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Research Article

An Enhanced PEGASIS Algorithm with Mobile Sink Support for Wireless Sensor Networks

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Energy efficiency has been a hot research topic for many years and many routing algorithms have been proposed to improve energy efficiency and to prolong lifetime for wireless sensor networks (WSNs). Since nodes close to the sink usually need to consume more energy to forward data of its neighbours to sink, they will exhaust energy more quickly. These nodes are called hot spot nodes and we call this phenomenon hot spot problem. In this paper, an Enhanced Power Efficient Gathering in Sensor Information Systems (EPEGASIS) algorithm is proposed to alleviate the hot spots problem from four aspects. Firstly, optimal communication distance is determined to reduce the energy consumption during transmission. Then threshold value is set to protect the dying nodes and mobile sink technology is used to balance the energy consumption among nodes. Next, the node can adjust its communication range according to its distance to the sink node. Finally, extensive experiments have been performed to show that our proposed EPEGASIS performs better in terms of lifetime, energy consumption, and network latency.

1. Introduction

Topology control is a very important research issue for the emerging mobile networks (EMN). Wireless sensor networks (WSNs), as part of the EMN, are usually composed of a large collection of tiny sensors nodes and they are developing very rapidly in recently years due to their wide applications [1]. These nodes are usually deployed in a random way and they can collect information from surroundings, and then transfer the data package to sink node using single or multiple hops communication to form WSNs. The outstanding performance of WSNs like fault tolerance, rapid deployment, self-organizing, timely response, etc. makes WSNs widely used in harsh environment such as military surveillance, industrial product line monitoring, medical health care, and smart homes [2, 3].

Energy efficiency and energy balancing have been a very hot and challenging research issue for WSNs for many years. Since large number of sensor nodes is deployed under very harsh environment, it is unrealistic to change the sensor batteries for them. Besides, the nodes close to the sink not only need to collect data, but also need to forward its neighbours' data. Thus, those nodes will exhaust their energy more quickly than other nodes far away from sink. This phenomenon is known as hot spots problem. When the first node dies because of energy exhausting, the performance of network in terms of connectivity, coverage, lifetime, etc. will decrease sharply [4, 5].

In order to solve the hot spots problem, sink mobility technology is introduced to many routing protocols [6–9]. By adopting sink mobility, the following advantages can be achieved. Firstly, the mobile sink moves along a certain trajectory so that the nodes close to the sink could take turns to be the forwarder, which will largely alleviate hot spots problem [10]. Secondly, the energy consumption of the whole network can be reduced because of the shorter average transmission distance between sensor nodes and mobile sink, if the mobile sink has a proper trajectory [11]. Thirdly, the performance of the network in terms of transmission latency and network throughput can be greatly improved under suitable moving strategy. Finally, mobile sink can enhance the network connectivity in sparse network [12–14].

The main contribution in this paper includes the following four aspects. First, we find the optimal communication distance for data transmission. Second, we set threshold value for each node to protect those nodes with low remaining energy. Third, we adjust nodes' communication distance according to its distance to the mobile sink. Finally, mobile sink technology is adopted to balance the energy of different regions. Numerous simulations are conducted to prove our proposed algorithm outperforms than some existing work.

The rest of the paper is organized as follows. In Section 1, we introduce the background of our work. In Section 2, we discuss some classic routing protocols and some latest research achievement. The system model which contains network and energy model is presented in Section 3. In Section 4, we describe our algorithm in detail. Extensive simulations are conducted and the experimental results are discussed and compared in Section 5. Section 6 concludes the paper with some future work.

2. Related Work

Many researchers have paid close attention to energy efficient routing protocols or algorithms in recent years. LEACH (Low-Energy Adaptive Clustering Algorithm) is one of the most famous hierarchical protocols which were proposed about twenty years ago [15]. In LEACH, there are two types of nodes, namely, cluster heads (CHs) and ordinary nodes (ONs). Each ON collects data from area of interest and sends the data package to a closest CH. Each CH take charge of fusing the data it receives and then transmits the fused data to the sink node. The introduction of CHs can avoid long distance communication between ON and sink node; thus much energy is saved. However, the selection of CHs is in a random way as a result of random selection. So, the CH distributes unevenly inside the whole network with degraded performance. Meanwhile, CHs communicate with sink node directly which causes much energy dissipation.

