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Efficient Algorithm for Prolonging Network Lifetime of Wireless Sensor Networks

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Abstract: One of the fundamental design challenges in designing a Wireless Sensor Network (WSN) is to maximize the network lifetime, as each sensor node of the network is equipped with a limited power battery. To overcome this challenge, different methods were developed in the last few years using such techniques as network protocols, data fusion algorithms using low power, energy efficient routing, and locating optimal sink position. This paper focuses on finding the optimal sink position. Relay nodes are introduced in conjunction with the sensor nodes to mitigate network geometric deficiencies since in most other approaches the sensor nodes close to the sink become heavily involved in data forwarding and, thus, their batteries are quickly depleted. A Particle Swarm Optimization (PSO) based algorithm is used to locate the optimal sink position with respect to those relay nodes to make the network more energy efficient. The relay nodes communicate with the sink instead of the sensor nodes. Tests show that this approach can save at least 40% of the energy and prolong the network lifetime.

Key words: wireless sensor network; lifetime; sensor node; relay node; particle swarm optimization; sink

Introduction

A Wireless Sensor Network (WSN) is a network of distributed sensors that can collect information from a physical environment. Low cost sensors are the backbone of a WSN. Improvement in the small scale computational devices leads the practical implementation of a WSN which is comprised of hundreds and thousands of physically embedded sensor nodes. The sensor nodes can communicate among themselves using radio signals. A wireless sensor node is equipped with sensing and computing devices, a radio transceiver and power components. After the sensor nodes are deployed, they are responsible for self-organizing an appropriate network infrastructure often with multi-hop connections between them. Then the onboard sensors start collecting information of interest which are routed towards a sink and it is assumed that these sensor nodes are aware of the sink location[1,2]. In multi-hop communication, all the information is routed from one node to another until all the information reaches the sink. In this process of data transmission and reception, the sensor nodes spend a significant amount of their stored energy[3,4]. Once the sensor nodes are deployed, it is often infeasible or un-desirable to recharge sensor nodes or replace their batteries. Thus energy conservation becomes crucial for sustaining a sufficiently long network lifetime. So the basic target behind the design of WSNs is to sustain the network for the required mission. There are normally, in practical systems, certain considerations taken at each layer to improve the network lifetime. In the physical layer, an optimal sink location can greatly improve the sensor network's lifetime. For a dynamic network this might not be easy or

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feasible but for a fixed network the use of a proper design algorithm accurately locating the sink can help save energy.

With respect to the optimal sink location there are several proposed algorithms available in literature. Pan et al.[5] provided two algorithms to locate the optimal location of the sink; for homogeneous nodes and as well as for heterogeneous nodes where single-hop routing was used. The limitation of this approach is that the energy consumption of nodes located far from the sink rises significantly as the distance increases in a wide area network. This limitation due to single-hop communication remains in Refs. [6,7] also, where an algorithm based on Particle Swarm Optimization (PSO) is described for finding the optimal position of the sink. Wang et al.[8] proposed the use of mobile relays along with the sensor nodes for extending the network lifetime. But the locations of mobile relays are limited to only two-hop distance from the sink. Hou et al.[9] worked on optimal sink selection for anycast routing. Here the authors considered multiple sinks in a wireless sensor network, which may not be feasible for many applications. In Ref. [10], the author's approach was based on PSO algorithm for locating the best position of the sink where multi-hop communication was considered. But in multi-hop communication the sensory data collected by all the nodes of the network reach the sink through the nodes close to the sink and thus these nodes tend to die soon as they have to pass a huge amount of data. In this paper, a simple scheme for improving the network lifetime is proposed and the performance with other existing approach is evaluated.

1 Approach on Improving the Lifetime of a WSN

In this work, we have introduced relay nodes in conjunction with the PSO based algorithm. These relay nodes reduce the burden of the data traffic on the sensor nodes, especially of those, which are close to the sink, by carrying the data traffic to the sink. Hence the energy consumptions of the sensor nodes decrease and the lifespan increases. The optimal location of the sink with respect to those relay nodes is found by using the PSO based algorithm.

