CONCURRENCY AND COMPUTATION: PRACTICE AND EXPERIENCE
Concurrency Computat.: Pract. Exper. (2014)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/cpe.3313

SPECIAL ISSUE PAPER

Multiple mobile sink-based routing algorithm for data dissemination in wireless sensor networks

Jin Wang[1], Liwu Zuo[1], Jian Shen[1], Bin Li[2] and Sungyoung Lee[3,*,†]

[1]*School of Computer & Software, Jiangsu Engineering Center of Network Monitoring, Nanjing University of Information Science & Technology, Nanjing, China*
[2]*College of Information Engineering, Yangzhou University, Yangzhou, China*
[3]*Department of Computer Engineering, Kyung Hee University, Suwon, Korea*

SUMMARY

In recent years, many energy-efficient algorithms and data dissemination protocols have been proposed for wireless sensor networks (WSNs). Because sensor nodes close to sink node have more traffic loads, they will quickly deplete their limited energy in practical implementation, and it will finally lead to energy hole and network partition problem. Adding sink mobility into sensor networks can bring in new opportunities to improve energy efficiency for WSNs. In this paper, we proposed our multiple mobile sink-based routing algorithm for data dissemination to improve WSNs performance. Multiple mobile sinks will be utilized to collect the interested raw data. They will move back and forth along predetermined paths; one of which is the diameter of the circle, and the other two are fixed on arc lines. Mobile sinks will sojourn at some fixed points to collect raw data from relevant areas. Extensive simulation results show that our proposed algorithm can efficiently mitigate the hot spots problem and prolong the network lifetime of WSNs.

Received 20 December 2013; Revised 19 March 2014; Accepted 10 May 2014

KEY WORDS: wireless sensor networks; multiple mobile sinks; data dissemination; network lifetime; energy consumption

1. INTRODUCTION

Wireless sensor networks (WSNs) are composed of large number of distributed and autonomous sensor nodes, which have features of small size, low power, low cost and multifunction. Sensor nodes usually have the ability of sensing, processing and transmitting monitored data to base station (BS) or sink node in a direct or multihop transmission manner. Finally, BS will transmit final data to some remote control station or administrative office. Because of the intrinsic nature of WSNs, such as self-organizing, infrastructure less, local collaboration and fault tolerance, they have been widely utilized to applications such as environment monitoring and forecasting, military surveillance and tracking, wildlife protection, home automation and healthcare [1, 2].

One of the most significant restrictive factors for WSNs is the limited battery power of sensor nodes. Because sensor nodes are usually randomly deployed in inaccessible terrains, it is unlikely to recharge them [3, 4]. Thus, energy resource of sensors should be managed efficiently to extend the network lifetime.

Many energy-efficient routing algorithms and protocols have been proposed for WSNs in recent years. However, most of these studies assume that sink node is fixed either inside or outside the

*Correspondence to: Sungyoung Lee, Department of Computer Engineering, Kyung Hee University, Suwon, Korea.
†E-mail: sylee@oslab.khu.ac.kr

WSNs [5–8]. Because nodes close to sink have to participate in forwarding data to the sink node for other sensors, they will deplete their energy more quickly, and it will lead to the hot spots problem [9].

The idea of exploiting mobile sinks rather than static sinks to extend network lifetime for WSNs has attracted much attention recently [10]. It is better to deploy mobile sink nodes rather than mobile sensor nodes for WSNs, which is easier to implement. Because sensor nodes close to mobile sink nodes may change from time to time, energy consumption among sensor nodes can be balanced, and the hot spots problem can get mitigated. As a result, the network lifetime can be largely prolonged. Some other benefits of using mobile sinks include increased throughput and decreased latency if the sink moving strategies are carefully designed.

In this paper, multiple mobile sinks rather than one static sink will be utilized to improve WSNs performance. Mobile sinks will move with constant speed along predetermined paths and sojourn at some fixed points to collect interested raw data. Here, one of the paths is the diameter of the circle area, and the other two are fixed on arc lines. We divide the whole network into two main parts: the concentric circle of the area with radius r and the rest part of the area. When the mobile sink sojourns at the center of the circle area, it will collect relevant data from sensor nodes in the first part, and when the mobile sinks reach the other fixed points, they will collect data from sensor nodes in the second part.

