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An Energy Efficient and Load Balancing Routing Algorithm for Wireless Sensor Networks

Jin Wang[1,2], Tinghuai Ma[1], Jinsung Cho [2], and Sungoung Lee[2]

[1] Jiangsu Engineering Center of Network Monitoring, Nanjing University of Information Science & Technology, 210044, Nanjing, China
{wj0514, ma_tinghuai}@hotmail.com
[2] Department of Computer Engineering, Kyung Hee University, 449-701, Yongin City, South Korea
chojs@khu.ac.kr; sylee@oslab.khu.ac.kr

Abstract. Many energy aware routing algorithms and protocols have been proposed for wireless sensor networks recently to achieve aims like minimum energy consumption, maximized network lifetime, reduced communication latency and overhead etc. The problem of hotspot can not be well addressed under many routing algorithms since some nodes which are on the shortest path or close to the base station tend to deplete their energy quickly and consequently cause network partition. In this paper, we propose a Ring-based Energy Aware Routing (REAR) algorithm for wireless sensor networks which can achieve both energy balancing and energy efficiency for all sensor nodes. Our algorithm considers not only the hop number and distance but also the residual energy of the next hop node during routing process. Simulation results validate that our algorithm outperforms some other routing algorithms in the aspects of energy consumption and network lifetime etc.

Keywords: wireless sensor networks, hop number, energy efficiency, energy balancing, network lifetime.

1. Introduction

Wireless sensor networks (WSNs) are composed of huge number of sensor nodes which can monitor the environment by collecting, processing as well as transmitting collected data to the remote sink node through direct or multi-hop transmission. WSNs have attracted lots of attention in recent years due to their wide applications such as battlefield surveillance, inventory and wildlife monitoring, smart home and healthcare etc [1].

Since the tiny sensor nodes are powered by limited battery resources, energy efficiency is one of the primary challenges to the successful application of WSNs. Usually energy is consumed during three processes which are sensing, processing and communication process. Here, we only focus on energy consumption during communication process since it prevails over the other two processes.

Many energy aware routing algorithms or protocols have been proposed for WSNs in recently years [2-22]. Among these routing algorithms, techniques like data aggregation [3-5], clustering [6-11], evolutionary based algorithms [12-15] are adopted to achieve better energy efficiency. However, many of these algorithms aim to minimize metrics such as energy consumption, latency during routing process, which will cause certain hotspot nodes as well as partitioned network area due to the overuse of certain nodes on shortest path or close to the BS. Since the network lifetime is usually defined as the time when the first node dies from lack of energy, huge amounts of energy will be wasted by the remaining sensor nodes when the first node dies.

To efficiently mitigate the hotspot problem which is caused by imbalanced consumption of energy among sensors, the network metrics like hop number, hop distance as well as remaining energy need to be carefully considered. In fact, these network metrics have very important impact on network performance such as energy consumption, network lifetime, routing overhead, latency and interference etc [16]. Intuitively, if the hop number is too large, the energy consumption can be reduced at the cost of long end-to-end latency and large control overhead. If the hop number is too small (e.g., direct transmission), the latency will be very small while the energy consumption can be very large due to the nature of long distance wireless communication. Thus, an optimal hop number with suitable individual distance can be deduced to achieve energy reduction and energy balancing. The authors in [17-19] study the energy consumption from a new viewpoint by studying the transmission manner which proves to be effective.

Based on our previous work, we try to achieve both energy efficiency and energy balancing from hop and distance based point of view in this paper. We first deduce a suitable hop number with individual distance based on our theoretical analysis of energy and traffic models. Then, we propose our Ring-based Energy Aware Routing (REAR) algorithm which considers not only hop number and hop distance but also the residual energy during routing process.

The remainder of the paper is organized as follows. Section 2 presents some related work. Section 3 gives the theoretical deduction of hop number and hop distance based on the energy and traffic models. In Section 4, the REAR algorithm is proposed and Section 5 provides extensive simulation results. Section 6 concludes this paper and gives some future work.

