic data reporting applications.

TTDD is not suitable for the network where events occur frequently. In order to send data to multiple mobile sinks efficiently and reduce the power consumption of sensor nodes, a grid-based energy-efficient hierarchical routing protocol (GBEER) [10] is proposed, which constructs a grid structure for all the source nodes using global location information. As a mobile sink reaches a new position, data request will be sent to the closest cell-header along the grids by local flooding, and then data is sent back to the sink along the opposite direction of the original path. The approach enables high overhead to be limited in a separate cell. However, construction of the grid is non-trivial.

Similarly with GBEER and TTDD [9, 10], a novel Grid-Based Dynamic Routes Adjustment Scheme is put forward in [11], aiming to reduce the routes reconstruction cost of the sensor nodes to extend the network lifetime. VGDRA adopts four propagation rules to adjust routes to copy with the routes readjustment. The scheme can realize routes readjustment by just adjusting part of routes, thereby reducing routes reconstruction cost and improving the network lifetime significantly. Even though dynamic routes adjustment in VGDRA shows good performance in prolonging the network lifetime, cell-headers adjacent to the sink deplete energy quicker than others.

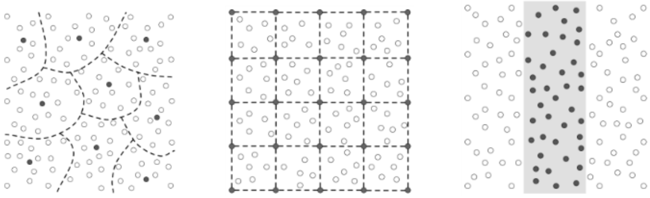

Fig. 1. Various hierarchical structures: (a) Clusters (MSE [8]), (b) Rectangular grid (TTDD [9], GBEER [10], VGDRA [11]), (c) Line (LBDD [12]).

Apart from rectangular structures and cluster-based structure, the line-based network structure is also adopted in [12], LBDD is the most efficient among the above-mentioned methods, since it successfully alleviates hotspots. However, it suffers from poor structure accessibility. Thus, we consider a grid structure to design the network in this paper.

B. Energy-aware Transmission Range Adjusting

In general, a node with a larger transmission range will increase the number of its neighbors. This means that the node will perform more tasks of long distance message relaying and it will die faster. Wang proposed an energy-aware transmission range adjusting scheme [13] to tune the transmission range of nodes according to the current residual energy of nodes.

The scheme defines the current residual energy of the sensor node u is $E(u)$ and its transmission range is $R(u)$. Assuming that the total battery capacity of a "healthy" node is B and the transmission range of a "healthy" node is r, Wang gave three types for the battery capacity of a sensor node. A sensor node will adjust its transmission range according to the residual energy as described in Fig. 2.

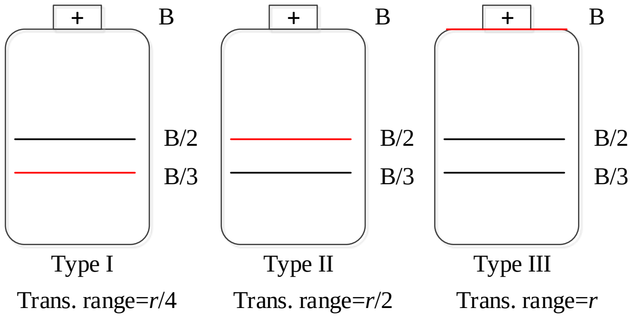

Fig. 2. The energy-aware transmission range adjusting mechanism

C. MU-MIMO in WSNs

The feasibility of employing MIMO techniques in WSNs is verified in [14-16]. Duo to difficulties to install multiple antennas on a single sensor node, MIMO technique is adopted in WSNs to seek better performance when using multiple antennas. Energy efficiency [14, 15] and the schedule algorithm [7, 16] are two challenges in MIMO. Zhao [7] jointly consider the selections of the schedule pattern and selected polling points for the corresponding schedule pairs. Once the selected polling points of each cluster are determined, a heuristic algorithm for the TSP problem will be used to find a shortest moving trajectory among the selected polling points. Finally, a mobile data collector equipped with two antennas using MU-MIMO techniques will receive data along the shortest path.