The rest of this paper is organized as follows. In Section 2, we give an introduction about some related work. Section 3 presents the system model, which includes the network model and energy model. In Section 4, our proposed multiple mobile sink-based routing (MMSR) algorithm for data dissemination is described in detail. Section 5 provides extensive simulation results. Further discussions are presented in Section 6, and Section 7 concludes this paper.

2. RELATED WORK

The idea of using mobile sink for WSNs was first proposed in [11] where authors called them ‘data MULEs’. The MULEs move randomly through the network to pick up data in their close range and then drop off the data to some access points. In addition, communication among MULEs is also allowed. Because the transmission range is short, energy consumption for sensor nodes can be largely reduced. However, as the movements of MULEs cannot be predicted, sensor nodes cannot know the exact time when MULEs will come.

The authors in [12] treated lifetime maximization as a min–max problem and jointly studied the sink mobility and routing strategy. Their analytical results suggested that mobility did help to optimize the network lifetime. They claimed that when the sink is static, it should be deployed at the center of a circular area to get the best performance. They proved that when the sink is mobile, the best mobility strategy consists in following the periphery of the network.

In [13], the authors studied the WSN with one mobile sink and one mobile relay individually, and simulation results demonstrated that the improvement in network lifetime over the all static network was upper bounded by a factor of four. They also proved that the mobile relay needs to stay only within a two-hop radius of the sink.

In order to access all sensor nodes in the targeted networks, a novel method was proposed in [14], which is based on set packing algorithm and traveling salesman problem to improve efficiency as well as fairness of data gathering.

An intelligent agent-based routing protocol was proposed by authors in [15], which can provide efficient data delivery to mobile sinks. Through both mathematical analysis and simulation experiments, this protocol was proved to support sink mobility with low overhead.

To solve the data delivery problem in large-scale WSNs with mobile sinks, the authors in [16] proposed a novel data collection scheme called maximum amount shortest path. This scheme simultaneously improves the total amount of data and reduces the energy consumption.

In [17], the authors claimed that there is a lack of systematic analysis on behaviors of mobility-assisted data collection (MADC) schemes as per throughput and lifetime. They first proposed a general MADC model that included some important parameters such as the number of mobile sinks

DOI: 10.1002/cpe

and the traveling path. Besides, they developed a theoretical method to obtain achievable throughput and network lifetime.

In [18], the authors proposed a solution to change the location of mobile sinks when their nearby nodes' energy became low. Mobile sinks search for zones with higher energy to determine their new location.

Based on the geographic routing protocol Greedy-FACE-Greedy (GFG), the authors in [19] proposed a novel localized integrated location service and routing (ILSR) scheme for data communications from sensor nodes to a mobile sink in WSNS. In ILSR, sink updates location to neighboring nodes after or before a link breaks and whenever a link creation is observed. They also proposed two versions, considering both predictable and unpredictable sink mobility, and both of them can guarantee delivery in a connected network modeled as unit disk graph.

A simulation-based analysis of the energy efficiency of WSNs with static and mobile sinks was provided by the authors in [20]. They mainly focused on mobility path of the sink and duty cycling value of the nodes. The authors quantitatively analyzed the influence of duty cycling and mobility radius of the sink and their interrelationship in terms of energy consumption for a well-defined model scenario.

The general problem of sink mobility in the context of trade-offs between data delivery delay and network lifetime was first explored and categorized by the authors in [21]. They also proposed a novel mobility control solution in which the network nodes cooperatively determine the sink trajectory and navigate the mobile sinks for delay and energy optimized data collection.

In [22], the authors proposed a novel geographic routing for mobile sinks, which took advantage of wireless broadcast transmission nature of sensors. The new location information is propagated along the reverse geographic routing path to the source during data delivery as the sink moves. Simulation results were also presented to verify their approaches.

In [23], a unified framework for analyzing joint sink mobility and routing problem was proposed by the authors. They presented efficient solutions for the induced subproblems, generalized them and then proposed a polynomial-time optimal algorithm for the origin problem. Furthermore, the authors studied the effects of different trajectories of the sink and provided important insights for designing mobility schemes in real-world mobile WSNs.

