Prolonging the Lifetime of Wireless Sensor Networks via Hotspot Analysis

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Abstract—Energy consumption is not well balanced for all sensor nodes in most of the energy efficient routing protocols for wireless sensor networks (WSNs). In this paper, we optimize each individual distance so that all sensor nodes consume their energy at similar rate. After the theoretically analysis of hotspot based on certain energy and traffic models, we propose our Distance-based Energy Aware Routing (DEAR) algorithm for WSNs. Simulation results show that our DEAR algorithm has a better performance in energy consumption as well as network lifetime.

I. Introduction

Wireless Sensor Networks (WSNs) [1,2] have been extensively explored recently due to their wide applications like military surveillance, home network, healthcare, inventory management and monitoring etc. The sensor nodes will sense, process and then transmit the data to certain remote sink node (or base station) in an autonomous and unattended manner.

Ubiquitous healthcare (u-healthcare) system can be deployed at large scale with WSNs acting as part of a sub-system. Under such u-healthcare environment, energy efficiency of each component (e.g. sensors, PDAs) needs to be carefully considered from cost aspect. In fact, energy efficiency is one of the primary challenges of WSNs since the tiny sensors are powered with limited battery which can not be recharged afterward. Up to now, many energy efficient routing protocols [3-10] have been proposed to prolong the network lifetime with aid of hierarchical and multi-hop routing mechanisms etc.

Among the hierarchical structured energy efficient routing protocols, LEACH [3] is the most popular and representative one. Energy consumption is balanced via the rotation of 5% of the cluster heads and it is greatly reduced by data aggregation inside each cluster head. PEGASIS [4] is an improved version of LEACH which adopts the chain-based routing mechanism. Messages can get aggregated along the chain and finally be sent to the sink node via direct transmission by one random node on the chain. HEED [5] can not only minimize the control overhead during communication process but also prolong network lifetime since the cluster heads are well distributed. PEBECS [6] reduces and balances energy consumption by considering node's residual energy, degree and relative location during selection of cluster head nodes.

It is commonly agreed that multi-hop routing is more energy efficient than direct transmission routing under large scale network or when the source to sink distance is relatively large [7-9]. In [7], the authors focus on theoretical analysis of multi-hop routing based on various energy models. In [8], the authors also suggest to use sub-optimal candidate route occasionally so as to protect the optimal minimal energy route from being overused. In our previous work [9], we propose a Hop-based Energy Aware Routing (HEAR) algorithm which is an energy efficient multi-hop routing algorithm.

Even though energy efficiency can be achieved by most of the routing protocols or algorithms mentioned above, they can not solve the hotspot problem due to the intrinsic nature of many-to-one traffic patterns in WSNs. For direct transmission routing, the nodes far away from sink node will drain out of energy very quickly due to the characteristics of wireless channel. For multi-hop routing, the nodes close to sink node will have more traffic load to forward under most routing mechanisms and also drain out of energy quickly. The network lifetime is commonly defined as the time when the first node dies out of energy, and the whole network will get partitioned and be out of function afterward. Thus, the residual energy of the remaining alive nodes will be wasted, which is not desirable.

Based on our previous work in [9], our objective in this paper is to optimize each individual distance so that all sensors will consume their energy at similar rate. After the theoretical analysis of hotspot, we propose our Distance-based Energy Aware Routing (DEAR) algorithm for WSNs with simulation results.

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II. Hotspot Analysis

A. Energy Consumption Model

Fig. 1 shows the one dimensional linear network with N sensor nodes placed along a line from source to sink node. Usually, one dimensional linear sensor network can be used in linear applications such as highway traffic monitoring, congestion control etc.

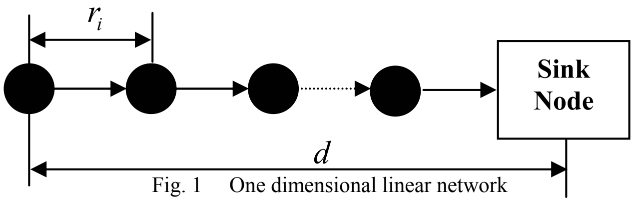

Fig. 1 One dimensional linear network

The energy consumption model here is called first order radio model [3, 7, 9]. Radio device will consume the following E_{Tx} amount of energy to transmit a l-bits message over distance d:

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

E_{Rx} amount of energy to receive the message:

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

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

$$\begin{aligned} E_{Fx}(l,d)&=E_{Tx}(l,d)+E_{Rx}(l) \\ &=\begin{cases} 2l\cdot E_{elec}+l\cdot\varepsilon_{fs}\cdot d^2, & if\, d<d_0 \\ 2l\cdot E_{elec}+l\cdot\varepsilon_{mp}\cdot d^4, & if\, d\geq d_0. \end{cases} \end{aligned} \quad (3)$$

Definition of radio parameters is listed in Table 1.