2. Related Work

A survey about different routing protocols in sensor networks is given in [2] which classifies traditional routing algorithms into three types, namely data-centric, hierarchical and position-based routing algorithms. Direct Diffusion [3] is viewed as a representative data-centric routing protocol for flat structure

WSNs. The data generated by sensor nodes is named by attribute-value pairs. Once a sink node inquires certain type of information, it will send a query and the observed data will be aggregated and transmitted back to the sink node. Rather than always using the lowest energy paths, the authors in [4] use sub-optimal paths occasionally so that the network lifetime is increased by 40% compared to [3]. In [5], the authors propose a centralized and decentralized routing protocols named UBERP by carefully selecting the transmission path with residual energy larger than certain threshold.

Hierarchical routing protocols [6-11] are very suitable for WSNs since they can not only provide good scalability but also perform data fusion by each cluster head. LEACH [6] can prolong network lifetime to 8-fold more than other ordinary routing protocols. However, 5% of cluster head nodes are randomly chosen and cluster head nodes use direct transmission. PEGASIS [7] is viewed as an improved version of LEACH. It is a chain based routing protocol which can save more energy compared to LEACH. HEED [8] considers the residual energy as the primary parameter and a secondary parameter like node's degree etc. ERA [9] is similar to [6] during route setup phase while energy balancing is achieved during cluster head association phase since each node selects its cluster head with maximum residual energy. DHAC [10] provides a simple six-step bottom-up clustering method rather than traditional top-down methods with better network lifetime performance. The authors in [11] try to distribute energy load among all sensors in order to achieve both energy efficiency and lifetime maximization.

An improved version of LEACH is presented in [12] to improve energy efficiency and system stability by using genetic algorithm (GA) during the selection of cluster heads. In [13], each swarm agent can carry and exchange the residual energy information during route selection process to maximize network lifetime in ad hoc and sensor networks. In [14], an improved ant colony optimization (ACO) method is applied to the communication network routing problem with better performance in terms of hop number. An energy balanced unequal clustering protocol is proposed in [15] with particle swarm optimization technique so that the hot-spot problem is avoided and network lifetime is prolonged.

The authors in [17] present some pioneering work by studying different energy models under general wireless network environment. In [18], the authors use a probability of P_i to transmit data through multi-hop manner and a probability $(1-P_i)$ to transmit through single hop to sink node. The authors in [19] also study the energy consumption under both single hop and multi-hop transmission. They claim that the preference of multi-hop routing to single hop routing depends on source to sink distance and reception cost. In [20,21], the authors study the energy consumption from hop and distance point of view and propose a hop-based energy aware routing algorithm which can reduce energy consumption and prolong network lifetime effectively. The authors in [22] consider the hot-spot phenomenon and propose a load balancing data gathering algorithm which classifies sensors into different layers based on their distance to sink node.

In this paper, we aim to achieve both energy efficiency and balancing by building BS oriented ring structure in a centralized manner from BS side. The BS determines the ring size as well as final route from source node to BS.

3. Theoretical Analysis

3.1. Network Model

The traditional WSNs can be viewed as an undirected graph G = <V, E> where V represents the set of vertices and E represents the set of edges. We assume there are N nodes randomly placed in an area $[X, Y]$. There exists a link $E(i, j)$ between node i and node j if the Euclidean distance $d(i, j)$ is not larger than the radio transmission radius R. Here, undirected graph means bi-directional communication link. In other words, if node j can receive packet from its neighboring node i, it is believed that node i can receive packet from node j in a reverse way. The objective in this paper is to find a set of optimal or sub-optimal individual distances during routing process so that the energy is consumed at similar rate for all involved sensors.

3.2. Energy Model

The first order radio model is commonly used as an energy consumption model [6, 8, 17, 20]. Based on this model, radio consumes E_{Tx} amount of energy to transmit a l bits message over a distance of d :

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

and E_{Rx} amount of energy to receive this message:

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

and E_{Fx} amount of energy to forward this message:

$$E_{Fx}(l,d) = E_{Tx}(l,d) + E_{Rx}(l) = \begin{cases} 2l \cdot E_{elec} + l \cdot \varepsilon_{fs} \cdot d^2 \\ 2l \cdot E_{elec} + l \cdot \varepsilon_{mp} \cdot d^4 \end{cases} \quad (3)$$

Definition of radio parameters above are the same as [6, 8, 20] etc.