In order to improve efficiency of collecting data from WSNs via a mobile sink, the authors in [24] presented an accelerated random walk on random geometric graphs. They defined and experimentally evaluated a novel random walk that they called γ-stretched random walk, the basic idea of which was to favor visiting distant neighbors of the current node toward reducing node overlap and accelerate the cover time. The authors also defined a new performance metric called proximity cover time, along with other metrics, to evaluate the performance of their proposed algorithm.

3. SYSTEM MODEL

3.1. Basic assumptions

We make some basic assumptions as follows:

- All sensor nodes are homogeneous, and each of them has a unique ID.
- All sensor nodes are stationary and location aware after deployment.
- There exists a multihop routing protocol. Here, shortest path routing protocol is used.
- Sink can be located at certain points, and it moves from one site to another via mobility control.
- Each sensor node generates equal amount of data per time with same data length.

3.2. Network model

In this paper, we assume that a set of sensor nodes are randomly dispersed within a circular field and continuously monitor the surrounding environment. The whole sensor network can be described as a graph $G = < S, E >$, where S and E represents the set of sensor nodes and the set

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of links (i, j), respectively. Here, i and j are neighboring nodes. Figure 1 demonstrates the network model. The sink node, which plays the role of BS, can move either along the diameter or the periphery of the circle.

3.3. Energy model

The first-order radio model [2] is used as the energy model in this paper. If the distance between the transmitter and the receiver is larger than a threshold d_0, the multipath model (d^4 power loss) is used; otherwise, the free space model (d^2 power loss) is used. Therefore, the energy spent to transmit an l-bit packet over distance d can be calculated as follows:

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

where E_{elec} denotes the electronics energy, which depends on factors such as the digital coding and modulation; ε_{fs} and ε_{mp} denote the amplifier energy to maintain an acceptable signal-to-noise ratio; and $d_0 = \sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ is a constant.

The energy spent to receive this message can be calculated as follows:

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

The energy spent to forward this message by intermediate node can be calculated as follows:

$$E_{Fr} = E_{Tx} + E_{Rx} \tag{3}$$

4. OUR PROPOSED MMSR ALGORITHM

In this section, we plan to use three mobile sinks to collect data from different areas of WSNs.

We divide the whole network into two main parts to collect data, as shown in Figure 2. The concentric circle of deployed area with radius r is represented as area A, and the other part is represented as area B, which is further divided into $B1$, $B2$, …, $B8$. One of the mobile sinks will move along the diameter of the circle, and the other two sinks will move along arc lines to collect data packets from sensor nodes.

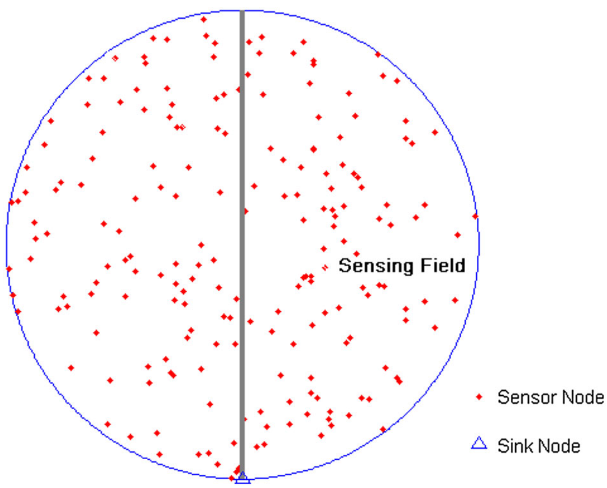

Figure 1. Network model.

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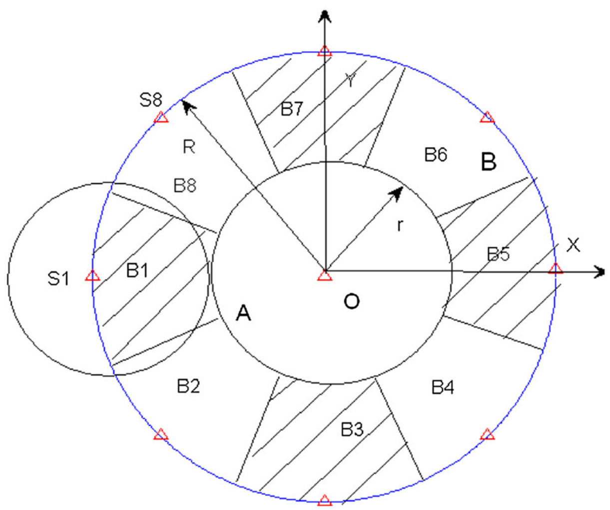

Figure 2. Network partition.