In this paper, the GEERM adopts MU-MIMO techniques to cope with the problem of dual data uploading from two cluster heads.

III. System Model

We design a virtual grid-based network structure which partitions the sensor field into some rectangular grids with the same size. *N* sensor nodes are randomly deployed in a WSN which is shown in Fig. 3, and the mobile sink receives data packets along the straight-line trajectory through the network.

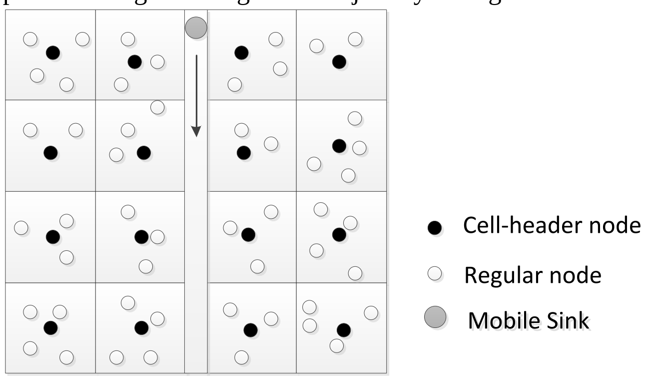

Fig. 3. Grid-based network structure.

A. Network Model

Before describing the specific method of GEERM, we give the following assumptions about network characteristics.

- Nodes are randomly deployed throughout the sensing field and all remain static.
- All nodes are aware of their own location information.
- Sensor nodes can adjust their transmission power in accordance with the distance between nodes.
- The sink moves along the center line of the network and has no resource constrains.
- There is no communication block within the network.
- Two antennas equipped on the mobile sink have the same performance in data collection.

B. Energy Model

We adopt the first order radio energy model [13] as energy consumption model of performance simulation. When the distance between two nodes is greater than a threshold called d_0, the multi-path channel path model (d^4 power loss) will be used instead of the free space (d^2 power loss).To transmit *l*-bit length message at distance d, the energy consumed can be calculated by Equation 1.

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

E_{elec} is the energy consumed to transmit or receive one-bit length data, ε_{fs} and ε_{mp} are the energy required for the transmitter amplifier, $d_0 = \sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ is a constant.

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

Equation 2 is used to calculate the energy consumed for receiving this message.

IV. The Proposed GEERM Algorithm

In this section, we give detailed description of our GEERM algorithm, including how to select cluster heads and how to maintain the fresh sink position formation to source nodes. Similarly with most hierarchical routing methods, cluster heads obtain and store the latest location of the mobile sink and regular nodes only need to retrieve their corresponding cluster heads to relay information. Adjacent cluster heads communicate with each other via gateway nodes. The set of cluster-head nodes together with gateway nodes constructs the virtual backbone structure.

A. The Virtual Grid Structure Construction

The GEERM algorithm constructs the virtual grid structure by first partitioning the sensor field into several uniform sized grids based on the number of nodes in the sensor field.

To determine the optimal number of grids and the mobile sink's trajectory, we adopt the heuristics used in LEACH [17] which considers 5% of the total number of sensor nodes. Considering the straight-line moving trajectory of the mobile sink in GEERM (see Fig. 3) and network load balancing, GEERM adopts the following Equation 3 to divide the sensor field with *N* sensor nodes into *K* grids of uniform size, where *K* is a square number, and *K*=4, 9, 16 when *N*=100, 200, 300, respectively.

$$K = \begin{cases} 4 & N \times 0.05 \le 6; \\ 9 & 6 < N \times 0.05 \le 12; \\ 16 & 12 < N \times 0.05 \le 20; \\ \vdots & \end{cases} \quad (3)$$

After finishing the network construction, clusters are determined and a grid is equivalent to a cluster. In the virtual grid structure, each cluster is static, which means the network structure won't be changed once constructed successfully.