3.3. Theoretical Analysis

For simplicity, we first study energy consumption under one dimensional linear network which can be used in linear applications such as highway monitoring, congestion control etc.

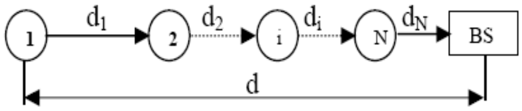

Fig. 1. One dimensional linear network

In Fig.1., there are N sensors randomly placed along a line from source node 1 to the BS with individual distance $\{d_1, d_2, ...d_i, d_N\}$, and $\sum_{i=1}^{N} d_i = d$. Now, we suppose each node takes turn to transmit its l bits message via direct or multi-hop transmission to the BS. In Fig. 1. we find that node N will forward the data for $(N-1)$ times and node i will forward $(i-1)$ times. If we let $d_1 = d_2 = ... = d_N = d / N$, node N will become hotspot node and dies quickly. Here, our objective is to find the set of individual optimal distance $d_1, d_2, ..., d_N$ as well as the optimal or sub-optimal hop number N so that $E_1 = E_2 = ... = E_N$. In the mean time, we try to let each involved nodes consume the least energy in order to achieve energy efficiency.

For certain forwarding node i, the energy consumed for both receiving and then transmitting the data will be:

$$E_i = l \cdot (E_{elec} + \varepsilon_{amp} \cdot d_i^{\alpha}) + l \cdot (i-1)(2E_{elec} + \varepsilon_{amp} \cdot d_i^{\alpha}) = l \cdot (2i-1)E_{elec} + l \cdot i \cdot \varepsilon_{amp} \cdot d_1^{\alpha} \quad (4)$$

Here, $\varepsilon_{amp} = \varepsilon_{fs}$ when $\alpha = 2$ and $\varepsilon_{amp} = \varepsilon_{mp}$ when $\alpha = 4$.

Let $E_{i+1} = E_i$, we can finally get:

$$d_{i+1} = \sqrt[\alpha]{\frac{-2E_{elec} + i\varepsilon_{amp} d_i^{\alpha}}{\varepsilon_{amp}(i+1)}} = \sqrt[\alpha]{\frac{-2iE_{elec} + \varepsilon_{amp} d_1^{\alpha}}{\varepsilon_{amp}(i+1)}} \quad (5)$$

Since $d_n > 0$, it must satisfy:

$$d_1 > \sqrt[\alpha]{\frac{2(n-1)E_{elec}}{\varepsilon_{amp}}} \quad (6)$$

Given multi-hop number n, we can get the lower bound of distance value d_1 as well as the minimal source to sink node distance $d = \sum d_i$. Here, we let $E_{elec} = 50nJ/bit$, $\alpha = 4$ and $\varepsilon_{amp} = 0.001pJ/bit/m^4$.

On the other hand, given the source to sink node distance d, there might be several multi-hop routes with different hop number n. For example, when d = 300, we can use either 2-hop or 3-hop route to achieve energy balancing. If the hop number $n \geq 4$, the minimal $d = \sum d_i \geq 307.6$ which is contrary to d = 300. Thus, there exists a highest hop number route with minimal energy consumption for each sensor node and this is the multi-hop route we need. For example, when d = 800, we can either choose an 8-hop route with $d_1(8)$ = 164.8 or choose one 7-hop route with $d_1(7)$ = 170.5. The corresponding individual distance d_i can be deduced from Equation (5).

From the analysis of energy consumption above, we can see that the suitable multi-hop route with hop number n as well as corresponding individual distance d_i can be achieved to gain energy balancing with $E_1 = E_2 = ... = E_N$ when the source to BS distance d is given. In the mean time, we try to find multi-hop route with more intermediate nodes involved in order to gain energy efficiency. Thus, our REAR algorithm below can be both energy balancing and efficient if the routing algorithm is carefully designed.