Each sensor node maintains two tables: sink table and route table. Sink table records whether there is a sink node in its transmission range, and if it is true, then the sink table will be marked with a flag NEIGHBOR_OF_SINK= TRUE; otherwise, the flag is set to FALSE. Route table records the next hop information of a sensor node to reach a sink. Next, we will present the trajectory of each mobile sink and how the data packets are forwarded by sensor nodes to sink nodes.

4.1. Mobility trajectory

The black thick straight line in Figure 3 is the diameter of the circle area, and it is one of the predetermined movement paths. The other two paths are represented by black thick arc lines. The mobile sinks will move back and forth along these paths and only sojourn at some fixed points to collect data packets from fixed areas of the network. For example, when a mobile sink sojourns at point O, it will only collect data from sensor nodes in area A. While it reaches point $S1$, only sensor nodes in area $B1$ will transmit data to it. A mobile sink will broadcast a hello message to its neighbors when it reaches the scheduled sojourn location. All the sensor nodes receiving this hello message will know that the mobile sink is in their transmission range and then forward their data packets to it.

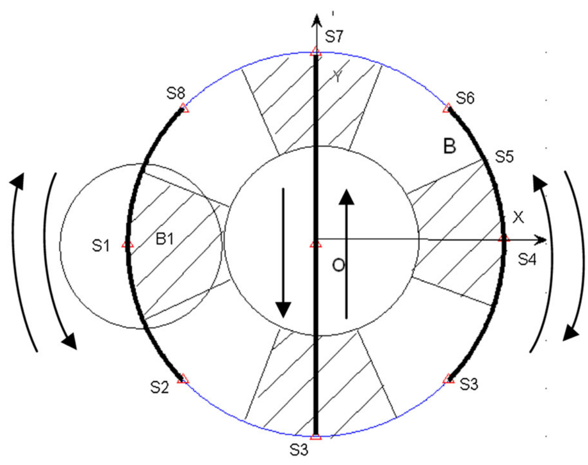

Figure 3. Mobility trajectory.

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As is shown in Figure 3, each predetermined path has three fixed points that mobile sink should sojourn at. We assume that it takes the same time to collect data packets form each area, which means that mobile sinks will sojourn at different points for the same time. In this paper, we use three mobile sinks to move along three predetermined paths respectively. Therefore, transmission delay can be significantly reduced, and the cost of adding three mobile sinks is also acceptable.

In order to further improve network performance and prolong network lifetime, the annulus area of the network can be divided into more small areas, and more mobile sinks can be utilized to move along the periphery of the circle and collect data from sensor nodes. However, more cost will be introduced, considering that mobile sink node is more expensive than normal sensor node. In the meantime, through simulation result, which is shown in Figure 4, we can find out that adding more mobile sink nodes can indeed improve network performance, but not significantly. Therefore, by synthetically considering the cost and performance of the network, we decide to use three mobile sinks to collect data in this paper.

4.2. *Data packets forwarding*

The shortest path routing protocol is used in this paper, which means that when a sensor node wants to send its data packet, it checks all its neighbors and find the one that is the nearest to the sink to be its next hop, which will be recorded in its route table.

Once a sensor node receives a data packet from its neighbor, it will first do data fusion and then look up sink table to find if NEIGHBOR_OF_SINK flag is true. If so, it means that it is a neighbor of the sink, and the data packet will be forwarded to the sink directly; otherwise, it will look up the route table to find the information of its next hop and then forward the data packet to that sensor node.

4.3. *Routing maintenance*

Route maintenance, by its name, should address the problem when a route becomes worse or even broken. It is obvious that as operation of sensor networks goes on, the residual energy of each sensor node decreases gradually. Therefore, in a certain round, some sensor nodes may die or have insufficient residual energy to forward data to its next hop. As a result, corresponding links will break, causing some areas to be unreachable and finally making data forwarding incomplete.