PEGASIS (Power Efficient Gathering in Sensor Information Systems) is a chain-based routing protocol for WSNs [16]. In PEGASIS, each sensor node only needs to transmit data to its neighbour which is closer to the sink node. Several chains could be constructed according to the greedy algorithm and the leader of each chain takes the responsibility to transfer the data to the sink node. Due to the heavy burden of the leaders of chains, each node takes turns to be the leader to balance the energy consumption. Because of multihop propagation, long distance communication between sensor node and sink node is avoided and much energy is saved. Meanwhile, due to multihop propagation, the delay of the network is very serious and it is not suitable for delay sensitive applications.

In [17], the authors propose an energy efficient routing protocol using mobile sink based on clustering and it is suitable for WSNs with obstruction. Mobile sink moves along the CHs and collects data by single hop communication. In this protocol, an efficient scheduling mechanism based on spanning graphs is proposed to find a shortest path for mobile sink to avoid obstacle. Simulation result shows that the lifetime of the network is prolonged and complexity of network is reduced.

In [18], the authors proposed a data collection algorithm using mobile sink based on tree clustering. This algorithm contains three phases, namely, tree construction, tree decomposition and subrendezvous points (SRP) selection, and data collection phases. Mobile sink moves towards rendezvous points (RP) and SRP to collect data via single hop communication. After data collection in each round, sensor nodes will reselect RP and SRP. Simulation result proves that the proposed algorithm performs better in terms of network lifetime and the moving path of the mobile sink is short.

In [19], the authors study the event-driven application for WSNs with mobile sinks. In this paper, each sensor node has two statuses: monitoring and transmission status. When an event is caught, the status of node changes from monitoring to transmission and the group of active sensor nodes (ASN) is constructed to forward the data to the mobile sink. In large-scale WSNs, the area of interest is divided into several subareas due to the limit of the speed of the mobile sink. Each subarea contains a mobile sink and ASNs are selected to collect and transmit data. In the meantime, the continuous and optimal trajectory (COT) can be calculated for the mobile sink to achieve better performance.

In [20], the authors propose an energy efficient routing protocol for mobile sensor networks using a path-constrained mobile sink. This protocol is suitable for WSNs which limits on the moving path of the mobile sink, such as mobile sinks deployed in bus. Source node sends the data package to the target node which is closest to the location where the mobile sink will arrive next time and ensure the shortest path to transmit data. This kind of protocol is very suitable for delay-tolerant network and it possesses higher robustness and lower energy consumption.

In addition, some heuristic algorithms are used to improve the performance of the network [21–26]. In [21], the authors combine the Particle Swarm Optimization (PSO) algorithms with cluster technology to enhance the network lifetime. In [22], the authors propose an Ant Colony Optimization (ACO) based on clustering algorithm to find an optimal moving trajectory for mobile sink. In [23], techniques like Glow-worm Swarm Optimization (GSO), clustering and mobile sink are combined together to improve energy efficiency as well as to prolong the lifetime of wireless sensor network.

3. System Model

3.1. Basic Assumptions. In this paper, we make some basic assumptions as follows:

(1) All the sensor nodes are randomly deployed and keep static after deployment.

(2) Each sensor node has a unique ID to differ from each other.

(3) All the sensor nodes have the same initial energy and batteries of them cannot be changed.

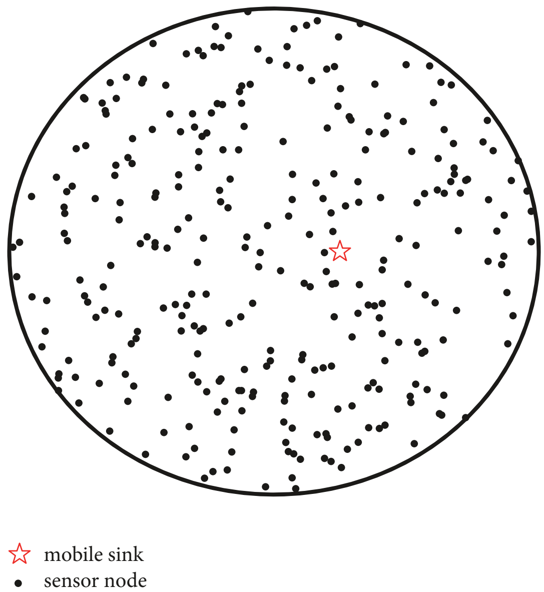

Figure 1: Network model.

(4) Mobile sink can move freely and owns unconstrained energy.

(5) Transmission power of sensors can be adjusted based on communication distance [27].

3.2. Network Model. In this paper, N nodes are deployed randomly in a circular field with radius R. These sensor nodes are denoted as $\{n_1, n_2, n_3 \cdots n_n\}$, respectively, as is shown in Figure 1. In each round, every sensor node should transmit one package to the sink using single hop or multihop communication based on the relatively distance.