4. Our REAR Algorithm

4.1. Basic Assumptions

We make the following basic assumptions:
1) All sensor nodes are static and homogeneous after deployment.
2) The communication links are symmetric.
3) Each sensor node has several power levels which they can adjust.
4) Each sensor node can know the distance to its neighbors and to the BS.
5) There is no obstacle between nodes.

In this paper, we do not consider mobile sink nodes or mobile sensor nodes and all the homogeneous sensors are randomly deployed and left un-attended after deployment. We assume the link is symmetric which means if node i can receive a message from its neighbor node j then node j can also get a message from node i. As is shown in many papers, current sensor nodes can have several transmission power levels so that they can dynamically adjust its power to its neighboring node to save energy. By adopting some localization or positioning techniques, the sensors can know its relative distances to its neighbors as well as to the BS. Also, we do not consider obstacles between nodes even though our algorithm can avoid this phenomenon by choosing another alternative neighboring node as a solution. It is worth noting that we make no assumption of the uniform distribution of sensor nodes or the knowledge of global network topology here.

4.2. Route Setup Phase

Once some source node has data to send, it will select its next hop node and try to set up a route from itself to the BS as follows.

Route Setup Phase Algorithm

Begin

Source node i has data to send to BS

if $d_{i,BS} < \sum d_i(1) = 100$ *then*

    direct transmission

else

  Source node i broadcasts multi-hop request to BS

  BS determines optimal hop number n and distance $[d_1 : d_n]$

  BS builds ring structure with

      $r_1 = d_1$

      $r_2 = d_1 + d_2$

    until $r_n = d_1 + ... + d_n = d_{i,BS}$

  BS classifies sensors into different levels based on ring size

    if $d_{k,BS} \le r_1$ *then*

      node $k \in$ Level 1

    elseif $r_{k-1} < d_{k,BS} \le r_k$ $(k \ge 2)$

      node $k \in$ Level k

    end

  BS determines the final route of node i as follows

    i chooses its neighbors set A with $d_{i,j} \in (d_n, d_n + \Delta]$, $j \in A$

    i chooses its neighbors sub-set $B \in A$ where node $k \in$ Level $(n-1)$

    i chooses its final neighbor $j^* \in C$ with maximal residual energy

  node j^* finds its final next hop in an iterative way like node i until BS

  BS send the final multi-hop route with individual nodes to source node i

$end-if$

Source node i start sending its data to BS based on the route table

End

Fig. 2. Route setup phase algorithm

As is shown in Fig. 2., the source node will first determine the transmission manner. Namely, if the source to BS distance $d < \sum d_i(1)$, source node will use direct transmission (line 3) to send its data to the BS. Or else, it will broadcast a multi-hop request to BS (line 5).

When BS receives the multi-hop request from source node, it will determine the final multi-hop route with the optimal number n and individual distance $\{d_1 \ldots d_N\}$ (line 6), based on the source to BS distance. Then, it will build a ring structure with different ring size (line 8-10). Next, it will classify sensor nodes into different levels based on ring size (line 11-16).

Once the sensors are associated with different levels, BS will determine the final multi-hop route as follows. First, it will choose some candidate next hop nodes of source node with distance $d_{i,j} \in (d_n, d_n + \Delta]$ (line 18). Here, Δ is used under practical random network topology. Within these candidates, BS will choose those which belong to level $(n-1)$ to make progress from source to BS (line 19). Finally, BS will choose the one from level $(n-1)$ with maximal remaining energy as the final next hop node (line 20).

BS will perform the same process in a similar way for the next hop node until a multi-hop route from source to BS is built (line 21). Finally, BS will send the complete multi-hop route information to the source node (line 22). Source node will start the transmission of its data when it receives the complete multi-hop route information (line 24).

