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An Mobile-sink Based Energy-efficient Clustering Algorithm for Wireless Sensor Networks

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Abstract

Wireless sensor networks with one static sink often suffer from energy hole problem, which means energy consumption of certain sensors near the sink or on critical paths is much faster than other nodes. Consequently, network partition and isolated nodes are caused. To solve the problem, we propose a Mobile-sink based Energy-efficient Clustering Algorithm (MECA) for wireless sensor networks. MECA aims at minimizing and balancing energy consumption for all sensor nodes. We divide the network into several equal clusters and the intra-cluster routing exploits multi-hop routing to save energy. We study the effect of both mobility and multiplicity of the sink on total energy consumption. Simulation results show that our proposed routing algorithm consumes much less energy than traditional routing algorithms like LEACH.

Keywords: wireless sensor networks, mobile-sink, clustering, muti-hop

1. INTRODUCTION

Wireless sensor networks (WSNs) [1] are composed of hundreds or thousands of sensors that work cooperatively to monitor the environmental conditions of the sensor field.. Sensor nodes collect sensed data and pass them to sink nodes. WSNs have various applications in many fields such as military, agriculture and health care etc.

Study on efficient routing algorithms is an important and challenging research issue. As the battery, capability of computing, storage and data processing of a sensor are limited, how to reduce the energy consumption while prolonging the network lifetime stays the key problem.

In traditional routing scenarios, reducing the hops and data quantity in data transmission is preferable. However, as the sink node remains static, certain sensor nodes that are located close to the sink are obliged to relay data for most parts of the network. The heavy traffic load consumes them much energy and depletes their batteries very quickly. Therefore, they are more likely to suffer from early disconnection of the network. This so-called energy hole problem leads to the imbalance of energy consumption, and seriously affects the lifetime of the entire network.

Intuitively when the sink becomes movable, sensor nodes around the sink are changed over time, so that the energy consumption is balanced to some extent. I. Akyildiz et al.[2] demonstrate the effectiveness of the application of the mobile sink both by theoretical analysis and experimental study. Results show that the joint mobility and routing strategy achieves a 500% improvement of the network lifetime.

Sink mobility can be classified into three categories, namely: random, predictable and controllable mobility. First, random mobility is relatively easy with no real-time information in need. However, there is a chance that the sink moves back to the area with little energy. And as links break and connect frequently, huge data latency may exist. Second, using predictable mobility, sensor nodes have known the trace of the sink, so they often wait until the sink moves to its optimal location. It saves energy, but the network structure must be fixed and the cache of sensor nodes might be overflowed. Third, controllable mobility allows the sink to decide its movement according to the real-time parameters or the feedback of the sensors. It is much complicated, and the frequent relocation brings heavy overhead.

Clustering is an efficient routing method where the entire network is divided into multiple clusters. Each cluster has one cluster head which is responsible for data aggregation. Instead of direct communication with the sink, all the member nodes in one cluster send data to the cluster head. In this way, the traffic load can be reduced.

In this paper, we propose a Mobile-sink based Energy-efficient Clustering Algorithm (MECA) for WSNs. In MECA, energy consumption is our primary focus. We deploy the mobile sink at the edge of the sensing field. The sink moves along a fixed track and it is predictable. The network is divided into several equal clusters. Each cluster head collects data and sends it to the mobile sink. It is selected based on the residual energy. An intra-cluster routing algorithm is also proposed using multi-hop scheme. Therefore, it not only saves energy through clustering, but ensures that the workload is dispersed so as to alleviate the problem of the unbalanced energy consumption around one static sink.

The rest of the paper is organized as follows. Section 2 introduces some related work of clustering algorithms and mobile sink applications. In Section 3 we first present relevant network and energy models. Then we show clustering-related method and describe the relocation of the sink and routing algorithm in our MECA. Performance evaluation is given in Section 4 and Section 5 concludes this paper.

2. RELATED WORK

LEACH[3] is a classical clustering algorithm. In a periodical way, it randomly chooses the cluster heads. PEGASIS[4] is an improvement over LEACH. It's a chain-based protocol. Each node communicates only with a close neighbor and take turns transmitting to the sink. HEED[5] also improve LEACH. Cluster heads are decided based on the average minimum reachability power. In TTDD[6], a grid structure is maintained. It provides scalable and efficient data delivery.

Mobile-sink based schemes have been proposed to balance energy consumption and prolong network lifetime for WSNs in recent years.