3.3. Energy Model. The first ratio model is adopted here to calculate the energy consumption [28, 29]. As is shown in Figure 2, the energy consumption mainly contains two parts which are transmission consumption and reception energy consumption.

Transmission consumption mainly includes the energy consumed for transmission circuit and the power amplifier expenditure. The reception consumption mainly includes the energy of reception circuit expenditure. Transmission consumption can be calculated by using the following formula:

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

where E_{elec} is the energy cost to use transmitter or receiver circuit to process one-bit signal. Symbols ε_{fs} and ε_{mp} denote the amplification coefficient for the free space model and the multipath fading model separately. Metric d_0 is the threshold value and can be calculated as $d_0 = \sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$.

The energy consumption for reception can be calculated according to formula (2):

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

4. Our Proposed Algorithm

4.1. Overview of EPEGASIS. In this section, we will illustrate our proposed algorithm in detail. Our proposed algorithm is called Enhanced PEGASIS (EPEGASIS), which belongs to the chain-based routing algorithms. In EPEGASIS, each node uses optimal communication distance to choose the relay node from its neighbours for data transmission. In order to avoid excessive energy consumption for some nodes with special location, we set a protection mechanism according to the average residual energy of its neighbours. A mobile sink is utilized to gather data for different region energy consumption balancing. The workflow of each node in the network is shown as Figure 3.

4.2. Study on Optimal Communication Distance. According to the energy consumption model, the energy consumption raises rapidly with the increasing of the communication distance. In order to conserve energy, multihop transmission is adopted to avoid long distance communication. However, too much hops may increase the burden of forwarding and cause increased end-to-end delay or latency.

We assume that the source node is m meters away from the mobile sink and it sends a one-bit data package to the mobile sink by k hops, and the total energy consumption can be calculated using formula (3):

$$E_{total} = \begin{cases} k\left[E_{elec} + E_{fs}\left(\dfrac{m}{k}\right)^2\right] + (k-1)E_{elec} & \text{if } \dfrac{m}{k} < d_0 \\ k\left[E_{elec} + E_{mp}\left(\dfrac{m}{k}\right)^4\right] + (k-1)E_{elec} & \text{if } \dfrac{m}{k} \geq d_0 \end{cases} \quad (3)$$

The relationship between total energy consumption and hop counts can be shown as Figure 4. From Figure 4, we can clearly see that, as the hop counts increases, the total energy consumption drops first to reach its lowest point and then rises. The triangle in each line denotes the energy consumption when $m/k = d_0$ and it also denotes the lowest point of each line. Therefore, the optimal communication distance and optimal hop counts is shown as formulas (4) and (5).

$$d_{optimal} = d_0 \quad (4)$$

$$optimal\_hop\_counts = \left\lceil \frac{m}{d_0} \right\rceil \quad (5)$$

4.3. Initial Phase of the Network. After nodes deployment, the network enters into initial phase. During the initial phase, the main object is to exchange information to prepare for data transmission. At the very beginning, the mobile sink broadcast a NETWORK_INIT package to remind all the nodes to initial the network. Each node maintains a route table called "NBR_TABLE" to record its neighbours' information. Then each node broadcast a NODE_INFO package with its maximal transmission distance. Neighbours who receive NODE_INFO package will write relevant information into route table. After the initial phase, each node will have

Table 1: Package information.

Package type	Content
NETWORK_INIT	The initial location of the mobile sink, the moving speed and direction of the mobile sink, time of duration of each round, TDMA schedule of nodes.
NODE_INFO	The location, the residual energy, ID of source node.
ENERGY_INFO	The residual energy and ID of source node.
SINK_INFO	System time, the current location of mobile sink, the speed and direction of mobile sink.

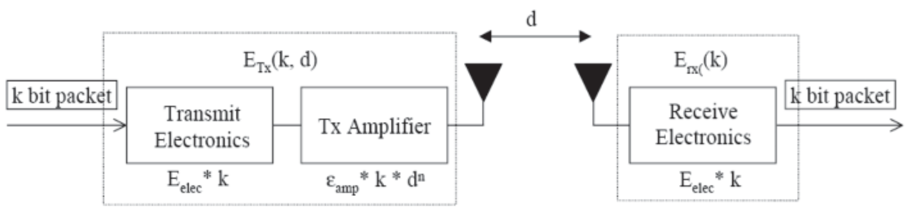

Figure 2: Energy model.

the knowledge of its neighbours. In order to update the energy information of sensors, an ENERGY_INFO package is broadcasted by each node during each round. With the running of the network, the system time and the location of the mobile sink may go awry, so the mobile sink will broadcast a SINK_INFO package in the whole network at fixed periods. The detailed information of packages is illustrated in Table 1.