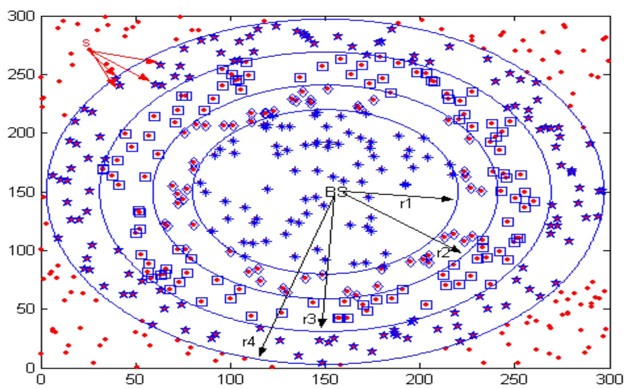

Fig. 3. BS oriented ring structure in WSNs

It is worth noting that the multi-hop route is built by BS in a centralized way due to the fact that BS has more powerful resources such as memory, computation and communication etc. We treat the hop number and individual distance as the primary metric during the selection of next hop. In the mean time, we treat the remaining energy as the secondary metric during the selection of the final nodes from many candidates (line 20).

From Fig. 3. we can see the building of BS oriented ring structure multi-hop route more clearly. BS will determine the multi-hop route from source node until itself as follows. First, source nodes selects its candidate neighbors which belong to level $(n-1)$ with distance $d_{i,j} \in (d_n, d_n + \Delta]$. Then, it will choose the one with maximal remaining energy as the final next hop node. This process will continue in an iterative way until the BS.

4.3. Route Maintenance Phase

A link failure is usually caused by reasons like the depletion of energy, physical damage, and mobility of certain nodes or BS etc. Due to the centralized routing nature in our REAR algorithm, BS will always choose the node with high remaining energy to ensure the multi-hop route reliability. In other words, the link failure probability is relatively low until most of the nodes run out of energy. From the simulation part, we can also validate this point.

5. Experimental Results

5.1. Simulation Environment

There are N nodes randomly deployed in a WSNs area. The BS is placed either inside or outside the monitoring area. In each round, each sensor node takes turn to transmit their 2000 bits message to the BS with either direct transmission or multi-hop transmission. Some of the simulation parameters are listed in Table 1.

Table 1. Simulation Environment

Parameter	Value
Network size	$300 \times 300\, m^2$
Number of nodes	300
Transmission radius R	[50, 140] m
Initial energy	2 J
BS location	inside and outside
Data size	2000 bits
Δ	[20, 40] m

We compare our REAR algorithm with three other existing algorithms which are direct transmission, greedy algorithm and max-remaining energy (MRE) algorithm. In direct transmission algorithm, all sensor nodes simply transmit their message directly to the BS. This algorithm is simple and energy efficient when the network scale is small. In greedy algorithm, each node prefers to choose its neighbor which is closest to the BS as its next hop neighbor. This algorithm can be energy efficient when the transmission radius is carefully designed. In MRE algorithm, the neighboring node with high residual energy will be chosen as next hop in order to prolong network lifetime. It is worth noting that some of these factors such as distance and residual energy can be jointly considered which can further reduce energy consumption and prolong network lifetime.

5.2. Study of Hop Number

Fig. 4. shows the average hop number for 4 algorithms where BS is placed in the middle of the area. The transmission radius R is varying from 50 to 140 meters and $\Delta = 40$.

We can see from Fig. 4. that the average hop number decreases as the transmission radius R increases. Greedy and REAR algorithms have almost the same performance when $R \leq 100$. When $220 \leq R \leq 140$, our REAR algorithm is better than greedy algorithm and when $R \geq 140$, greedy algorithm has a shorter hop number than REAR at the cost of more energy consumption.

