A Hop-based Energy Aware Routing Algorithm for Wireless Sensor Networks *

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Abstract - **Wireless sensor networks (WSNs) have attracted quite attention due to their wide potential applications. Up to now, a huge amount of energy efficient routing protocols or algorithms have been proposed to improve energy efficiency. In this paper, we try to prolong network lifetime by studying the relationship between hop number and energy consumption. A Hop-based Energy Aware Routing (HEAR) algorithm for WSNs is proposed. The simulation results show that our algorithm outperforms several existing protocols, such as shortest path algorithm, maximum remaining energy algorithm in the aspect of energy consumption and network lifetime. Depending on the real network environment, our algorithm can reduce energy consumption up to 50% and improve the network lifetime up to 125% comparing with the existing routing algorithms.**

Index Terms – wireless sensor network, energy consumption, network lifetime, routing, hop number.

I. INTRODUCTION

Wireless sensor networks (WSNs) are composed of hundreds or thousands of tiny sensor nodes, which can effectively monitor their surrounding environment. Due to the wide potential applications in military surveillance, environmental monitoring, healthcare etc [1], WSNs have attracted quite attention from both academic and industrial fields in recent years.

One of the primary challenges to the successful application of WSNs is the energy consumption problem since it is not practical to re-charge the limited battery once they have been deployed. The energy consumption usually consists of three parts, which are the energy consumed during sensing, processing and communication process. Here, we only focus on the energy consumption during communication process since it prevails over the other two processes.

Numerous energy efficient routing protocols or algorithms for WSNs [2-10] have been proposed, as can be seen from the related work section. Although it is commonly agreed that multi-hop transmission manner is usually more energy efficient than direct transmission (also called one hop transmission) manner, especially when the BS is far away from the source node. However, it is not well known that how many hops are needed and how to determine the corresponding intermediate nodes.

II. RELATED WORK

Currently, numerous works have been done to improve the routing performance, especially the lifetime for WSNs. The authors in [2] present a taxonomy about most of the routing protocols for WSNs and categorize them into three classes which are data-centric [3, 4], hierarchical [5-7], and location-based [8, 9] protocols.

Data aggregation (a.k.a. data fusion) is an important technique adopted by the data-centric routing protocols [3, 4]. It can reduce the energy consumption due to the fact that many nearby sensor nodes might sense and collect similar information. So, there is some similarity among those collected sensor data. Through this method, both the size and the number of transmission can be reduced largely. SPIN (Sensor Protocols for Information via Negotiation [3]) can be viewed as the first data-centric routing protocol which uses data negotiation method among sensor nodes to reduce data redundancy and save energy. Direct Diffusion [4] is a famous and representative data-centric routing protocol for WSNs.

In WSNs with hierarchical structure [5-7], the whole network is further divided into smaller areas called clusters. In each cluster, there exists a cluster head which functions like a base station (BS). Within each cluster, ordinary node communicates with cluster head and the cluster heads form a backbone network to forward the data to the remote BS. In this way, not only the resource can be better utilized, but that network is scalable. More importantly, the energy consumption can be greatly reduced since the communication range is largely reduced within one cluster and the ordinary sensor nodes can be set to sleeping mode according to certain Time Division Multiple Access (TDMA) schedule, which is sent by cluster head.

Location-based routing protocols [8, 9] require sensor location information which can be gained either through global positioning system (GPS) devices or through certain estimation algorithms based on received signal strength. The advantage of this type of routing protocols is that there is no need to make blind broadcasting, so the routing overhead can be largely reduced. In addition, the remote BS can make a global control based on all sensors' information, such as designating a specific routing path.

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III. THEORETICAL ANALYSIS

In this section, we will study the relationship between hop number and energy consumption from both theoretical and experimental point of view. We will present two important design parameters which lay the foundation of our HEAR algorithm.

A. *Energy Consumption Model*

A commonly used energy consumption model is known as first order radio model [5, 6, 10]. According to this model, radio will consume 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 the radio parameters is listed in Table I.

TABLE I
RADIO PARAMETERS

Parameter	Definition	Unit
E_{elec}	Energy dissipation rate to run radio	50 nJ/bit
ε_{fs}	Free space model of transmitter amplifier	10 pJ/bit/m^2
ε_{mp}	Multi-path model of transmitter amplifier	0.0013 pJ/bit/m^4
l	Data length	2000 bits
d	Source-sink distance	m
d_0	Distance threshold	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ m

B. *Deduction of Distance Threshold*

Given the practical distance from source node to the base station d , how can we determine the transmission manner? Here, we will propose a judging criterion of transmission manner based on Theorem 1 and its proof.