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R.C. Shah et al.[7] propose a three-tier architecture having mobile entities called Data Mobile Ubiquitous LAN Extensions (MULEs). The MULE moves randomly in the sensing field, and collects data within the transmission range of certain sensors along the path. It traverses the entire network. Once it reaches the resource, all data is delivered. R. Sugihara et al.[8] also formulate a data mule which traverses the sensing field and collects data if any sensor is in close proximity. However, the mules are controllable. A heuristic algorithm is designed to minimize the data delivery latency. Both location and time constraints in the scheduling problem are under consideration. M. Ma et al.[9] propose an energy efficient data gathering mechanism, in which a mobile data observer called SenCar works as a mobile sink. As the transmission range of a sensor is limited, it is necessary to plan the clusters of the network and find the proper turning points. It prolongs the network lifetime, but the latency is relatively high. In [10], the adaptive SPIN protocol is used to deliver critical data out of the communication range between the sensor and the sink. The sink moves randomly within the sensing field, and it has been proved that neither its speed nor direction would affect the transmission efficiency. G. T. Shi et al.[11] propose a data gathering scheme MADG, in which the sink moves in a stationary area exploited for data buffering. The gathered data is sent into the buffer and got collected by the sink. Both energy consumption and load balancing are considered in the scheme, a relatively optimal location can be determined respectively. J. M. Wang et al. [12] improve MADG with a more concise style for the design of the data buffer. A location which provides the network with the longest lifetime is found. However, both schemes take large latency. A. Kansal et al.[13] propose a communication protocol between the sensors and the sink, which supports a fluid infrastructure and long sleep durations on energy-constrained devices. Adaptive algorithms are used to control mobility. The Shortest Path Tree (SPT) is used to select the sub-sink and relay data. S. Gao et al.[14] solve the imbalance of both traffic load and energy consumption of SPT using an algorithm called MASP. MASP is formulated as an integer linear programming problem which is solved by a generic algorithm. It optimizes the mapping between the members and sub-sinks.

Despite the mobility of the sink, multiplicity can also achieve some improvement in the aspects of network lifetime and energy consumption

X. Wu et al.[15] propose an energy-efficient and distributed protocol for data collection (Dual-Sink). A fixed sink locates in the center of the network, while a mobile sink moves randomly. Sinks broadcast their locations, and each sensor chooses one sink for data transmission. Y. B. Weng et al.[16] propose a data gathering scheme with both static and mobile sinks. The network is divided into two areas, which are controlled by one sink respectively. The best radius of data gathering of the static sink can be determined, which balances the lifetime and total energy consumption. L. Friedmann et al.[17] propose a dynamic approach exploits the mobility and multiplicity of sinks. The mobility should ensure the optimization of the performance as well as the minimization of the overhead. The algorithm is centralized and complicated. In [18], a hierarchical topology of clustering is applied. Cluster heads work as mobile sinks, allowing collaboration with each other. Three heuristic strategies are proposed, respectively taking priority of the residual energy, event and a hybrid of both factors.

3. OUR PROPOSED MOBILE-SINK BASED ENERGY-EFFICIENT CLUSTERING ALGORITHM

3.1 RELEVANT MODELS

3.1.1 NETWORK MODEL

We assume that the network is composed of N sensor nodes, denoted as: $\{S_1, S_2, ..., S_N\}$ respectively. They are uniformly dispersed within a square field with a radius of R and continuously monitor their surrounding environment. We initially deploy one mobile sink BS at the edge of the square. The sink moves counterclockwise (or clockwise) with certain velocity along the arc, as is shown in Figure 1. Its track is fixed and the movement is predictable. We make the following assumptions:

(1) All nodes are homogeneous and stationary after deployment.
(2) The sink node is pre-located at the edge of the sensing field.
(3) Nodes can adjust their transmission power according to the relative distance to receiver
(4) Links are symmetric.

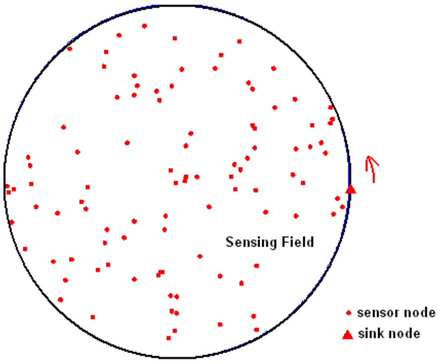

Figure 1 Network model

3.1.2 ENERGY MODEL

We use similar energy model as [19]. Based on the distance between transmitter and receiver, a free space (d^2 power loss) or multi-path fading (d^4 power loss) channel models are used.