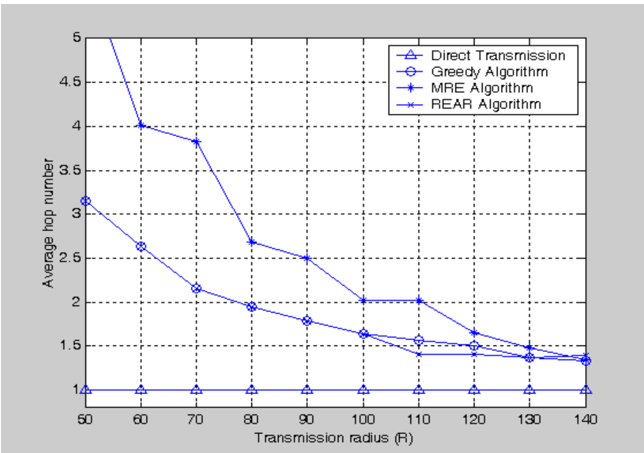

Fig. 4. Average hop number under different R

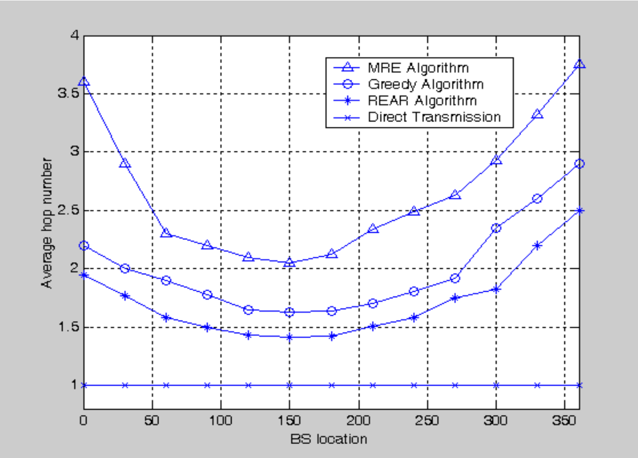

Fig. 5. Average hop number under different BS location

Fig. 5. shows the average hop number for 4 algorithms under the same simulation environment as Fig. 4., where BS moves along the diagonal line from position (150, 0) to (150, 360) with step size 30.

From Fig. 5. we can see that it is nearly symmetric based on line $x = 150$ as BS moves from (150, 0) to (150, 360). When BS moves from (150, 150) to (150, 360), the average hop number increases since the average source to BS distance is getting larger. It is worth noting that the x label value in Fig. 5. means the y coordinate of BS location here.

5.3. Study of Energy Consumption

Fig. 6. shows the energy consumption under different source to BS distance d with similar simulation environment to Fig. 4 and 5. Here, the BS is placed in the middle of the area. The transmission radius $R = 110$ and $\Delta = 20$.

From Fig. 6. we can see that when $d \le R = 110$, direct transmission manner can be chosen by all these 4 routing algorithms and they have almost the same energy consumption which is also very small. When $d > 110$, direct transmission is not possible for the other 3 routing algorithms except direct transmission. Direct transmission consume the largest energy since multi-path model is used under which power attenuates in the fourth order of distance. The performance of MRE and greedy algorithms are in the middle while our REAR algorithm consumes the least energy.

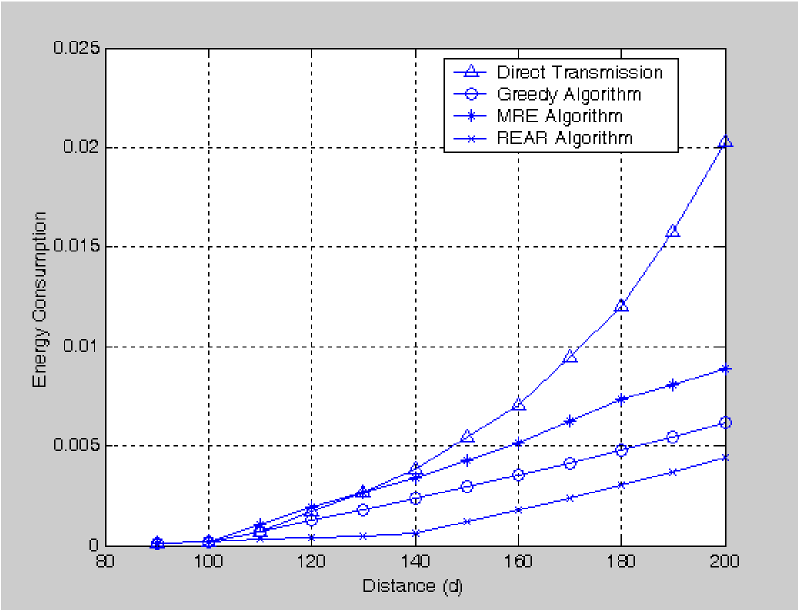

Fig. 6. Energy consumption under different d

In Fig. 7. we study the energy consumption under different BS location. The simulation environment is also similar to Fig. 4 to 6. where BS moves along the diagonal line from position (0, 0) to (300, 300).