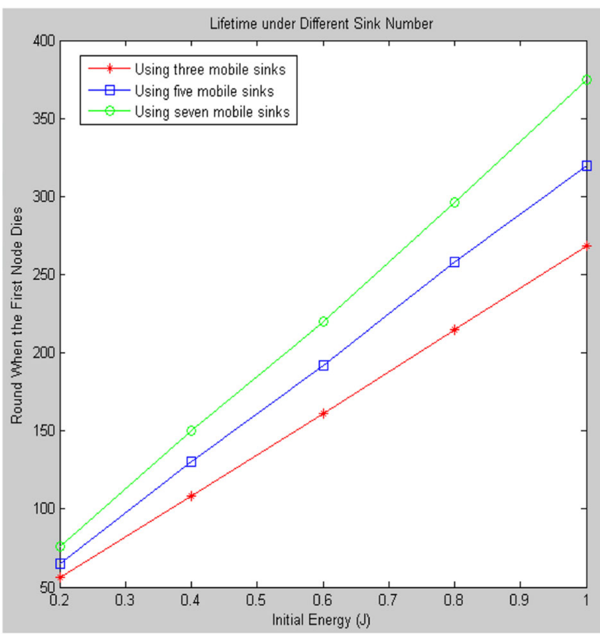

Figure 4. Lifetime under different sink number.

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In order to solve the problem mentioned earlier, substitute nodes should be selected to forward data instead of the dead nodes or nodes with insufficient residual energy. The flowchart of route maintenance is shown in Figure 5. From this flowchart, we can find out that before sending out a data package, a sensor node will check whether it has sufficient residual energy or not. It will send out a STOP_MSG message to its neighbor nodes and delete itself from the network if its residual energy is insufficient to send the data package. Those sensor nodes receiving this message will delete this sensor node from their neighbors. After confirming that it has sufficient

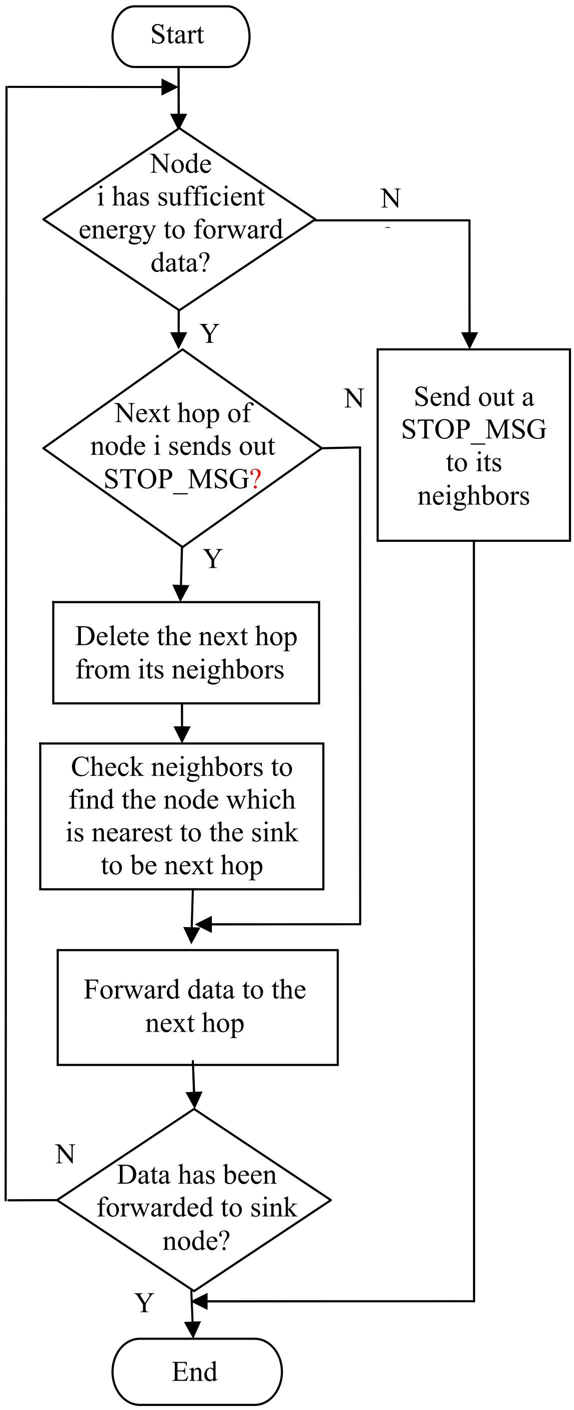

Figure 5. Flowchart of route maintenance.

