Residual-energy Aware LEACH Approach for Wireless Sensor Networks

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***Abstract*—In wireless sensor networks (WSNs), sensor nodes are randomly deployed in a monitoring area. Due to the energy of each sensor node is limited, it is vitally important to reduce the node's energy consumption for prolonging the lifetime of WSNs. In this paper, we develop a residual-energy aware low energy adaptive clustering hierarchy (LEACH) approach to equalize the energy consumption of the nodes and prolong the system lifetime. Specifically, the optimal number of cluster heads (CHs) is determined by optimizing the energy consumption of the whole WSNs, and the threshold of selecting CHs is achieved to leverage the node's energy consumption. Simulation results show that the performance of the proposed approach performs better than the conventional LEACH approach in terms of the energy consumption of every node as well as the number of surviving nodes, and it effectively prolongs the lifetime of the WSNs.**

***Keywords*: wireless sensor networks, low energy adaptive clustering hierarchy, cluster heads, energy consumption**

I. Introduction

Wireless sensor networks (WSNs) consist of a large number of sensor nodes, which are randomly scattered to collect environmental condition of an area, such as temperature, humidity, pressure, solar radiation and concentration of carbon dioxide [1]-[6]. Because of its self-organization, rapid deployment, high fault-tolerance and strong concealment, WSNs have been widely developed in industry and agriculture, national security, urban monitoring, and space exploration [7]-[10]. However, it is noted that the resources of sensor nodes are constrained, generally lacking of stable and continuous energy supplement. Due to the reason that the sensor nodes are usually located in inaccessible or dangerous areas where the battery cannot be replaced in low cost, it is a great challenge to improve the resource utilization and reduce the energy consumption cost in the resource-constrained WSNs.

While deploying wireless sensor networks, the optimal control of energy consumption is a primary problem [11]. Topology control is quite important to reduce the number of dead nodes thus prolonging the lifetime of WSNs [12] [13]. Heinzelman et al. [14] proposed a low energy adaptive clustering hierarchy (LEACH) protocol for WSNs which can reduce the node's energy consumption effectively. However, there are still some disadvantages for the LEACH application. When selecting a cluster head (CH), the CH is generated by a random number (between 0 and 1) without consideration of the residual energy of the node. It is extremely likely to select the low energy node as the CH by mistakes, which may accelerate the death speed of nodes. At the same time, overmuch clustering would reduce the efficiency of energy in WSNs considering of the uncertain number of CHs.

In view of the problems above, the LEACH scheme is investigated in terms of the lifetime of WSNs and the number of CHs [15]-[19]. In [15], LEACH-C used a centralized clustering algorithm to disperse the CHs. According to the probability which is related to the node's residual energy, the base station (BS) uses the simulated annealing algorithm to perform the unified clustering and select the CHs [16]. Compared with LEACH, this protocol effectively increases the amount of data received by the BS and extends the lifetime of the system. However, due to the centralized clustering algorithm, each node must communicate with the BS, it relies on the BS too much and cannot be applied to large-scale WSNs. In [17], the existing LEACH protocol was modified by introducing a threshold limit for CH selection with simultaneously switching the power level between the nodes, but it didn't consider the number of clusterings. In [18], it presented a data-stream aggregation algorithm called W-LEACH for WSNs which extends LEACH. W-LEACH is able to handle non-uniform networks as well as uniform networks, while not affecting the network lifetime, but it cannot avoid the premature death of certain nodes. In [19], it presented an energy efficient clustering algorithm to select the CHs based on modified LEACH without using the location information of nodes, which is likely to cause the earlier death of some nodes. Thus, how to ameliorate the mechanism of selecting CHs and also to optimize the number of CHs in LEACH become the key to enhance the lifetime of WSNs.

In this paper, we develop a residual-energy aware LEACH approach. In particular, the optimal number of CHs is determined by optimizing the energy consumption of the whole

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networks, and the threshold of selecting CHs is obtained according to the balance of energy consumption. Simulation results demonstrate that our proposed residual-energy aware LEACH approach performs better than the conventional LEACH approach in terms of energy consumption, the number of surviving nodes and sensing areas, respectively.