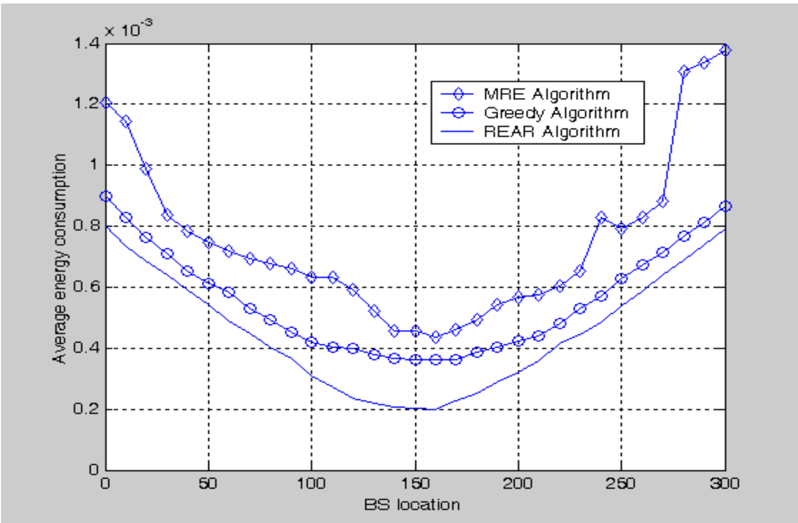

Fig. 7. Energy consumption under different BS location

From Fig. 7. we find that the distribution of energy consumption for the 3 algorithms is almost symmetric based on line $x = y$ and the minimal energy consumption can be achieved if BS is placed at (150, 150) (middle of WSNs). It is easy to understand the symmetry property from energy consumption model since the average energy consumption tends to get the minimum value when BS is located at the center of network area. It is worth noting that we do not compare with the direct transmission algorithm since it is relatively large and the symmetry property is not very clear as BS moves.

5.4. Study of Average Network Lifetime

We define the network lifetime as the time when the first sensor node dies out of energy. We compare the average network lifetime under similar network environment to Fig. 4. to 7. The simulation is done under 100 different network topologies to see an average performance and $R = 110$ and $\Delta = 20$.

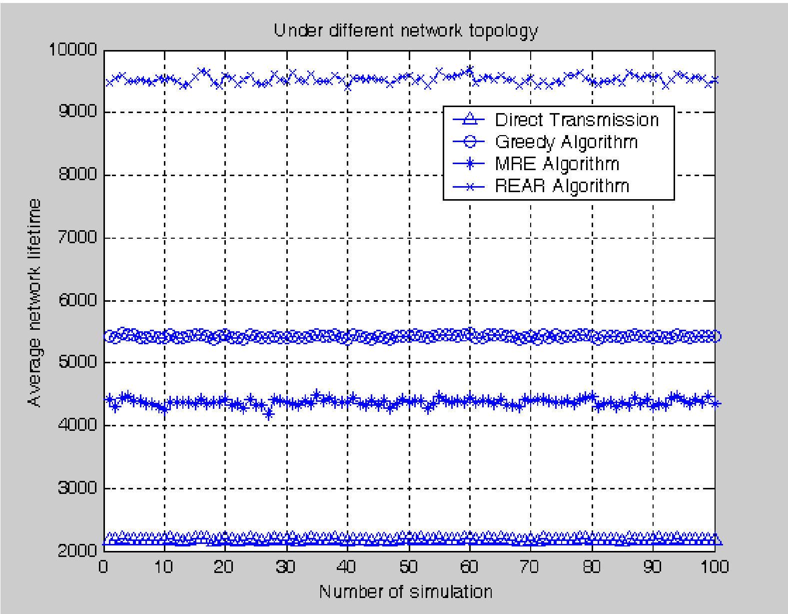

Fig. 8. Average network lifetime under different topology

From Fig. 8. we can see that our REAR algorithm has the longest lifetime while direct transmission algorithm has the worst average network lifetime. The reason lies in the average energy consumption mechanisms of each algorithm, as we have explained. It is worth noting that our REAR algorithm has a factor of 2 to 4 times longer network lifetime than the other 3 routing algorithms on average.