4.4. Network Topology Generation. In PEGASIS, each node selects its closest neighbour as relay node for data forwarding and that causes heavy burden of transmission and long network delay. In our proposed algorithm, we mainly decrease the times of data forwarding and achieve an optimal energy consuming. We use optimal communication and optimal hop counts for data transmission. Node selects a forwarder among its routing table and the forwarder satisfies the following two formulas.

$$d\left(n_{forwarder}, \text{mobile\_sink}\right) < d\left(n_{source}, \text{mobile\_sink}\right) \quad (6)$$

$$d\left(n_{source}, n_{forwarder}\right) = \min \left| d\left(n_{source}, n_{forwarder}\right) - d_{optimal} \right| \quad (7)$$

where $d(n_i, n_j)$ denotes the distance between node i and node j.

When the mobile sink is in the optimal communication of sensors, they will transmit data to the mobile sink directly. After relay node selection, nodes far away from the mobile sink transmit data to it by several relays and the topology of the network is generated. The topology of the network is shown as Figure 5.

4.5. Protection Mechanism for Dying Node. Nodes close to the sensor field centre take on a heavy burden for data forwarding; however, nodes close to the edge of the sensor field only need to send their own data and that cause the hot spots problem. Figure 6 describes the hot spots phenomenon after the network running for several rounds.

In order to protect nodes from dying too early, we set a threshold value for nodes according to average neighbour energy. When node's residual energy is less than a threshold value, it will not take the role of forwarder and only sends its own generated data. The threshold value is calculated using formula (8).

$$E_{threshold} = \frac{\sum_{n \in C_i} E_{residual}}{N} \quad (8)$$

where C_i denotes the set of the neighbours of node i, N is the number of its neighbours, and $E_{residual}$ is the current energy of node n.

By means of setting threshold value, nodes in the central area are protected and time of first node die is greatly delayed. During the initial round, all nodes' residual energy reach threshold value and all of them can be chosen as relay node. With round increasing, nodes close to the central area own lower residual energy than threshold value; therefore, nodes close to the edge will gradually become relay nodes and cause ring routing. The ring routing is illustrated as Figure 7.

4.6. Communication Distance Adjustment for Edge Node. Nodes in the edge area hardly need to be the forwarder and it causes the unbalanced energy consumption among different region. In order to take full advantage of edge nodes, communication distance adjustment is introduced to further balance the energy consumption. Namely, the communication distance of nodes is adjusted according to the distance to the mobile sink. Nodes far away from the mobile sink use longer communication distance for fully energy utilizing and nodes close to the mobile sink use shorter transmission distance to reduce energy consumption.

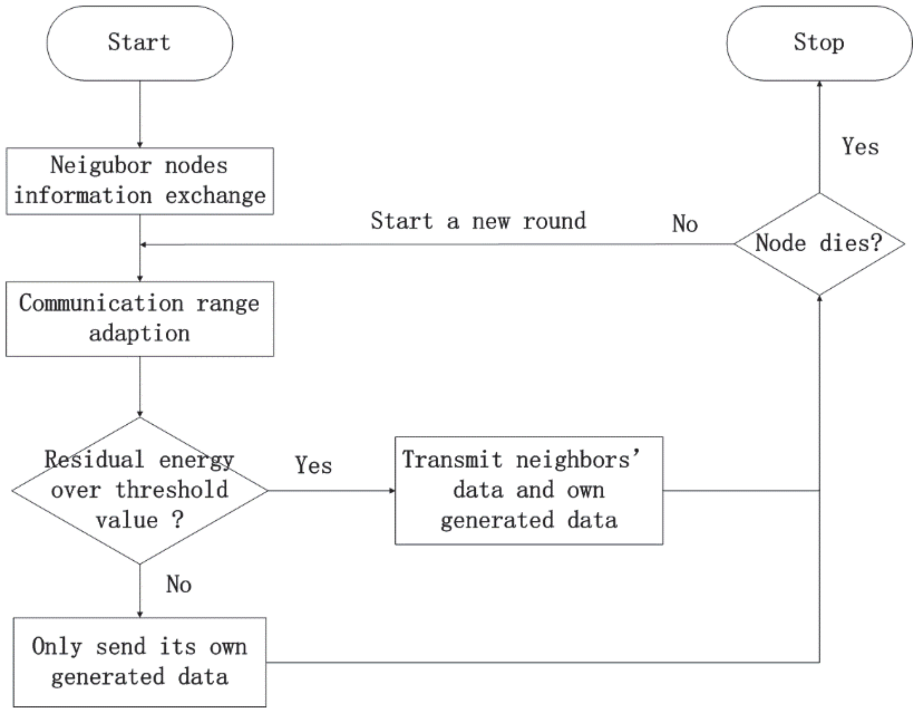

Figure 3: Workflow of nodes.