Theorem 1. When $d>d_T\approx 104.4$, there always exists an n -hop route with $d_1,\cdots,d_n<d_0$, so that multi-hop transmission will consume less energy than direct transmission.

Proof. Let $f(d)=E_{Direct}-E_{Multi-hop}>0$ and $l=0$, so:

$$f(d)=(E_{elec}+\varepsilon_{mp}\cdot d^4)-((2n-1)E_{elec}+\frac{\varepsilon_{fs}\cdot d^2}{n})$$

$$=\varepsilon_{mp}\cdot d^4-\frac{\varepsilon_{fs}\cdot d^2}{n}-2(n-1)E_{elec}>0 \quad (4a)$$

Inequality (4a) will always hold true when:

$$d>\sqrt{\frac{\frac{\varepsilon_{fs}}{n}+\sqrt{(\frac{\varepsilon_{fs}}{n})^2+8\cdot(n-1)\varepsilon_{mp}\cdot E_{elec}}}{2\cdot n\cdot\varepsilon_{mp}}} \quad (4b)$$

and the distance threshold $d_T\approx 104.4$ when $n=2$ in inequality (4b). It gives a low bounder of the distance, above which there always exists a multi-hop path that consumes less energy than direct transmission.

TABLE II
JUDGING CRITERION OF TRANSMISSION MANNER

d	Direct Trans.	Multi-hop Trans.
$d<d_T$	√	
$d>d_T$		√

We can get a judging criterion of transmission manner based on the proof above, as is shown in Table II. We will choose direct transmission when $d<d_T$. We will divide d into several $d_i<d_0$ and choose multi-hop transmission when $d>d_T$.

C. *Deduction of Hop Number*

In small scale WSNs with not-too-many nodes, direct transmission is more energy efficient than multi-hop transmission. In large scale WSNs when $d>>d_0$, energy consumption for direct transmission will be much larger than multi-hop transmission. In this section, we will study how to determine the hop number of multi-hop transmission based on experimental analysis, given the practical distance from source node to BS d .

We first study two numerical demonstrations in Table III and IV. In Table III, there are two examples with $d=240\in[2d_0,3d_0)$ and $d=300\in[3d_0,4d_0)$. In the first example, we find that 3-hop transmission is more energy efficient than other transmission manners. And 4-hop transmission is most energy efficient for the second example. So, we can tentatively draw the conclude that when $d\in[(n-1)d_0,nd_0)$, the transmission with $d_1,\cdots,d_n<d_0$ is more energy efficient than any other transmission alternative.

In Table IV, we also give two similar examples with $d=180\in[2d_0,3d_0)$ and $d=270\in[3d_0,4d_0)$. We find that when $d \in [(n-1)d_0, nd_0)$, $(n-1)$ -hop transmission with $d_0 < d_1, \cdots, d_{n-1}$ is more energy efficient . The reason is that d is very close to $(n-1)d_0$, so $d_1, \cdots, d_{n-1}$ are also very close to d_0. That is why $(n-1)$ -hop transmission consumes the least energy. Considering the real WSNs topology, it is very hard to find such $(n-1)$ intermediate nodes, especially in a sparse network. So, we will still choose n -hop transmission. Also, we find that there is little difference of energy consumption between these two multi-hop transmissions.

TABLE III
ENERGY CONSUMPTION UNDER DIFFERENT HOP NUMBER (1)

d_i (m)	240*1	120*2	80*3	60*4	40*6
$E(10^{-7}J)$	43.6	6.9	4.4	4.9	6.5
d_i (m)	300*1	150*2	100*3	75*4	60*5
$E(10^{-7}J)$	105.8	14.6	6.4	5.8	6.3

TABLE IV
ENERGY CONSUMPTION UNDER DIFFERENT HOP NUMBER (2)

d_i (m)	180*1	90*2	60*3	45*4	30*6
$E(10^{-7}J)$	14.1	3.2	3.6	4.3	6.0
d_i (m)	270*1	135*2	90*3	68*4	54*5
$E(10^{-7}J)$	69.6	10.1	5.1	5.3	6.0

Now, we provide our judging criterion of hop number, as is shown in Table V. Given the distance from source node to BS d, we can determine hop number based on its relationship with d_0 and d_T. If $d \in (0, d_T)$, we will choose direct transmission which is more energy efficient, as is explained in Table II. If $d \in [(n-1)d_0, nd_0)$, we will divide d into n hops with $d_1, d_2, \cdots, d_n < d_0$ and use n -hop transmission .