When determining the number of grids in the sensor field, a unique serial number will be assigned to each grid, which can be seen in Fig. 4.

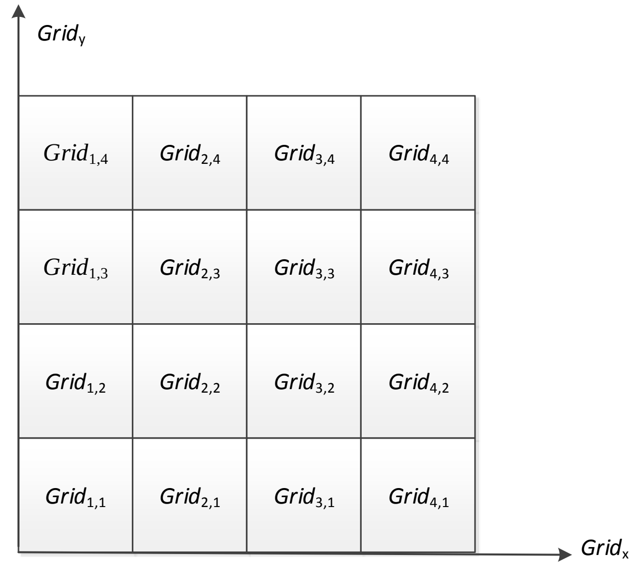

Fig. 4. Sketch map of virtual grid.

According to the number of grids which is calculated from Equation 3, we can get the length of grids as $L/\sqrt{K}$. So the grid serial number of each node can be calculated by Equation 4.

$$Grid_x = \left\lceil \frac{x}{\frac{L}{\sqrt{K}}} \right\rceil = \left\lceil \frac{x\sqrt{K}}{L} \right\rceil, \qquad Grid_y = \left\lceil \frac{y}{\frac{L}{\sqrt{K}}} \right\rceil = \left\lceil \frac{y\sqrt{K}}{L} \right\rceil. \quad (4)$$

where L is the length of the side of the network, (x, y) is the location coordinate of a node. Then, each grid selects the node whose distance to the mid-point of the grid is minimum as the cluster head. The cluster head sends a message to tell member nodes and adjacent cluster-head nodes its role.

B. Data Transmission

In our proposed GEERM, we consider two data transmission phase, i.e. intra-cluster routing and adjacent cluster routing, respectively.

(1) Intra-cluster Transmission

In the GEERM method, we incorporate the technique of energy-aware transmission range adjusting [13] to tune the transmission range of each sensor node according to its residual battery energy. After performing rounds of message relaying and environment sensing tasks, the residual energy of nodes get low and their transmission range will be tuned to be small for energy saving. At first, the GEERM sets transmission range of a "healthy" node to R, and the first cluster head can communicate with all nodes within its grids, so we can get the following result:

$$R \le \left(\frac{L}{\sqrt{K}} \times \sqrt{2}\right)/2 \le \frac{\sqrt{2}L}{2\sqrt{K}} \quad (5)$$

where the length of the side of the rectangular network is L and K is the number of grids.

At the beginning of the network operation, the transmission range of the cluster head can cover the entire grid. Member nodes communicate with their cluster head via single hop. After performing several rounds of message relaying, the cluster-head node will not be "healthy" and its transmission range will be tuned to be small for energy-saving [13]. Member nodes far away from the cluster head will relay messages in a multi-hop manner.

(2) Inter-luster Transmission

Cluster-head nodes relay data packets to the mobile sink via multiple hops. In order to cope with dynamic network topology caused by sink mobility, flooding is the most effective way, however, it will give rise to non-negligible energy dissipation.