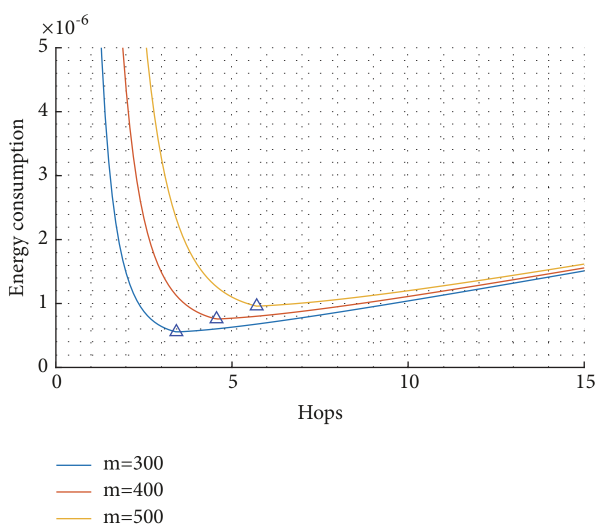

Figure 4: Energy consumption of different hop counts.

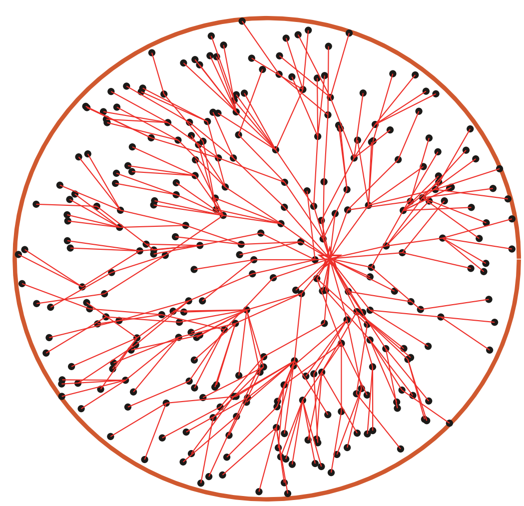

Figure 5: Network topology.

The communication distance of node i can be calculated according to formula (9):

$$d_{adjust\_optimal} = d_{optimal} + \left(d\left(n_{source}, \text{mobile\_sink}\right) - \frac{R}{2}\right) \cdot \alpha \qquad (9)$$

where R is the radius of the network and α (as is discussed in next section) is the adjusting parameter. The chain structure after communication distance adjustment is shown as Figure 8.

4.7. Mobile Sink Moving Schema. In our proposed algorithm, the mobile sink moves with a predetermined direction and speed. The mobile sink moves around the centre of the circle with a constant radius (as is discussed in next section). Therefore, the mobile sink only needs to broadcast its position in initial phase. After $\triangle t$ time interval, the mobile sink moves to a new position as is shown in Figure 9.

5. Performance Evaluation

5.1. Simulation Environment. In order to evaluate the performance of our proposed EPEGASIS algorithm, we use Matlab

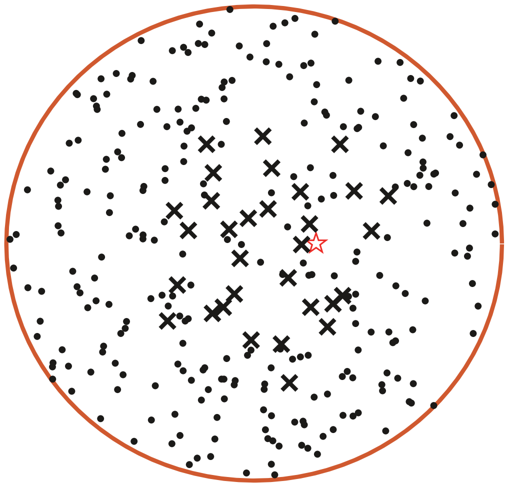

Figure 6: Network topology.