From the simulations results in Fig. 4 to 7, we can seen that our REAR algorithm can achieve both energy balancing and energy efficiency as comparing with other routing algorithms. We only focus on studying energy efficient routing mechanism from appropriate hop number and distance point of view in this paper and do not consider clustering and data fusion here.

6. Conclusions and Future Work

We propose a ring-based energy aware routing (REAR) algorithm for WSNs in this paper which can achieve both energy efficiency and balancing from hop number and distance point of view. Given the source to sink node distance, the multi-hop number and corresponding individual distance can be determined so that all sensor nodes can consume energy at a similar rate. During the routing process, we consider the hop number and distance as the primary factor and the residual energy as the secondary factor. Simulation results show that our REAR algorithm is superior to some existing routing algorithms in terms of energy hop number, consumption as well as network lifetime on average.

For future research, we plan to extend our work by exploring the effect of hop number and hop distance on other network metrics such as latency, communication overhead etc. Also, we plan to further extend network lifetime by combing clustering mechanism with our REAR algorithm in the future.

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Jin Wang received the B.S. and M.S. degree in the Electronical Engineering from Nanjing University of Posts and Telecommunications, China in 2002 and 2005, respectively. He received Ph.D. degree in Ubiquitous Computing laboratory in the Computer Engineering Department of Kyung Hee University Korea in 2010. Now, he is a professor in Nanjing University of Information Science & technology. His research interests include routing protocol and algorithm design, analysis and optimization, and performance evaluation for wireless ad hoc and sensor networks.

Tinghuai Ma is an associate professor in Computer Sciences at Nanjing University of Information Science & Technology, China. He received his Bachelor (HUST, China, 1997), Master (HUST, China, 2000), PhD (Chinese Academy of Science, 2003) and was Post-doctoral associate (AJOU University, 2004). From Nov.2007 to Jul. 2008, he visited Chinese Meteorology Administration. From Feb.2009 to Aug. 2009, he was a visiting professor in Ubiquitous computing Lab, Kyung Hee University. His research interests are in the areas of Data Mining and Privacy Protected in Ubiquitous System, Grid Computing. His research interests are data mining, grid computing, ubiquitous computing, privacy preserving etc. He has published more than 70 journal/conference papers. He is principle investigator of several NSF projects. He is a member of IEEE.

Jinsung Cho received his B.S., M.S, and Ph.D. degrees in computer engineering from Seoul National University, Korea, in 1992, 1994, and 2000, respectively. He was a visiting scholar at IBM T.J. Watson Research Center in 1998 and a research staff at SAMSUNG Electronics in 1999~2003. Currently, he is an assistant professor of Department of Computer Engineering at Kyung Hee University, Korea. His research interests include mobile networking & computing and embedded systems & software.

Sungyoung Lee received his B.S. from Korea University, Seoul, Korea. He got his M.S. and Ph.D. degrees in Computer Science from Illinois Institute of Technology (IIT), Chicago, Illinois, USA in 1987 and 1991 respectively. He has been a professor in the Department of Computer Engineering, Kyung Hee University, Korea since 1993. He is a founding director of the Ubiquitous Computing Laboratory, and has been affiliated with a director of Neo Medical ubiquitous-Life Care Information Technology Research Center, Kyung Hee

University since 2006. Before joining Kyung Hee University, he was an assistant professor in the Department of Computer Science, Governors State University, Illinois, USA from 1992 to 1993. His current research focuses on Ubiquitous Computing and applications, Context-aware Middleware, Sensor Operating Systems, and Real-Time Systems etc.

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