In this paper, the GEERM uses a dynamic routes adjustment scheme to keep fresh sink position information to source nodes. Starting from the originating cluster head, the downstream cluster head checks whether the sender cluster head is the same as its previous hop or different. If it is the same, the downstream cluster head drops the data packet of the mobile sink's position update and does not transmit it to the next downstream cell-header. If different, the downstream cluster head updates itself as the new sender cluster head and performs the same operation. The procedure is repeated until all source nodes adjust their routes. From Fig. 5, we can know that only one-hop route change around the mobile sink when S1 moves to S2.

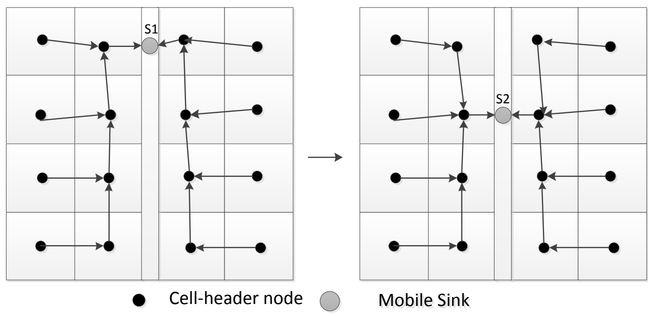

Fig. 5. Example of the sink's position changes.

C. Cluster Maintenance

(1) Cluster-head election

To prolong the network lifetime, cluster-head election is necessary. We define an energy threshold called T which is equal to one third of the current residual energy of a node. When the residual energy of a cluster-head node is less than T, the cluster-head re-election within the grid will happen.

Three parameters are taken into consideration for election of cluster heads, the number of data packets called n_i that nodes need to relay, the Euclidean distance to the mid-point of the grid called $d_{i,M}$, the residual energy of each node called E_i, respectively.

In the previous proposed cluster-head election approaches, cluster-head election approaches based on the residual energy [18] and the distance to the mid-point of the grid [11] have been introduced. In the GEERM algorithm, a new parameter, which is the number of messages that nodes need to relay, is considered.

Assuming that each node has the same residual energy and distance to the mid-point of the grid, and relaying a message from one node to another will consume the fixed energy called *E*, according to our cluster-head election approach, Fig. 6(b) is the final topology and its total energy consumption of member nodes is 22*E*. If another node with the same distance to the mid-point of the grid is selected as the cluster head, Fig. 6(c) is the final topology and its total energy consumption of member nodes is 34*E*, which is obviously larger than 22*E* consumed using our proposed cluster-head election.

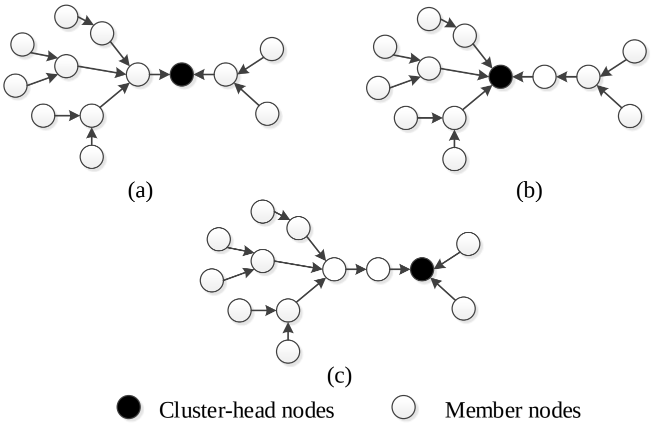

Fig. 6. Cluster-head election process.