Table 1 Radio parameters

Parameter	Definition	Unit
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}	Multi-path model of transmitter amplifier	0.0013 pJ/bit/m^4
l	Data length	2000 bits
d_0	Distance threshold	$\sqrt{\varepsilon_{fs}/\varepsilon_{mp}}$ m

B. Energy Consumption of Hotspot Analysis

1) Event based traffic pattern

Under the event based traffic pattern, each sensor node is randomly chosen to send its sensed event to the sink node through direct or multi-hop routing. So, the data length is same for all intermediate sensor nodes along multi-hop route.

In [7, 9, 10], the optimal individual distance d_i to get minimal energy consumption for intermediate nodes is:

$$d_i=d_{opt}=\sqrt[\alpha]{\frac{2\cdot E_{elec}}{\varepsilon_{amp}(\alpha-1)}} \quad (4)$$

where $\alpha\in[2,4]$ and $\varepsilon_{amp}=\varepsilon_{fs}$ when $\alpha=2$, $\varepsilon_{amp}=\varepsilon_{mp}$ when $\alpha=4$.

2) Time based traffic pattern

Under time based traffic pattern, each sensor node will take turns to transmit their data through direct or multi-hop routing. Taking Fig. 1 as an example, there is a multi-hop route $\{n_1\rightarrow n_2\rightarrow\cdots\rightarrow n_N\rightarrow BS\}$ with distance $\{r_1,r_2,\cdots,r_N\}$, where $\sum_{i=1}^{N}r_i=d$. Our objective in this paper is not to minimize the sum of energy consumption for all nodes as in Eq. (4), but to get the optimal distribution of $\{r_1,r_2,\cdots,r_N\}$ when $E_1=E_2=\cdots=E_N$.

After N rounds when all N sensors finish their own data transmission and forwarding, each node i will fulfill one time own data transmission and (i-1) time(s) forwarding. From Eq. (1) to (3), we can get the overall energy consumption for node i as follows:

$$\begin{aligned} E(i)&=E_{Tx}(l,r_i)+(i-1)\cdot E_{Fx}(l,r_i) \\ &=l\cdot((2i-1)E_{elec}+i\varepsilon_{amp}r_i^{\alpha}) \end{aligned} \quad (5)$$

Now, let $E(i)=E(i+1)$, namely:

$$\begin{aligned} &l\cdot((2i-1)E_{elec}+i\varepsilon_{amp}r_i^{\alpha})= \\ &l\cdot((2i+1)E_{elec}+(i+1)\varepsilon_{amp}r_{i+1}^{\alpha}) \end{aligned} \quad (6)$$

Finally, we can get an iterative formula as:

$$r_{i+1}=\sqrt[\alpha]{\frac{-2E_{elec}+i\varepsilon_{amp}r_i^{\alpha}}{\varepsilon_{amp}(i+1)}}=\sqrt[\alpha]{\frac{-2iE_{elec}+\varepsilon_{amp}r_1^{\alpha}}{\varepsilon_{amp}(i+1)}} \quad (7)$$

Under the constraint $\frac{-2iE_{elec}+\varepsilon_{amp}r_1^{\alpha}}{\varepsilon_{amp}(i+1)}>0$, we get:

$$\frac{\varepsilon_{amp} r_1^{\alpha}}{2E_{elec}} > i \geq 1 \tag{8}$$

Let the hop number i equal to [1..8] and we can get the lower bound value of r_1 and corresponding $\sum r_i$, as is shown in Table 2. Thus, given r_1 and hop number $i = N$, $\{r_2, \cdots, r_N\}$ can be found based on Eq. (7).

Table 2 Lower bound value of r_1 and $\sum r_i$

r \ i	1	2	3	4	5	6	7	8
r_1	100	119	132	142	150	157	163	169
$\sum r_i$	100	224	340	450	554	662	766	886

It is worth mentioning that event based traffic pattern is similar to time based traffic pattern if the observation or monitoring time is large enough. Thus, it is better to optimize each individual distance r_i under constraint $E_1 = E_2 = \cdots = E_N$ rather than to minimize energy consumption in order to alleviate hotspot problem and to prolong network lifetime.

III. Distance-based Energy Aware Routing (DEAR) Algorithm

Based on the theoretical and numerical analysis above, we propose our Distance-based Energy Aware Routing (DEAR) algorithm which consists of route setup and route maintenance phase.

The following assumptions are made:

i) Sensor nodes are stationary and homogenous.
ii) The communication links are symmetric.
iii) Sensor nodes can adjust their transmission radius.
iv) There is no obstacle between sensors and sink node.