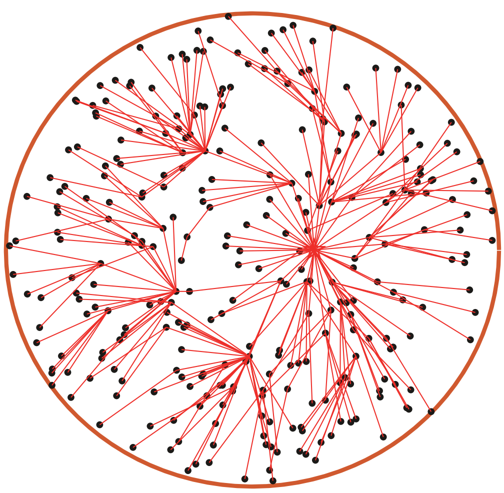

Figure 7: Ring routing.

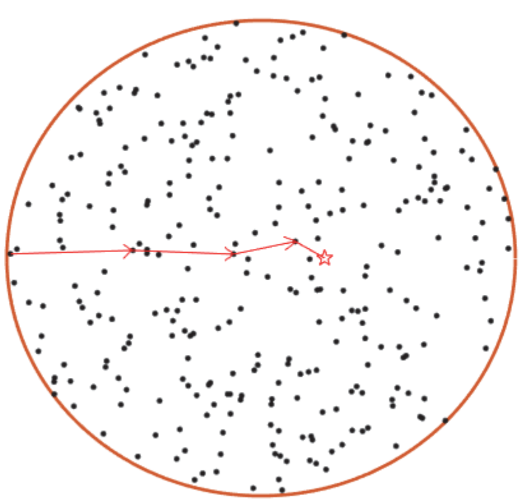

Figure 8: Chain structure after communication distance adjustment.

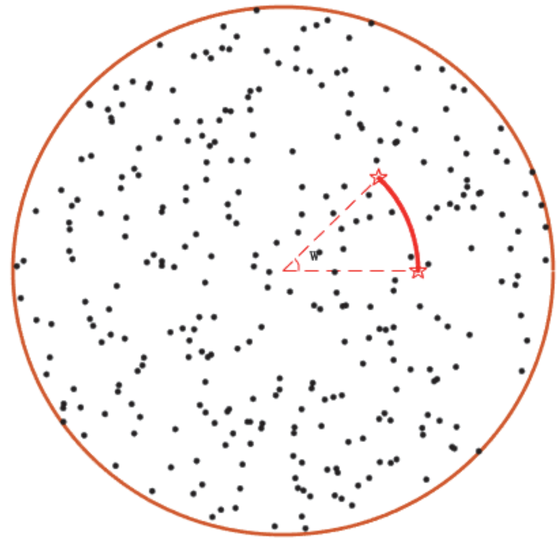

Figure 9: Moving schema of mobile sink.

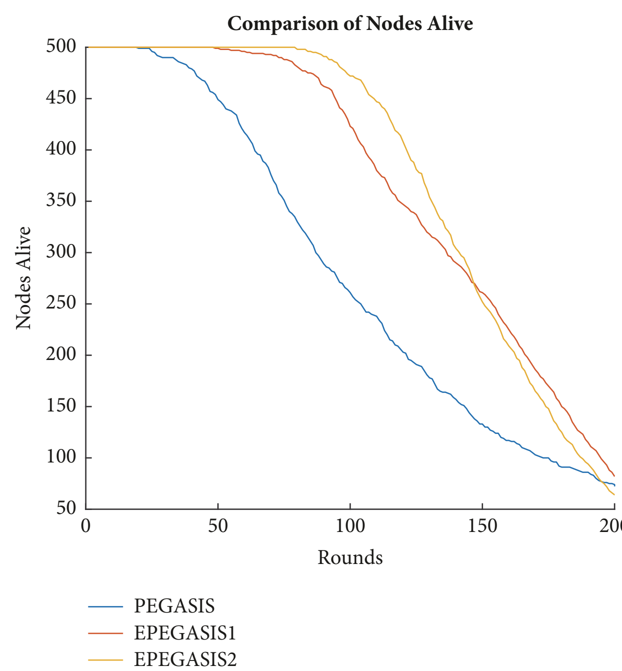

Figure 10: Network lifetime comparison under different routing protocols.

simulator to conduct the experiment. We will compare our proposed algorithm with typical PEGASIS. And the simulation parameters are listed in Table 2.

5.2. Network Lifetime Analysis. As is mentioned above, PEGASIS is a classic chain-based routing protocol and we will compare our algorithm with it. The protocol we proposed without communication range adaption is called EPEGASIS1, and the protocol with further improvement which introduces communication distance adjustment is called EPEGASIS2. The simulation results are shown in Figure 10.