Therefore, considering the number of messages that need to relay is feasible and the weight of a sensor node called W_i can be calculated by Equation 6.

$$W_i = (n_i \times E_i)/d_{i,M} \quad (6)$$

The current cluster head will determine its candidate cluster head according to W_i. When a cluster is selected, it will broadcast an advertisement packet to its member nodes and "join" packets will be sent to cluster heads. In order to avoid inter-cluster interference, each cluster head will select a unique CDMA code [19] and informs its member nodes within the grid to use this spreading code to transmit data packets. After all nodes within the cluster receive messages, the cluster head creates a TDMA schedule, and broadcasts the TDMA table to its member nodes. All member nodes will send their message to cluster heads during their allocated TDMA slot.

In order to reduce communication cost during cluster-head election, we also define a distance threshold *d*, only those nodes can participate in the cluster-head election whose distance to the mid-point of the grid is within *d*. If no node are found within d around the mid-point of the grid, the distance threshold *d* will be increased slightly until conditions are met.

(2) Local grid protection

Our grid-based network model is non-uniformly distributed, so the total energy of each separate grid is different. It may occur that nodes in some grids die prematurely, thereby causing network topology changes. In the GEERM algorithm, when the average residual energy of all nodes in a grid is less than the energy threshold T, this grid will be marked as the protected grid and does not collect data from the external environment but forward data from other adjacent cluster heads to maintain the network normal operation.

V. Performance Evaluation

We use MATLAB R2012b to evaluate the performance of our proposed GEERM algorithm. As shown in Table I, 300 sensor nodes are randomly deployed in a rectangular region of $200 \times 200m^2$. By calculating, we can get the transmission range of a "healthy" node is approximately equal to 17*m* and the number of grids is 16. Specific simulation parameters are listed in Table I.

TABLE I
Simulation Parameters

Parameter	Definition	Unit
E_0	Initial energy of sensor nodes	0.2J
E_{elec}	Energy dissipation to run the radio device	50nJ/bit
ε_{fs}	Free space modes of transmitter amplifier	10pJ/bit/m^2
ε_{mp}	Multi-path model of transmitter amplifier	0.0013pJ/bit/m^4
d_0	Distance threshold	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ m
l	Packet length	2000bits

A. Static-Sink based Data Collection

In our proposed GEERM algorithm, three parameters are taken into consideration into cluster-head election. Therefore, in a given period of time, GEERM can save more energy theoretically. At first, we compare the GEERM algorithm with LEACH protocol. To maintain consistency, a static sink is located at coordinates (100, 0) to receive data. As shown in Fig. 7, the energy consumption rate of LEACH is much larger than our GEERM algorithm. For the better illustration of these two energy consumption curves, we only choose the data 1000 rounds.

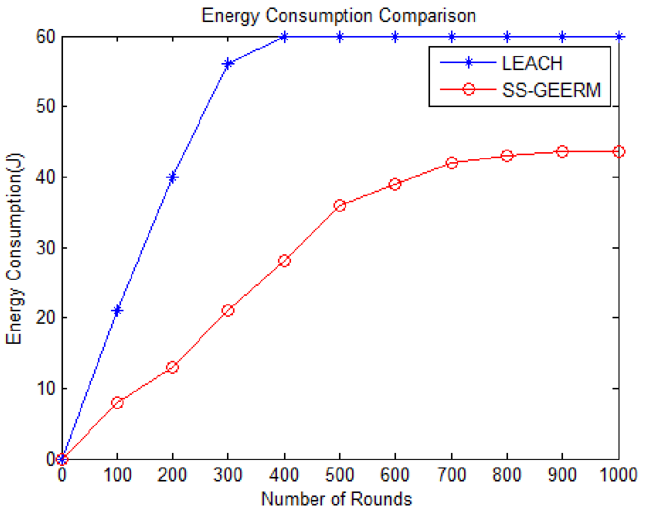

Fig. 7. Energy consumption comparison.