TABLE V
JUDGING CRITERION OF HOP NUMBER

d	d_i	Hop number
$(0, d_T)$	$d_1 < d_T$	1
$[d_T, 2d_0)$	$d_1, d_2 < d_0$	2
$[2d_0, 3d_0)$	$d_1, d_2, d_3 < d_0$	3
$\vdots$	$\vdots$	$\vdots$
$[(n-1)d_0, nd_0)$	$d_1, \cdots, d_{n+1} < d_0$	n

Based on the preliminary theoretical analysis and experimental comparison on distance threshold and hop number, we can then propose our HEAR algorithm.

IV. OUR HOP-BASED ENERGY AWARE ROUTING (HEAR) ALGORITHM

Our Hop-based Energy Aware Routing (HEAR) algorithm , there are no sensor nodes which are more powerful than the others so that they can form a backbone network to relay the data. In addition, we do not consider data aggregation and routing overhead in this paper.

B. Route Setup Phase

Let us consider a wireless sensor network with N stationary nodes randomly deployed in a [X, Y] area. The route setup phrase consists of the following steps:

Step 1: When WSN is first deployed, the BS will get the information of all the sensor nodes through GPS devices or algorithms based on received signal strength.

Step 2: Once a source node n_s has data to send to BS, it will first send a short routing request (RREQ) message directly to BS. Then, BS will determine the hop number n based on their distance d, as is demonstrated in Table III.

Step 3: After the determination of n, BS will next determine the corresponding intermediate nodes as follows:

Step 3.1: Starting from n_s, BS will choose its neighbours with distance $d_i \in (d/n, d/n + \Delta)$ as the next hop candidates.

Step 3.2: From all the candidates, BS will finally choose the one with shortest distance to BS as the next hop n_1.

Step 3.3: Finally, BS will replace n_s with n_1 and choose n_1's next hop in an iterative way until the last hop n_{n-1}, which is a neighbour of BS.

Step 4: Once the multi-hop route $n_s, n_1, \cdots, n_{n-1}$ is chosen, BS will send the final route result in a route reply (RREP) message to the source node and the source node will begin its traffic session until the end.

Step 5: Finally, BS will update the information of the involved intermediate nodes, such as their remaining energy, live or dead status etc.

C. Route Maintenance Phase

Usually, a dead node will not be chosen by BS as an intermediate node. So, the route is very stable and there is little chance of link failure. However, if an intermediate node malfunctions due to unexpected reasons, such as hardware failure or natural disaster, a route maintenance phase will be lunched. First, its previous hop node will hold its data and send a route error (RERR) message directly to BS. Then BS will again compute the remaining route according to the principles from Step 2 to 5. Finally, BS will set the malfunctioned node as a dead node unless it sends an updated message to BS later.

V. Simulation Results

This section presents the performance analysis of Hop-based Energy Aware Routing (HEAR) algorithm.

A. *Simulation Environment*

There are N nodes randomly deployed in WNS with certain range. The BS is placed either inside or outside the monitoring area. In each round, there is only one node that has a 2000 bits data to send to the BS. All nodes will take turns to send their data with either direct transmission or multi-hop transmission within N rounds. The relevant simulation parameters are listed in Table VI.

We compare our HEAR algorithm with 3 other existing algorithms which are direct transmission algorithm, shortest-path algorithm and max-remaining energy algorithm.

TABLE VI
SIMULATION ENVIRONMENT

Parameter	**Value**
Network size	$[100\times100,\ 300\times300]\ m^2$
Number of nodes	[100, 300]
BS location	Inside or outside
Data size (l)	2000 bits
Initial energy(E_0)	2 J
d_T	[110, 150]m
Δ	[10, 30]m

B. *Study of Average Energy Consumption*

Fig. 1 shows the average energy consumption of 100 sensor nodes in a $100\times100\ m^2$ sensor network with $R=50$, $d_T=120$ and BS placed at (50, 125). We define a new parameter named accumulative energy consumption which means the overall energy consumption after a number of rounds.