Each sensor node will consume the following E_{Tx} amount of energy to transmit a *l*-bits packet over distance *d*:

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

where the E_{elec} is the energy dissipated per bit to run the transmitter or receiver circuit, ε_{fs} and ε_{mp} represent the transmitter amplifier's efficiency and channel conditions.

To receive a packet, radio consumes energy:

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

3.2 RELOCATION OF THE SINK

Mobile sink schemes improves network lifetime. However, previous studies on sink mobility either assume that global information of the network is already available or the mobile sink convey the global information through repeated network-wide broadcasting. Thus the gain in network lifetime can be offset by the broadcasting which incurs extra high energy consumption.

In our algorithm, the moving direction (counterclockwise or clockwise) and velocity v of the sink are both pre-determined. Therefore the sink only needs to broadcast across the network to inform all sensor nodes of its current location P_0 at the very beginning for just one time. Later on, as sensor nodes keep record of the original location of the sink, they can reduce the changed angle θ after a time interval Δt:

$$v=\frac{\theta * R}{\Delta t} \Rightarrow \theta=\frac{v * \Delta t}{R} \qquad (3)$$

As P_0 is known to all, the new location $P_{\Delta t}$ can be determined, as is shown in Figure 2.

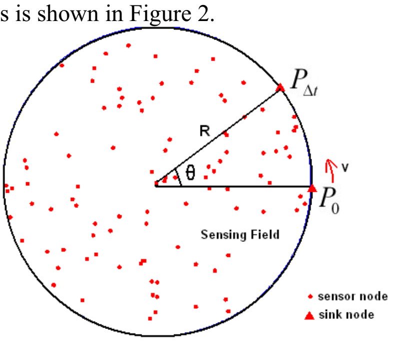

Figure 2 Relocation of the sink

After the broadcasting finishes, the mobile sink is prepared or collecting data. Here, we assume that the mobile sink stays at a site for a period long enough for the network to complete a round of data collection, and then moves to the next site.

3.3 CLUSTER FORMATION AND CLUSTER HEAD SELECTION

Different from other clustering algorithms, we divide the entire network into c equal clusters, so that the cluster formation is achieved first, as is shown in Figure 3. In our paper, we assume c=5.

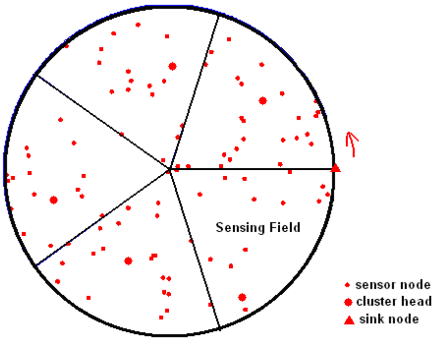

Figure 3 Cluster formation

Each cluster has only one cluster head. The other nodes in the same cluster send data to the cluster head. Then each cluster head makes data fusion and forward the aggregated data to the sink. The clustering method proposed in our MECA has various advantages. First and foremost, data aggregation reduces traffic load. Second, the cluster heads locate in a more uniform way comparing to the probabilistic deployment in LEACH. It is more suitable for the large-scale deployed networks. Last but not the least, as a majority of nodes close the communication module for relatively long time, it can prolong the network lifetime.

After equally dividing the sensing field into equal sectors, we will next choose each cluster head. As the network is considered to be heterogeneous, we determine each cluster head based on its residual energy.

When the selection begins, we first motivate the sensor node that is located in the center of each cluster like S_i. It is regarded as the cluster head candidate. It broadcasts one message within a neighborhood of radius R. This message aims to motivate other nodes for the competition of the cluster head. It contains the node's id and its residual energy. Only the nodes within the transmission range can receive the message and become active, while the outside nodes remain idle. If any node S_j has larger residual energy than S_i, it becomes the new cluster head candidate and broadcasts new message with its own information to the others. If S_j has equal residual energy with S_i, compare the ID. The node with a smaller ID wins. If S_j has smaller residual energy than S_i, it still broadcasts the message of S_i. As soon as the comparison is done, the un-chosen node becomes idle again. All nodes in the cluster should be compared only once. In this way, the node with the largest residual energy is chosen as the cluster head.

The cluster-selection algorithm can be formulated as to find $Max(E_{residual})$.

3.4 ROUTING PROCEDURE

In many clustering algorithms such as LEACH, the sensor nodes in the same cluster send data directly to the cluster head. Due to the inflection of the location, some sensor nodes may consume large amount of energy through long-distance transmission. Therefore, we set a multi-hop routing protocol for intra-cluster routing.