A. Route setup phase

Once source node n has data to send, it will set up a route to sink node as follows. First, it will compare its distance to sink node d_n with $\sum r_i$ values in Table 2. If $d_n \leq 100$, direct transmission will be used. Or else, multi-hop routing will be used.

When $\sum r_{N-1} \leq d_n < \sum r_N$, hop number N will be chosen rather than ($N-1$). This is because under practical sensor network, it is not easy to find such $(N-1)$ intermediate nodes with $\sum_{i=1}^{N-1} r_i = d_n$. Here, we use a larger $r_1(N)$ rather than $r_1(N-1)$ so that there are more next hop candidates.

Once hop number N is chosen, the corresponding distance $\{r_1, r_2, \cdots, r_N\}$ can be determined based on Eq. (7) and Table 2. So, node n will finally choose its neighboring node m as its next hop which satisfies: a) $d_{nm} \geq r_1(N)$; b) node m is as close to the direct line from n to sink node as possible.

After selection of next hop, a route request (RREQ) message is sent by node n to node m together with $\{r_1, r_2, \cdots, r_N\}$ inside RREQ. Node m will first send back an ACK message to node n when it gets RREQ. Then, it will choose its next hop in a similar way to node n until the RREQ message reaches sink node.

Finally, a route reply (RREP) message is sent back to source node n by sink node to confirm the setup of route based on the assumption of symmetric link. Once node n receives RREP, traffic session can get started.

B. Route maintenance phase

When a node does not receive an acknowledgement (ACK) message within certain time, link failure will be detected and route maintenance phase will be initiated.

If source node detects a link failure, it will restart the route setup phase by choosing another appropriate neighbor. If an intermediate node detects a link failure, it will first attempt a local link repair process by choosing another appropriate neighbor. If the local link repair process fails, a route error (RERR) message will be sent to source node. Finally, this route will be deleted from source node as well as the intermediate nodes and a new route setup phase will be initiated.

IV. Performance Evaluation

We use MATLAB for the simulation performance analysis. There are 100 to 300 sensor nodes randomly deployed in a $200 \times 200\, m^2$ area with BS at (100, 250).

Given $d_n = 500$ in Fig. 2, we have 3 multi-hop routes with hop number $N = 3,4,5$. Since node j has more traffic load to forward than node i $(j > i)$, therefore node j has smaller individual distance than i $(r_j < r_i)$. We can also get the average energy value for 3 multi-hop routes as {0.0031, 0.0014, 0.0010} which validates the next hop node selection criterion of our DEAR algorithm.

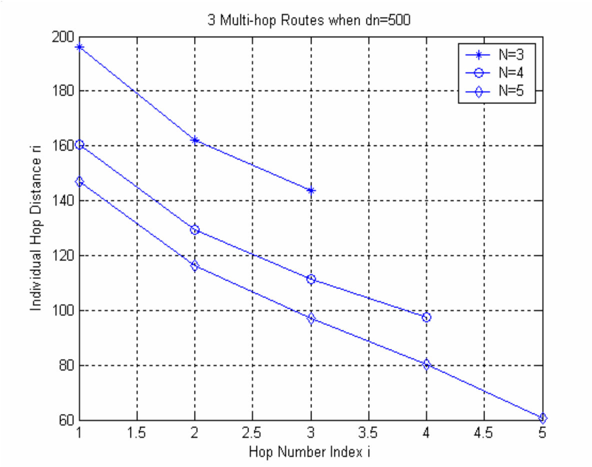

Fig. 2. Optimal individual distance r_i

Table 3 gives the comparison of network lifetime between LEACH [3] and our DEAR algorithm under different node number $N \in [100,300]$. Here, network lifetime is also defined as the time when the first node dies out of energy.

Our DEAR algorithm can prolong network lifetime about 80 to 100 percent than LEACH algorithm, see Table 3. This is because the 5% cluster heads in LEACH are randomly deployed in the network. So, the distance from cluster heads to sink node as well as the distances from ordinary members to cluster head within each cluster are not well distributed. Also, the number of 5% is not fixed for each round. All these factors lead to unbalanced energy consumption in LEACH.

Table 3 Network lifetime under different N

	N=100	N=200	N=300
LEACH	476	451	469
DEAR	854	917	953

V. Conclusions

In this paper, we propose a Distance-based Energy Aware Routing (DEAR) algorithm with aims to balance and reduce energy consumption and consequently prolong network lifetime. Different from traditionally energy efficient routing protocols which try to minimize the sum of energy consumption on certain route, we propose theoretical deduction and proof of the optimal individual distances when all involved sensor nodes consume their energy at similar rate or time. Simulation results validate the performance of our DEAR algorithm.

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