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residual energy, this sensor node will check whether it has received a STOP_MSG message from its next hop or not. If the answer is yes, which means its next hop node has died, then this node will first delete it from its neighbors and then check all its neighbors to find the one that is the nearest to the sink to be its next hop. In the end, this sensor node will just forward data package to its next hop.

Through this mechanism, sensor nodes with insufficient residual energy will be deleted from the network and will not participate in forwarding data packages. As a result, the route will be maintained, and the possibility of losing date packages will be reduced.

5. PERFORMANCE EVALUATION

5.1. Simulation environment

In this section, we use MATLAB to evaluate the performance of our proposed algorithm. Assume that 400 sensor nodes are randomly deployed within a circular field where the radius is 400 m. The relevant simulation parameters are listed in Table I.

5.2. Performance analysis

In order to analyze the network performance, we compare our proposed algorithm with three other different algorithms: using only one static sink in the center of the network; using three mobile sinks, which trisect the circle and move along the periphery of the network; and using three mobile sinks, which move randomly in the network. For simplicity, the second and third algorithms will be represented by Mobile-Periphery and Mobile-Random in the rest of this paper.

Network lifetime is an important scale to evaluate the performance of WSNs. Here, we define network lifetime as the round when the first node depletes its energy. We first analyze the network lifetime in different conditions, as is shown in Figure 6. Clearly, Mobile-Periphery has a longer network lifetime than Mobile-Random and the algorithm using one static sink. Meanwhile, we can find out that our proposed algorithm has the best performance. This figure also shows that as the round number increases, the nodes die much slower in our proposed algorithm.

The relation of the network lifetime and initial energy is shown in Figure 7. We see that lifetime increases as the initial energy increases accordingly. The increasing speed of our proposed algorithm is higher than the other three algorithms, which means the more initial energy the network is given, the better performance our proposed algorithm will have.

Figure 8 shows the comparison of our proposed algorithm with the other three algorithms in terms of residual energy. In our algorithm, three mobile sinks move along the predetermined paths and can sojourn at nine different fixed points to collect data. Therefore, the traffic load in our proposed algorithm is more balanced than the other three algorithms. Meanwhile, because the whole network

Table I. Simulation parameters.

Parameter	Definition	Unit
N	Number of sensor nodes	400
R	Network radius	400 m
r	Radius of inner circle area	200 m
E_0	Initial energy of nodes	0.5 J
R_0	Transmission radius	50 m
E_{elec}	Energy dissipation to run the radio device	50 nJ/bit
ε_{fs}	Free space model of transmitter amplifier	10 pJ/bit/m^2
ε_{mp}	Multipath model of transmitter amplifier	0.0013 pJ/bit/m^4
l	Packet length	1000 bits
d_0	Distance threshold	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}}^{\text{mp}}$ m

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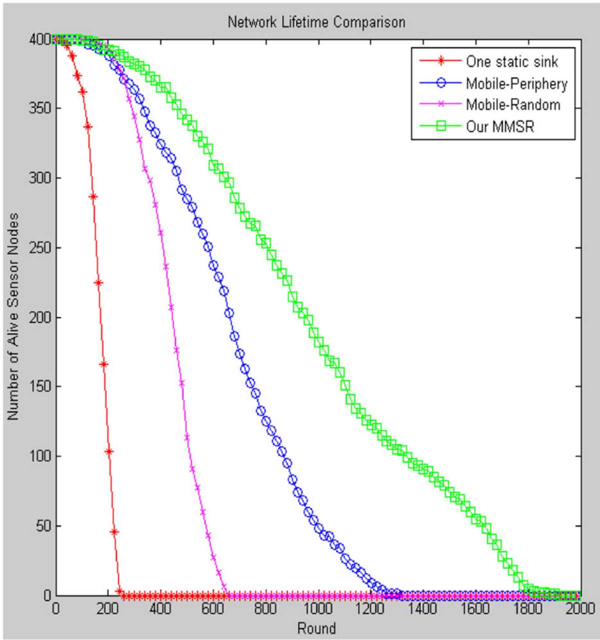

Figure 6. Lifetime comparison.