For any member node S_i in one cluster, the energy consumption it costs to send data directly to its cluster head CH_{S_i} is represented as $E_1(S_i, CH_{S_i})$.

$$E_1(S_i, CH_{S_i}) = \begin{cases} lE_{elec} + l\varepsilon_{fs} d(S_i, CH_{S_i})^2, d(S_i, CH_{S_i}) < d_o \\ lE_{elec} + l\varepsilon_{mp} d(S_i, CH_{S_i})^4, d(S_i, CH_{S_i}) \geq d_o \end{cases} \tag{4}$$

In the mean time, S_i tries to find another sensor node S_j to relay data which may consume less energy than that through directly communication with CH_{S_i}. Since the direction of data transmission can be randomly chosen, various nodes can be chosen, which turn out to cause various energy consumptions.

Suppose S_i chooses S_j as its relay node and let S_j have direct communication with the cluster head CH_{S_i}. To deliver a l-length packet to the cluster head, the energy consumed by S_i and S_j is calculated as

$$\begin{aligned} & E_2(S_i, S_j, CH_{S_i}) \\ & = E_{Tx}(l, d(S_i, S_j)) + E_{Rx}(l) + E_{Tx}(l, d(S_j, CH_{S_i})) \\ & = l(E_{elec} + \varepsilon d^{\alpha}(S_i, S_j)) + lE_{elec} + l(E_{elec} + \varepsilon d^{\alpha}(S_j, CH_{S_i})) \\ & = 3lE_{elec} + \varepsilon d^{\alpha}(S_i, S_j) + \varepsilon d^{\alpha}(S_j, CH_{S_i}) \end{aligned} \tag{5}$$

Where ε and α vary in different situations according to the energy model. If the sensing field is relatively small, the free space model is applied, so the variation of formula (5) depends on the value of $d^2(S_i, S_j) + d^2(S_j, CH_{S_i})$. Many researches adopt this case for simplicity, such as [20], where the shortest distance ensures the least energy consumption. Anyhow, our algorithm performs in a more concise way.

Each S_i chooses S_j with the smallest value of $E_2(S_i, S_j, CH_{S_i})$ as the relay node if necessary.

$$E_2(S_i, CH_{S_i}) = Min(E_2(S_i, S_j, CH_{S_i})) \tag{6}$$

Compare formula (4) and formula (6), and the smaller one is chosen.

$$E(S_i, CH_{S_i}) = Min(E_1(S_i, CH_{S_i}), E_2(S_i, CH_{S_i})) \tag{7}$$

In our algorithm, however, the sink node changes it location over time. Therefore, some nodes may consume less energy through sending data directly to the sink rather than to its cluster head. So it is necessary to compare $E(S_i, CH_{S_i})$ and $E(S_i, BS)$ and decide the final route.

The intra-cluster algorithm can be formulated as to find $Min(E(S_i, CH_{S_i}), E(S_i, BS))$.

4. PERFORMANCE EVALUATION

4.1 SIMULATION ENVIRONMENT

We evaluate the performance of the MECA via simulations in Matlab. The simulation environment is set up with the parameters listed in Table 1. We assume that all the senor nodes and the sink nodes are uniformly deployed in a square sensing area.

Table 1 Network parameters

Parameter Name	Value
Number of the sensor nodes (N)	100
Length of the packet (l)	6bit
Initial energy of the sensor nodes (E_{init})	0-2J
Energy consumption on circuit (E_{elec})	50nJ/bit
Channel parameter in free-space model (ε_{fs})	10pJ/bit/m^2
Channel parameter in multi-path model(ε_{mp})	0.0013pJ/bit/m^2

4.2 SIMULATION RESULTS

For performance evaluation, mobility of the sink remains the focus of our research. Figure4 shows the energy consumption in a 500*500 m^2 network when the sink moves with different velocity. The values of 20,30,45,60 respectively represent different changed angle of each movement within an interval time. Therefore, value of the angle reflects velocity of the sink. As is shown in Figure 4, there is little different among different situations. We can conclude that velocity of the sink has little influence on total energy consumption in our MECA.