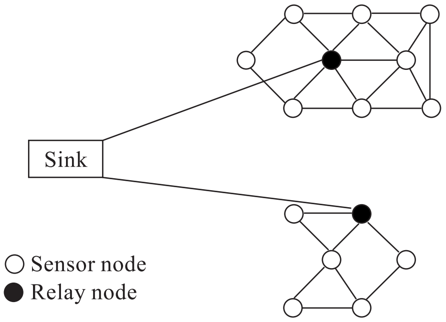

Fig. 1 Wireless sensor network using relay nodes

2 Models and Assumptions

The models and assumptions taken into account are described below.

2.1 Network model

The network model has the following properties:

- Each node performs sensing task periodically and always has some data to send to the sink.
- All nodes are stationary and energy constrained.
- All the nodes are located in a two-dimensional space.
- Location of each node is known, according to GPS or LPS[11].
- There is no energy hole in the network.
- Sink is externally powered.
- All the nodes use multi-hop routing method to forward the data to the closest relay node.
- Relay nodes carry the sensory data to the sink.
- Sink has the ability to communicate directly with all the sensors in the network.
- Interference range is twice of the transmission range.
- All the nodes use FDMA and data aggregation at each hop to avoid collision and interference.
- There is only one transmission range fixed for all the nodes.
- Each node has a data rate to carry all the data traffic.
- Each node is assigned a number according to its location.

2.2 Radio energy model

The basic radio energy model is used in this work. Path loss co-efficient is considered as 2. According to the model, we have:

$$E_{\mathrm{T},x}(l,d)=\begin{cases} l\times E_{\mathrm{elec}}+l\times E_{\mathrm{Fs}}\times d^2, \text{ if } d<d_0; \\ l\times E_{\mathrm{elec}}+l\times E_{\mathrm{Tr}}\times d^4, \text{ if } d>d_0 \end{cases} \tag{1}$$

$$E_{\mathrm{R},x}=l\times E_{\mathrm{elec}} \tag{2}$$

where $E_{\mathrm{T},x}$ is the transmission energy, $E_{\mathrm{R},x}$ is the energy used in reception, d is the distance between two nodes or between a node and the sink, E_{elec} is the energy dissipated per bit to run the transmitter or the receiver circuit, E_{Fs} and E_{Tr} depend on the transmitter amplifier model, d_0 is threshold transmission distance. l is the length of the data transmitted.

We have used the same values as used in Ref. [10] and E_{elec}=50 nJ/bit, E_{Fs}=10 $\mathrm{pJ\cdot bit^{-1}\cdot m^{-2}}$, E_{Tr}=0.0013 $\mathrm{pJ\cdot bit^{-1}\cdot m^{-4}}$, d = transmission radius, d_{tr}.

2.3 Lifetime model

The network lifetime is defined as the time elapsing from initial deployment to the instant of the probability of connectivity reaching the prescribed threshold[12]. In this work, the lifetime of the network is defined as the length of time from the network deployment until the first relay node runs out of its energy. Lifetime is expressed in terms of seconds in this paper and for a single node it can be evaluated by the following equation:

$$L=\frac{e_{\mathrm{initial}}}{e_{\mathrm{total}}} \tag{3}$$

where e_{initial} is initial energy of a sensor node, e_{total} is total energy spent in the process of data transmission and reception and so it is expressed as

$$e_{\mathrm{total}}=E_{\mathrm{T},x}(l,d_{\mathrm{tr}})+E_{\mathrm{R},x}(l) \tag{4}$$

The upper limit of the number of relay nodes, $\mathrm{Nr}_{\max}$, which can be used in a wireless sensor network, is given in Ref. [13]. It can be calculated by the following equation:

$$\mathrm{Nr}_{\max}=\sum_{i=1}^{N}\left\{\left\lceil\frac{D_i}{d_{\mathrm{los}}}\right\rceil-1\right\} \tag{5}$$

where D_i is the distance of the i-th sensor from the sink, d_{los} is near field distance, N is the number of sensor nodes.