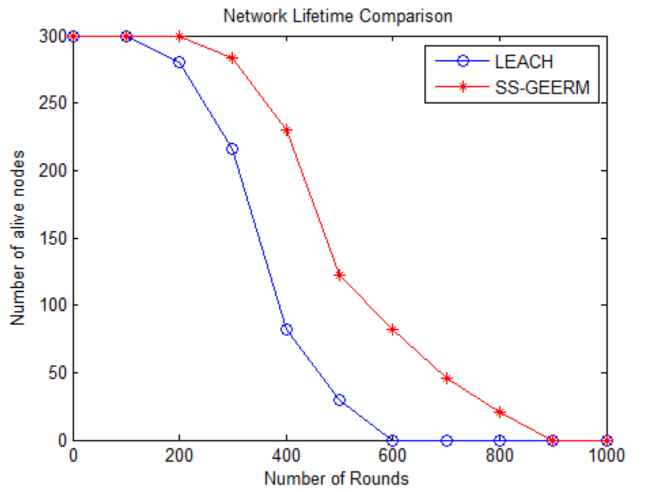

Fig. 8. Network lifetime comparison.

Fig. 8 describes the network lifetime of GEERM and LEACH with different rounds. It is clear that our GEERM algorithm, which employs a static sink to collect data, has better performance in prolonging network lifetime than LEACH. The round of the first death node and last node is list in Table II.

TABLE II
THE ROUND OF FIRST DEATH NODE AND LAST NODE

Algorithms	Rounds of First Death Node	Rounds of Last Node
LEACH	105	596
SS-GEERM	211	910

We compare our GEERM algorithm with LEACH protocol by adopting a static sink to collect data. Obviously, the grid-based clustering approach is better than LEACH.

B. *Mobile-Sink based Data Collection*

Compared with VGDRA, which employs a mobile sink to move around the network edge, we set a straight-line trajectory in our GEERM algorithm and adopt MU-MIMO technique to solve the problem of which receives data from two cluster heads in each time, which can speed up data collection time greatly and reduce the overall latency. In theory, Data Collection rate of our GEERM is quicker than that of VGDRA.

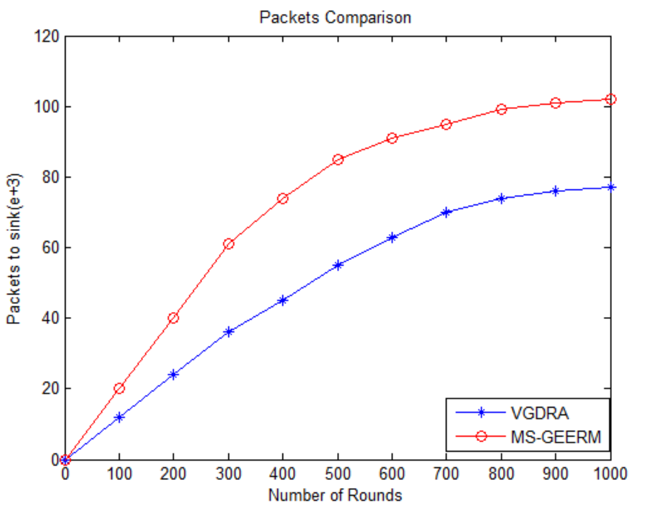

Fig. 9. Packets received by the sink node.

The mobile sink is placed at coordinates (100, 0) and then moves to (100,200) along the straight-line trajectory at a constant speed.

As shown in Fig. 7, GEERM can collect more data than VGDRA within the same rounds. We only choose the amount of data within 1000 rounds.

VI. CONCLUSION

In this paper, we present an energy-efficient routing method called GEERM for WSNs, which employs a mobile sink equipped with two antennas by adopting MU-MIMO techniques to move along a predetermined trajectory. Our GEERM algorithm shows good performance in decreasing energy dissipation and prolonging network lifetime. However, sensor nodes from two sides of the moving path suffer from more workload and die faster. We hope to use multiple mobile sinks or other moving pattern to improve the network performance.

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