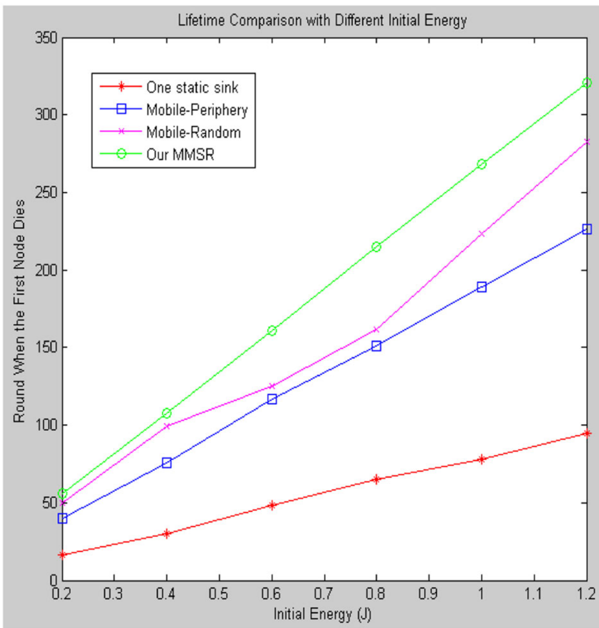

Figure 7. Lifetime comparison with different initial energy.

has been partitioned into several parts and sensor nodes in different areas only need to forward their data to relevant mobile sink with shorter transmission distance, more energy can be saved.

Comparison of packets sent to BS (sinks) with different schemes is shown in Figure 9. We assume that each sensor node generates an equal amount of data per time. Therefore, before the first node dies in the scheme using only one static sink, the numbers of packets sent to BS with different schemes are the same. However, because sensor nodes die much slower in our scheme than the other three algorithms, the number of packets sent to BS using our scheme is the largest.

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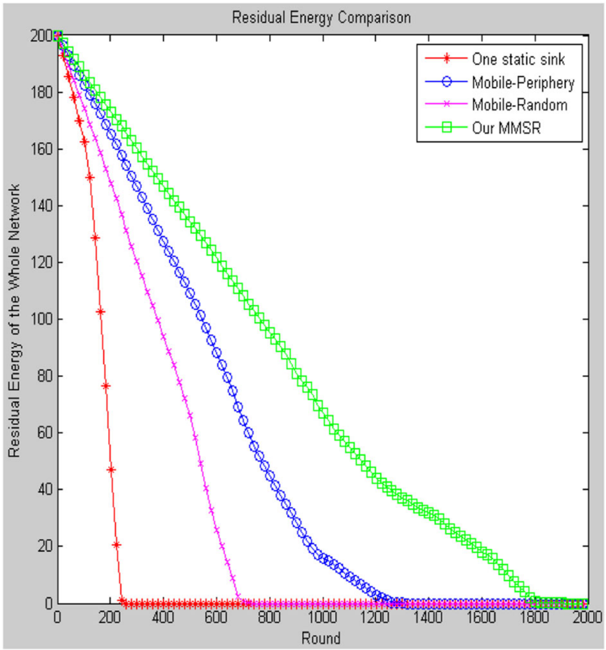

Figure 8. Residual energy comparison.

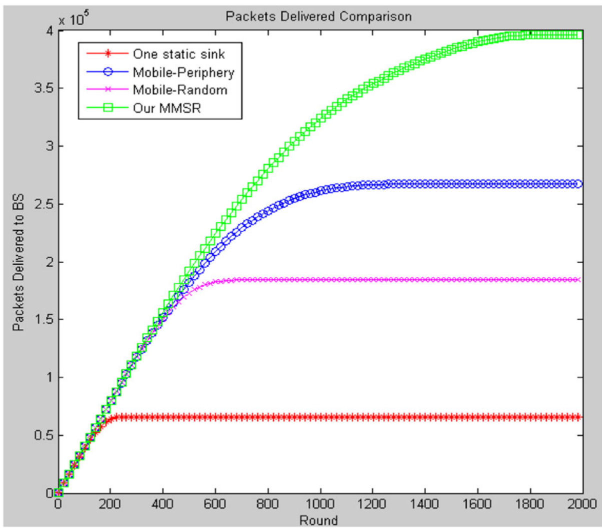

Figure 9. Packets delivered comparison.