In practical conditions, as one relay node relays more than one sensor node, the value of $\mathrm{Nr}_{\max}$ in Eq. (5) reduces greatly. In this work, as the optimal position of the sink is yet to be located, D_i will be the distance of the i-th sensor from a reference point. The reference point is taken in such a way that we can minimize the value of $\mathrm{Nr}_{\max}$.

3 Introduction to Particle Swarm Optimization

The particle swarm optimization is a population based optimization technique, introduced by Kennedy and Eberhert in 1995[14]. The model of this algorithm is based on the social behaviour of bird flocking. It works through initializing population of random solutions and searching for the optima by updating generations. The PSO technique uses several particles, each represents a solution, and finds the best particle position with respect to a given fitness function[15].

In PSO, each single solution is a “bird” in the search space. We call it “particle”. All of particles have fitness values that are evaluated by the fitness function to be optimized, and have velocities that direct the flying of the particles. The particles fly through the problem space by following the current optimum particles. PSO is initialised with a group of random particles (solutions) and then searches for optima by updating generations. In every generation, each particle is updated by following two “best” values. The first one is the best solution (fitness) it has achieved so far. (The fitness value is also stored.) This value is called pbest. Another “best” value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called gbest.

After finding the two best values, the particle updates its velocity and positions. The particle swarm optimization concept consists of, at each time step, changing the velocity of (accelerating) each particle toward its pbest and gbest locations. Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest and gbest locations.

In the past several years, PSO has been successfully applied in many research and application areas. It is demonstrated that PSO gets better results in a faster, cheaper way compared with other methods. Another reason that PSO is attractive is that there are few parameters to adjust. One version, with slight variations, works well in a wide variety of applications. Particle swarm optimization has been used for approaches that can be used across a wide range of applications, as well as for specific applications focused on a specific requirement.

4 PSO Algorithm and Optimal Sink Location

The PSO algorithm that have used for finding the optimal location of the sink is given below:

PSO Algorithm for Optimal Location of the Sink in Wireless Sensor Network Using Multi-Hop Routing

```
1. Initialization:
2. Generate a group of $n$ particles, each particle
3. representing
4. a possible solution for the sink $b$ and each group
5. contains $p$ elements
6. Set pBest and gBest equal to zero
7. Set the order of system to $p$
8. Set the maximum value of generation $m$
9. Set the upper and lower bound for the sink location
10. Set the inertia weight $w$
11. Generate an initial velocity
12. At each generation, $m$:
13. For each particle $n$
14.         loop
15.         for sink $b$
16.         calculate $d_{bi}$ and $p_b$
17.         for each node $i$
18.             calculate $d_{ij}$, $p_i$, $h_{ci}$, $L_i$, $E_{Li}$, $E_{\text{total\_}i}$
19.         calculate $l_{i(k)}$ for particle $k$
20.  calculate the lifetime of the whole network as its
21.         fitness value, fitness ($k$)
22.         if (fitness ($k$) > $\text{pBest}_k$)
23.             update $\text{pBest}_k$ = fitness ($k$)
24.         set gBest = $\max^{n}_{k=1}$ { $\text{pBest}_k$ }
25.         update the velocity of the $k$-th particle, $V_{id}$
26.         update the position of the $k$-th particle, $x_{id}$
27.         end
28. Repeat 14 to 28 until generation reached maximum
```

The definition of the parameters used in the algorithm is summarized in Table 1.

Table 1 List of variables

Parameters	Definitions
pBest_{id}	Particle's best position
gBest_{id}	Global best position
W	Inertia weight
x_{id}	The particle position
V_{id}	The particle velocity
d_{bi}	Distance from node i to the sink
p_b	Set of neighbors for the sink
d_{ij}	Distance between node i and node j
p_i	Set of neighbors for the node i
$h_{\mathrm{c},i}$	Hop count
d_{t}	Hop count distance
L_i	Link for a given node i
E_{L_i}	Consumed energy by the link L_i
$E_{\text{total\_}I}$	Total energy consumption by each node
$l_{i(k)}$	Lifetime of node i at k-th particle
fitness (k)	Fitness function
c_1, c_2	Learning factors
$R_1(\bullet)$, $R_2(\bullet)$	Random numbers between 0 and 1