II. Theoretical Preliminaries

A. The LEACH Architecture

LEACH is the earliest high-performance topology control algorithm, which transmits data to the BS by clustering [20]. It is a distributed clustering scheme proposed for uniform distribution of energy consumption among all the nodes in WSNs. The sensor nodes in WSNs are divided into the CHs and the ordinary nodes (ONs). The ONs play the role of monitoring and collecting data. The CHs perform the operations of processing (such as de-redundancy and data fusion) and delivering the data packets to the BS.

The LEACH approach executes in rounds such that each round can be divided into two phases namely, a setup phase and a stable state phase. It can prolong the lifetime of sensor nodes since it ensures fair energy consumption. It chooses the CHs uniformly, which does not fit for non-uniform networks.

In the setup phase, WSNs specify $P\%$ of n sensor nodes as CHs based on the comparison of a random number (between 0 and 1) and the threshold function $T(n)$ defined as

$$T(n) = \begin{cases} \frac{P}{1-P*\left(r \bmod \frac{1}{P}\right)}, & \text{if } n \in G, \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where P is the desired number of CHs, r is the current round, and G is the set of those nodes which are non-CHs in the last $\frac{1}{P}$ rounds. After the CHs are specified, clusters are dynamically set up such that the ordinary nodes (non-CHs) become the members of a cluster with the nearest CH.

In the stable state phase, the ONs transmit the collected data based on Time Division Multiple Access (TDMA) to the CHs. The CHs perform the information fusion over all of the nodes in the cluster and then transmit to the BS.

B. System Model

We assume that there are N sensor nodes which are randomly distributed in M m $\times$ M m monitoring area to form the WSNs, and the structure is shown in Fig. 1. For the sake of analysis, we make the following assumptions. Firstly, the monitoring area is free of obstacles, and the BS has sufficient energy which is installed at the center of the monitoring area. Then the communication between nodes which remain stationary and homogeneous is single-hop.

Fig. 1 shows that the system model consists of the ONs, the CHs and the BS. The ONs play the role of monitoring and collecting data. The CHs perform the operations of data processing such as de-redundancy and data fusion. Users control the network through the BS.

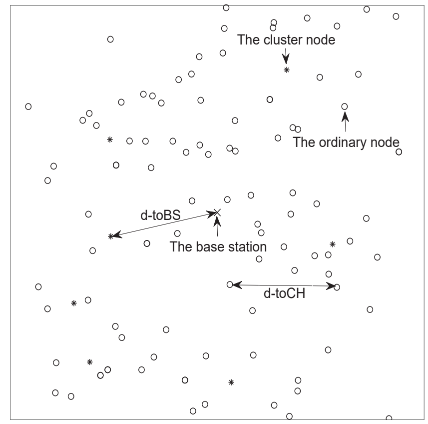

Fig. 1. The deployment diagram of WSN.

C. Modelling of Communication Energy Consumption

We adopt the first order radio model to describe the sensor status of communication energy consumption. The WSNs use a multipath fading model and a free space propagation model to calculate the energy consumption when exchanging information between the transmitting node and the receiving node in different situations. We assume that the energy consumption of transmitting and receiving 1-bit data is E_{elec}, and d is the distance between the transmitting node and the receiving node. Therefore, the energy consumption of transmitting l-bits is computed as

$$\begin{cases} E_{Tx}(l,d) = lE_{elec} + l\varepsilon_{fs}d^2, & d < d_0, \\ E_{Tx}(l,d) = lE_{elec} + l\varepsilon_{amp}d^4, & d \geq d_0, \end{cases} \tag{2}$$

where l is the length of the transmitting data package, d is the distance between the transmitting node and the receiving node, d_0 is the threshold of the multipath fading model and the free space propagation model, generally about 80 m. ε_{fs} is the parameter of free space propagation model, ε_{amp} is the parameter of multipath fading model. E_{elec} is the energy consumption for transmitting and receiving 1-bit data.

The energy consumption of receiving l-bits is computed as

$$E_{Rx}(l) = lE_{elec}. \tag{3}$$

If we know the length of the transmitting data package l, we can calculate the energy consumption of transmitting and receiving.

III. The Residual-energy aware Low Energy Adaptive Clustering Hierarchy approach

A. The Optimal Number of Cluster Heads

Let the initial number of CHs be k and use the energy consumption model to derive the optimal number of CHs K_{opt}.