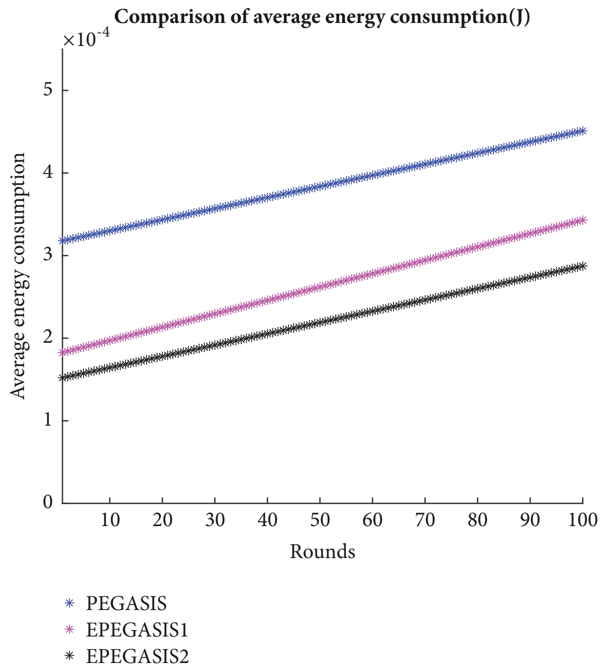

Figure 11: Average energy consumption comparison under different routing protocols.

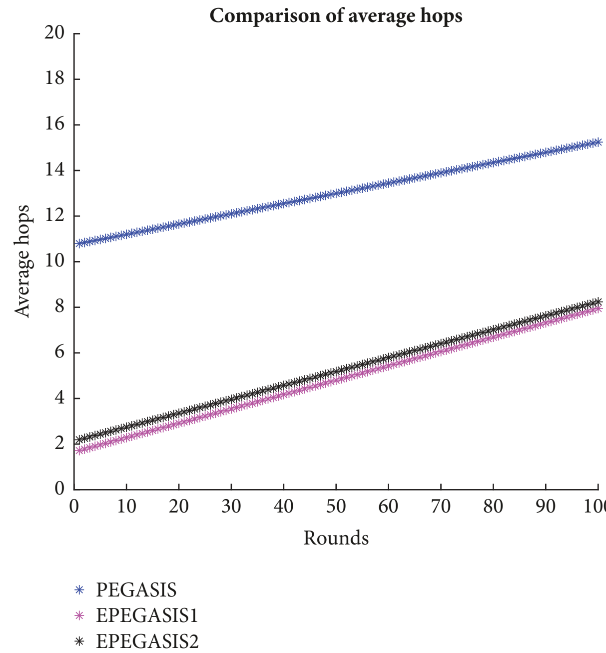

Figure 12: Average hops under different routing protocols.

Table 2: Simulation parameters.

Parameter Name	Parameter Value
Network radius(R)	300m
Mobile sink radius(r)	[0, 75, 150, 225, 300]m
Mobile sink speed(w)	pi/5
Number of nodes (N)	500
Packet length (l)	500 bits
Initial energy (E_0)	0.05 J
Energy consumption on circuit (E_{elec})	50nJ/bit
Free-space channel parameter (ε_{fs})	10pJ/bit/m2
Multi-path channel parameter (ε_{mp})	0.0013pJ/bit/m4
Adjusting parameter (α)	[0.1, 0.2, 0.3, 0.4]

Figure 10 describes that the lifetime of the network is greatly improved in EPEGASIS1 compared to PEGASIS. Due to the heavy burden to transmit the data packages of neighbours, nodes close to the sink begin to die at about 60 rounds. However, the first dies are at about 90 rounds in EPEGASIS2 because of the communication distance adjustment, nodes protection, and sink mobility.

5.3. Energy Consumption Analysis. We compare the average energy consumption per round of different routing protocols, and the result is shown as Figure 11. We can obviously see that the average energy consumption per round in EPEGASIS1 reduces about one-third that of PEGASIS due to the using of optimal communication distance.

5.4. Study on Network Latency. We also study the network latency between different routing protocols, and the result is shown as Figure 12. We can clearly see that the network latency has a great improvement in both EPEGASIS1 and EPEGASIS2. In EPEGASIS2, due to the adoption of communication distance adjustment, some nodes extend their communication distance and some nodes short their communication distance. Therefore, EPEGASIS1 and EPEGASIS2 almost have the same performance in terms of network latency.