Transmission delay is an important measurement for WSNs. We define transmission delay as the maximum hop number from source to BS. In Figure 10, the maximum hop number of different methods and transmission range is illustrated. We can see from this figure that the transmission delay decreases when the transmission range becomes larger because the shortest path routing protocol is used in this paper. As shown in the figure, the transmission delay of using only one static sink is about two times of using our proposed algorithm.

It is worth noting that we introduced three mobile sink-based data collection mechanisms for WSNs with better network performance than the other three cases we mentioned. In the meantime, more cost will also be introduced because the sink node is more expensive than normal sensor nodes. On the basis of the simulation results and analysis, we can claim that our multiple mobile sinks scheme is applicable by considering both network performance and system cost increase.

DOI: 10.1002/cpe

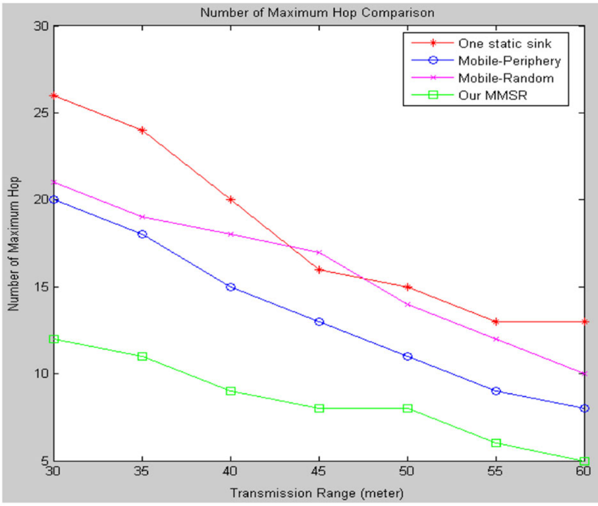

Figure 10. Maximum hop number comparison.

6. DISCUSSION

Exploiting mobile sinks, instead of static ones, to collect data for WSNs has been shown to be an effective method to shift the burden of acquiring data from sensor nodes to sink nodes. As a result, hot spots problem can be mitigated, energy consumption among sensor nodes can be balanced and thereby network lifetime can be prolonged to a great extent. Moreover, increased throughput and data fidelity can be achieved by utilizing mobile sinks to collect data from sensor nodes.

However, the number of mobile sinks should be decided appropriately because they cost much more than normal sensor nodes. In this paper, we use three mobile sinks to collect data from normal sensor nodes, which is acceptable for the object to improve network performance.

An important assumption we have made is that it takes the same time to collect data packets from each area, which means that mobile sinks will sojourn at different points for the same time. However, in real deployment, this is usually unrealistic. Thus, how long should mobile sinks sojourn at different points needs to be considered. We also made some other assumptions, such as sensor nodes are stationary and location aware, which limit the scalability of the algorithm. Thus, we should improve our algorithm with few assumptions in the future.

7. CONCLUSIONS AND FUTURE WORK

It is a wise choice to employ multiple mobile sinks to WSNs in order to prolong network lifetime. In this paper, we proposed our MMSR algorithm for data dissemination in WSNs, where three mobile sinks move along predetermined paths to collect data from sensor nodes. Simulation results validate the performance of our proposed MMSR.

In the future, we plan to study how our algorithm will work under larger-scale network environment. We are also studying sink movement strategies with proper sink number and velocity, among others.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (61070133, 61271240 and 61311140264) and the Natural Science Foundation of Jiangsu Province (BK2012461). It was also supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (2011-0030823), the industrial Strategic Technology Development Program (10041740) by MOTIE Korea, a Nanjing University of Information Science and Technology project (S8110246001) and the PAPD.

DOI: 10.1002/cpe

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