4.1 Velocity update

As the velocity of each particle dynamically changes according to pBest and gBest, the velocity, V_{id}, is updated according to the following equation:

$$V_{id}^{\text{new}} = w \times V_{id}^{\text{old}} + c_1 \times R_1(\cdot) \times (\text{pBest}_{id} - x_{id}) + c_2 \times R_2(\cdot) \times (\text{gBest}_{id} - x_{id}) \tag{6}$$

4.2 Location update

After the velocity is updated, the position for a particle is also updated:

$$x_{id}^{\text{new}} = x_{id}^{\text{old}} + V_{id}^{\text{old}} \tag{7}$$

4.3 Set of neighbours of node *i*

It is assumed that the positions of all the nodes are known in terms of x and y coordinates. So the distance d_{ij} between the nodes i and j is calculated according to the following formula:

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \tag{8}$$

Considering d_{tr} as the threshold transmission distance for all the nodes, node j is said to be the neighbor of node i if and only if:

$$p_i = \{j : d_{ij} \leqslant d_{\text{tr}}\} \tag{9}$$

4.4 Set of neighbours of the sink

As the location of the sink b is (x_b, y_b), therefore the distance from the node i to the sink b is:

$$d_{bi} = \sqrt{(x_b - x_i)^2 + (y_b - y_i)^2} \tag{10}$$

Thus we can evaluate the set of neighbours for the sink b by the following equation:

$$p_b = \{i : d_{bi} \leqslant d_{\mathrm{t}}\} \tag{11}$$

4.5 Calculation of hop-count

The hop count, $h_{\mathrm{c},i}$, of node i is calculated using the following formula where hop count distance is expressed as d_t:

$$h_{c,i}=\begin{cases}\lceil h_{f,i}\rceil, & \text{if } h_{f,i}\neq 0;\\ 1, & \text{if } h_{f,i}=0\end{cases} \tag{12}$$

The $h_{f,i}$ in the above equation can be written as follows where d_t is the hop count distance:

$$h_{f,i}=\frac{d_{bi}}{d_t} \tag{13}$$

4.6 Finding the optimal link

In order to find the optimal link for each node to the sink, the concept introduced in Minimum Transmission Energy (MTE) routing[16,17] has been used, and the link L_i for the node i is given by:

$$L_i=\{i,j: h_{c,j}=n;\ n \text{ is an integer; and } 1\leqslant n\leqslant h_{c,i}-1\} \tag{14}$$

4.7 Energy consumption of each link

As in a link, the first node consumes energy on transmission only and other nodes consume energy for both transmission and reception, so energy consumption of each link is:

$$E_{L_i}=h_{c,i}\times E_{T,x}+(h_{c,i}-1)\times E_{R,x} \tag{15}$$

4.8 Energy consumption of each node

According to Eq. (15), if a node is used to receive (n–1) times, it should transmit n times. Hence the energy consumption of each node is:

$$E_{\text{total}\_i}=n\times E_{T,x}+(n-1)\times E_{R,x} \tag{16}$$

But if a relay node transmits n times it also receives n times. So the energy consumption of each relay node is given by:

$$e_{\text{total}\_i}=n\times E_{T,x}+n\times E_{R,x} \tag{17}$$

4.9 Lifetime of node *i*

The lifetime $l_{i(k)}$ of node i at k-th particle is expressed by:

$$l_{i(k)}=\frac{e_{\text{initial}-i(k)}}{e_{\text{total}-i(k)}} \tag{18}$$

4.10 Fitness function

The fitness function for each particle has been used as:

$$\text{fitness}(k)=\operatorname*{Min}_{i=1}^{N}\{l_{i(k)}\} \tag{19}$$

5 Results

In this section, we evaluate the performance of our proposed scheme. The required parameters and their values are listed in Table 2. Figure 2 shows the further improvement of the network lifetime as compared to the recent work in Ref. [10] using the proposed scheme. This figure depicts that network lifetime of about 32% has been increased. The optimal location of the sink has been shown in Fig. 3 using a circular point.