5.5. Study on Communication Range Adaption. As we discussed above, each sensor node adjusts its communication distance in accordance with the distance to the mobile sink, and the adjusting parameter α determines the detailed changes. From Figure 13 we can obviously see that when α=0.2, the network has a better performance in terms of network lifetime.

5.6. Study on Mobile Sink Moving Trajectory. The moving trajectory of the mobile sink has a significant influence on the lifetime of the network. In our proposed PEGASIS2, the mobile sink moves around the centre of the circle, and we change the radius of the mobile sink to enhance the performance of the network. Simulation result is shown as Figure 14, and it demonstrates that when the mobile sink travels around the sensor filed with 0.25R radius, the network has a better performance in terms of network lifetime.

6. Conclusions

In this paper, we proposed an Enhanced PEGASIS algorithm with mobile sink support to improve the performance of

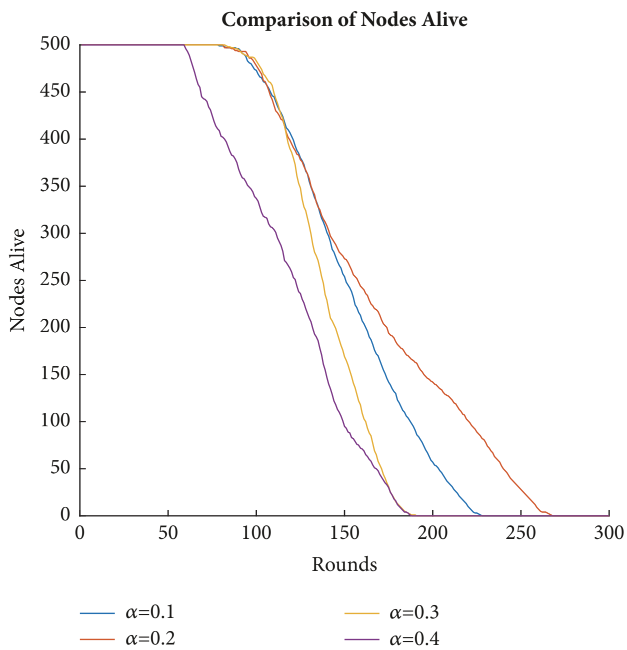

FIGURE 13: Network lifetime under different adjusting parameter.

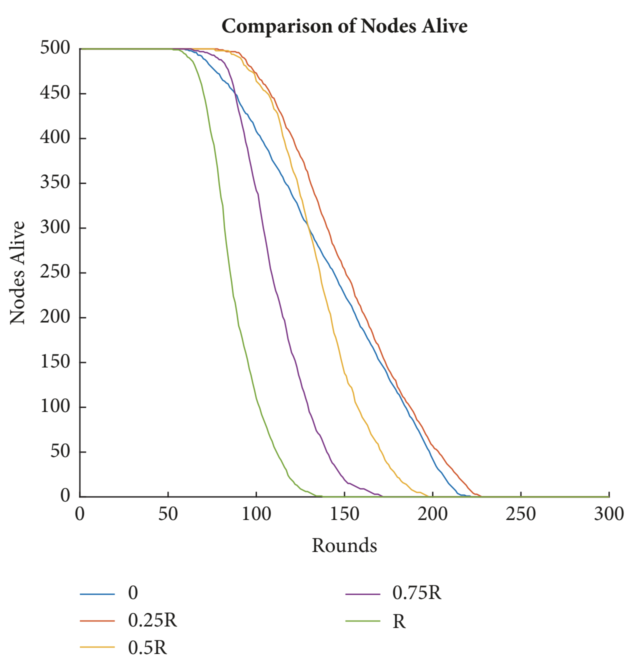

FIGURE 14: Network lifetime under different mobile sink moving trajectory.

WSNs. Nodes use optimal communication distance to select the forwarder and threshold value is set to protect nodes from dying too early. In order to further improve the performance of the network, we adjust the communication distance of nodes based on their distance to the mobile sink. Therefore, nodes close to the mobile sink will have short communication distance to decrease its energy consumption and the time of first node dies prolongs greatly. Extensive simulation results validate the performance of our proposed algorithms than traditional PEGASIS. However, the hot spots problem is not completely eliminated. Our future work mainly includes proper design of sink moving trajectory, as well as joint optimization of both routing algorithm and sink trajectory design.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

This paper is a revised and expanded version of a paper entitled "An Enhanced PEGASIS Algorithm with Mobile Sink Support for Wireless Sensor Networks" presented at ICCCS 2018 China, June 08-10.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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