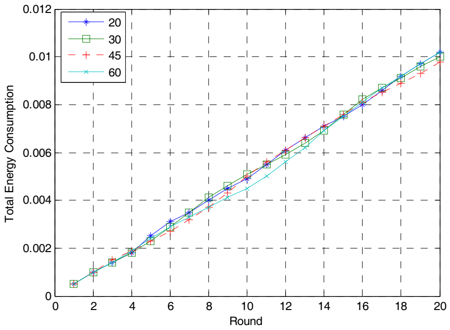

Figure 4 Energy consumption with different velocities of sink

Similarly, in our algorithm the movement track of the sink is initially set as the edge of the square. However, readers may wonder whether different track circles, as is shown in Figure5, affect total energy consumption. Figure 5 shows the simulation result considering that the sink moves along circles of different radius to the center in a 500*500 m^2 network. Energy consumptions are almost the same. Therefore, we can conclude that the movement track of the sink has little influence on total energy consumption in our MECA.

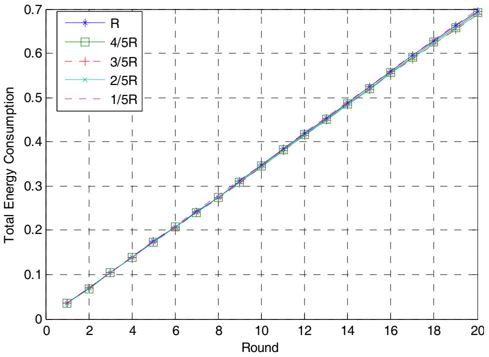

Figure 5 Energy consumption with different sink track

We compare the total energy consumption between our MECA and LEACH algorithm in a 500*500 m^2 network, as is shown in Figure 6. In 20 rounds, MECA consumes much less energy than LEACH algorithm. This is mainly because of the clustering method that implements data fusion to reduce the transmission cost along the path. Multi-hop also saves energy inside each cluster.

We also consider multiplicity of the sink. We assume that sinks are deployed with certain interval. As is shown in Figure8, four sinks move together with the same velocity and direction. Sensor nodes choose one of them for data transmission according to the energy consumption. The distribution is more uniform than the single sink.

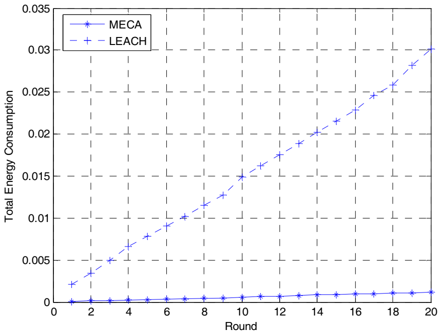

Figure 6 Total energy consumption of MECA andLEACH

Figure 7 and Figure 8 respectively show the total energy consumption of a 500*500 m^2 and 300*300 m^2 network respectively with different number of the sink nodes. Under all circumstances, it is obvious that the total energy consumption decreases while the number of the sinks increases. Both figures reflect that once four sinks are deployed, the energy consumption becomes so small that more sinks would hardly make any difference. Thus we can conclude that four sink nodes are actually enough as total energy consumption becomes relatively small.

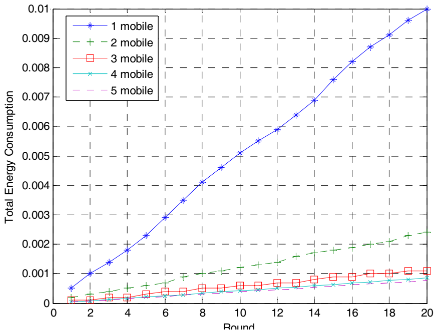

Figure 7 Multi-sink energy consumption in 500*500 m^2 network

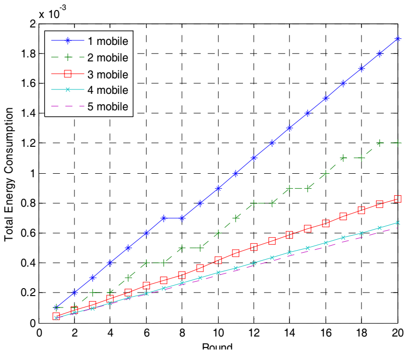

Figure 8 Multi-sink energy consumption in 300*300 m^2 network

5. CONCLUTION

Mobile-sink deployment helps solve the energy hole problem. We proposed a Mobile-sink based Energy-efficient Clustering Algorithm (MECA) for WSNs in this paper. The mobile sink moves around the edge of the square sensing field. Clustering technique is involved and multi-hop intra-cluster routing algorithm ensures less energy consumption. We mainly focus on studying the performance of both sink mobility and multiplicity. Simulation results show that the energy consumption of our MECA is largely reduced than LEACH algorithm.

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