Figure 4 shows the variation of the lifetime with respect to the size of the area over which the nodes are uniformly distributed. If a fixed amount of sensor nodes are uniformly distributed over a larger area, lifetime of the network decreases. It is because the distance between the nodes increases and thus more energy is spent in transmitting the same amount of data. Figure 5 and Fig. 6 show the changes in the optimal sink location as the size of the area is varied.

In Fig. 7, we have compared the lifetime when the number of sensor nodes is decreased from 676 to 484 and 196 relay nodes are also used. From the figure we can see that an increased network lifetime is achieved. In the network model it is assumed that in its turn, a sensor node always has some data to send. Moreover, the length of the data is fixed. Now when the number of senor nodes is decreased, at a given period of time the total data sent to the sink is also decreased, that means the data traffic is decreased. In the first case when only sensor nodes are used without any relay node, the lifetime is measured until the first sensor node drained of its energy, because when a single sensor node dies, it can damage a complete link to the sink. But, in the second case relay nodes are considered and they are responsible for transferring the data to the sink and therefore a single sensor node cannot damage a complete data link. So the lifetime and the best position of the sink is located with respect to those relay nodes and thus an improved network lifetime is achieved. Figure 8 shows the optimal sink location when 484 sensor nodes along with 196 relay nodes are used in the network.

Table 2 Simulation parameters

Parameters	Value
Terrain	1000 m×1000 m
No. of sensor nodes, N	676
No. of relay nodes, $\mathrm{Nr}_{\max}$	256
Node distribution	Uniform square grid
Hop count distance, d_t	61 m
Transmission radius, d_{tr}	91.5 m
Interference range, I	183 m
Propagation model	Free space
Initial energy, e_{initial_I}	2 J
Energy consumed by radio electronics, E_{elec}	50 nJ/bit
Energy consumed by power amplifier, E_{Fs}	$10\ \text{pJ}\cdot\text{bit}^{-1}\cdot\text{m}^{-2}$
Energy consumed by power amplifier, E_{Tr}	$0.0013\ \text{pJ}\cdot\text{bit}^{-1}\cdot\text{m}^{-4}$
Data rate	512 Kbps
Data generated by each node	1000 bit
Order of system, p	2
Particle number, n	20
Maximum iteration, m	800
Learning factors, c_1, c_2	1.5 each
Inertia weight, w	0.1 - 1.2
Upper bound	1000 m (x and y axes both)
Lower bound	0 (x and y axes both)

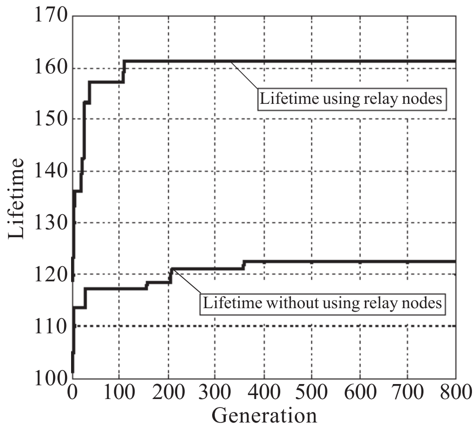

Fig. 2 Lifetime comparison

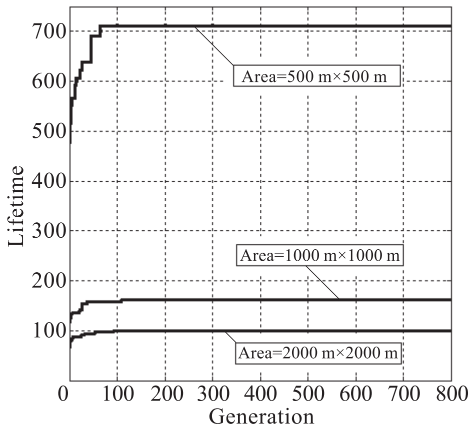

Fig. 4 Lifetime comparison with respect to the size of the area

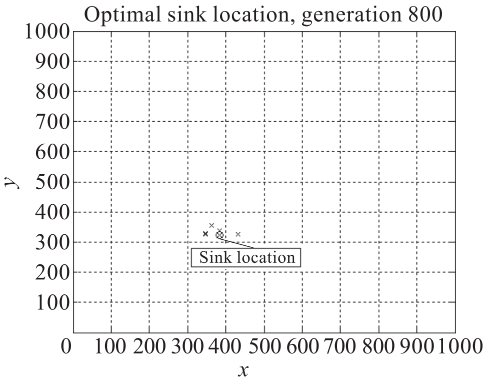

Fig. 3 Optimal sink location (area = 1000 m×1000 m)