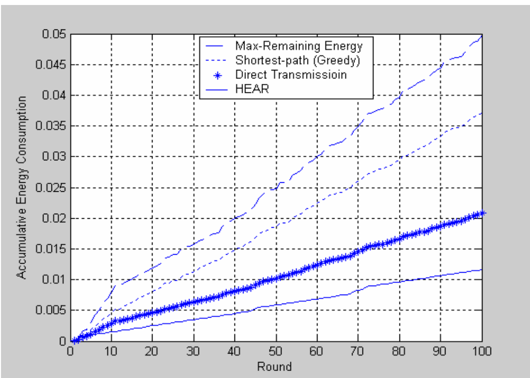
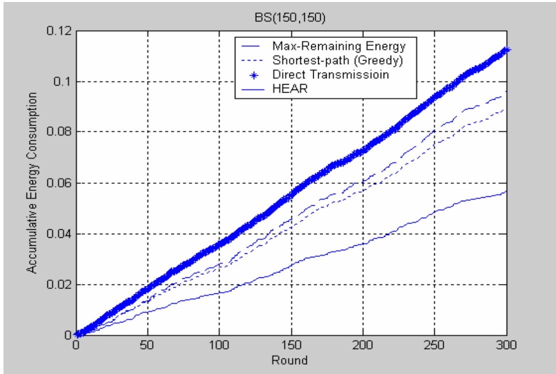
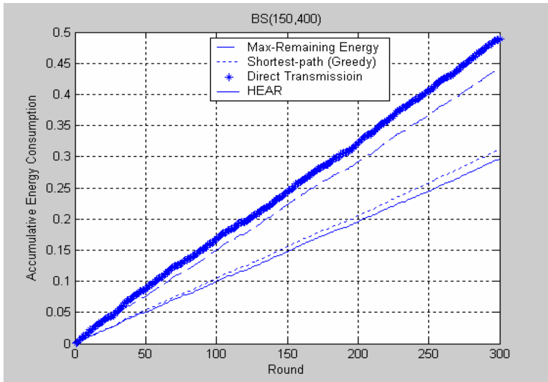


Fig. 1 Energy consumption in small scale network

We can see from Fig. 1 that max-remaining energy algorithm always consumes the largest energy since its next hop node is randomly chosen based on the randomly deployed remaining energy. The performance of shortest-path algorithm is also not desirable due to the unbalanced distribution of individual distance. Direct transmission is more energy efficient than the former two algorithms since most of the source to BS distance is less than d_T, so direct transmission is more energy efficient on average.



(a) BS placed inside



(b) BS placed outside

Fig. 2 Energy consumption in large scale network

Fig. 2 shows the energy consumption of 300 sensor nodes in a $300\times300\ m^2$ sensor network. Here, we set $R=130$, $d_T=150$, $\Delta=20$. The BS is placed either inside the network with BS placed at (150,150) or outside the network with BS at (150, 400). From both figures, we can see that direct transmission always consumes the largest energy since $d >> d_T$. Max-remaining energy algorithm still has a bad performance due to its randomness nature. Our HEAR algorithm is the best and it can save 37% to 50% energy in Figure 2 (a) and 5% to 40% energy in Figure 2 (b).

C. *Study of Network Lifetime*

We define the network lifetime as the time when the first sensor node dies out of energy. We compare the network lifetime performance under different network size. The name 1 to 3 in Fig. 3 is corresponding to the same simulation environment as Fig. 1, Fig. 2 (a) and Fig. 2(b).

We can see that HEAR algorithm is also superior to the other algorithms on average. It can prolong network lifetime up to 58% than all the other algorithms in the second group and up to 125% in the third group.

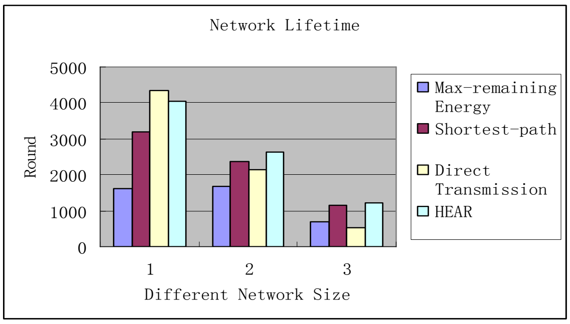


Fig. 3 Network lifetime under various algorithms

VI. CONCLUSION

In this paper, we clarify the idea that hop number has a very important influence on energy consumption. We deduce two important parameters which can be used as important guideline in our HEAR algorithm. The simulation results show that our algorithm is superior to some of the existing routing algorithms.

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