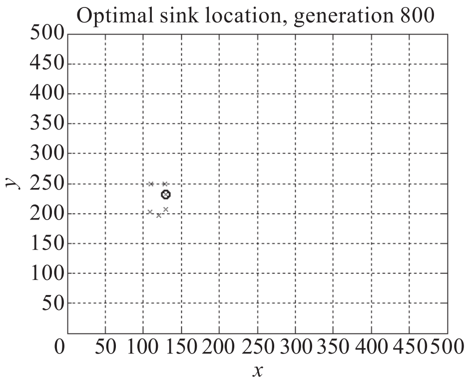

Fig. 5 Optimal sink location (area = 500 m×500 m)

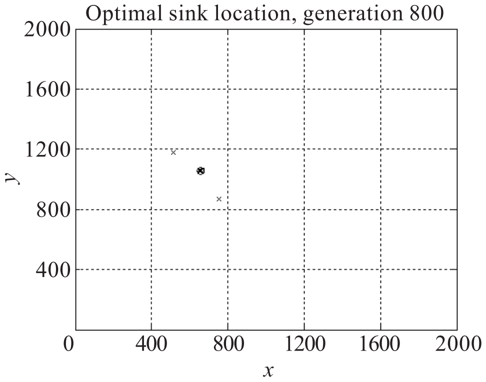

Fig. 6 Optimal sink location (area = 2000 m×2000 m)

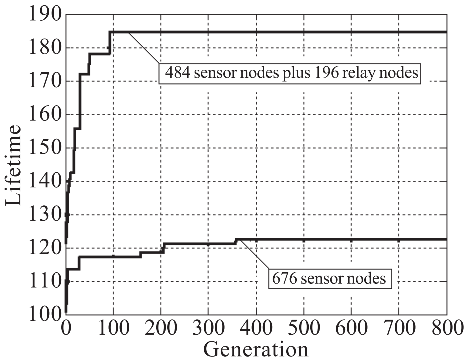

Fig. 7 Lifetime comparison (with and without relay nodes)

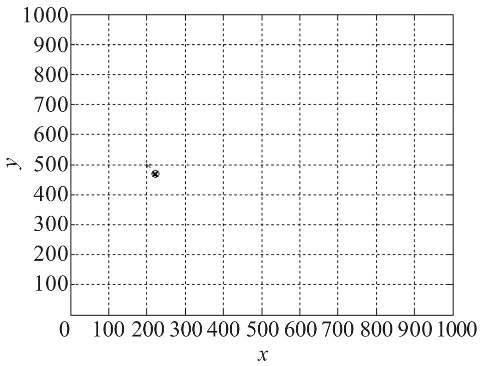

Fig. 8 Optimal sink location (484 sensor nodes and 196 relay nodes)

6 Conclusions

This paper presents a simple scheme for improving the network lifetime without compromising any of the strict requirements of wireless sensor networks. By utilizing relay nodes, the network is able to work for a longer lifetime. In this work, a scheme is proposed where relay nodes are used to collect data from the sensor nodes to pass them to the sink. We have calculated the required number of relay nodes to maintain the network connectivity successfully and then investigated their effect on network lifetime. The optimal location of the sink is determined with respect to those relay nodes with the help of the particle swarm optimization technique. To validate our experiment, we have compared our research work with recent work in this field. Experimental results show that the combination of the optimal location of the sink and relay nodes improve the network lifetime significantly. Therefore, this scheme can be used for designing a wireless sensor network of longer lifetime.

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