There are N sensor nodes which are randomly distributed in M m $\times$ M m monitoring area to form the WSNs. If there are k clusters, each cluster contains $\frac{N}{k}$ nodes, including a cluster head and $\left(\frac{N}{k}-1\right)$ ONs. The energy consumption of CHs mainly consists of three parts:

- the CHs broadcast a clustering message and receives the data from the ONs,
- the CHs perform the data fusion,
- the CHs transmit the processed data packets to the BS.

Therefore, when the CH processes a frame of data, the energy consumption is

$$E_{CH}=lE_{elec}\left(\frac{N}{k}-1\right)+lE_{DA}\frac{N}{k}+lE_{elec}+l\varepsilon_{amp}d_{toBS}^{4}, \tag{4}$$

where d_{toBS} is the distance between the CH and the BS, E_{DA} is the energy consumed in data fusion for 1-bit.

The ONs transmit the information collected to the corresponding CHs. In this paper, the ONs are close to the CHs, so the free space propagation model is adopted when communicating in a cluster. Therefore, the energy consumption of the member nodes is

$$E_{non-CH}=lE_{elec}+l\varepsilon_{fs}d_{toCH}^{2}, \tag{5}$$

where d_{toCH} is the distance between the ordinary node and the CH.

The area of each cluster is approximately $\frac{M^2}{k}$. The general perceptual area is distributed randomly and let the distributed density be $\rho(x,y)$. Here, the CH is located at the center of the cluster, hence

$$E_{d_{toCH}^{2}}=\iint(x^2+y^2)\rho(x,y)dxdy=\iint r^2\rho(r,\Theta)drd\Theta. \tag{6}$$

Assuming that the radius of this region is $R=\frac{M}{\sqrt{\pi k}}$, and $\rho(x,y)$ is constant for r and Θ, Eq. (6) can be simplified as

$$E_{d_{toCH}^{2}}=\rho\int_{\Theta=0}^{2\pi}\int_{r=0}^{\frac{M}{\sqrt{\pi k}}}r^3drd\Theta=\frac{\rho}{2\pi}\frac{M^4}{k^2}. \tag{7}$$

The density of the cluster is constant and $\rho=\left(\frac{1}{\frac{M^2}{k}}\right)$, then $E_{d_{toCH}^{2}}=\frac{1}{2\pi}\frac{M^2}{k}$, the energy consumption of the member nodes is $E_{non-CH}=lE_{elec}+l\varepsilon_{fs}d_{toCH}^{2}$. Thus, the energy consumption of each cluster is

$$\begin{aligned}E_{cluster}&=E_{CH}+\left(\frac{N}{k}-1\right)E_{non-CH}\\&\approx E_{CH}+\frac{N}{k}E_{non-CH}.\end{aligned} \tag{8}$$

Therefore, the total energy consumption of WSN is

$$\begin{aligned}E_{total}=kE_{cluster}=l\Big(&E_{elec}N+E_{DA}+k\varepsilon_{amp}d_{toBS}^{4}\\&+E_{elec}N+\varepsilon_{fs}\frac{1}{2\pi}\frac{M^2}{k}N\Big).\end{aligned} \tag{9}$$

Finally, we take a derivative with respect to k from E_{total} and calculate the optimal number of CHs K_{opt} in WSNs.

Algorithm 1 Residual-energy Aware Low Energy Adaptive Clustering Hierarchy Algorithm

```
initialize N, E_0, E_elec, ε_fs, ε_amp, E_DA, DM, CM
calculate the optimal number of CHs K_opt
select CHs based on the threshold T'(n)
if nodes is CHs then
    announce CHs status and create TDMA schedule, aggregate data and send data to BS
else
    wait for the announcement by CHs and the TDMA schedule from CHs, then send data to CHs
end if
go to the next round
Return result
```

$$K_{opt}=\sqrt{\frac{N}{2\pi}}*\sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{amp}}}*\frac{M}{d_{toBS}^{2}}. \tag{10}$$

B. Energy-based Cluster Head Selection Threshold

The scale of clusters and the selection of CHs have a great impact on the total energy consumption of WSNs. On the one hand, when the scale of clustering is small, it is easy to cause unreasonable energy consumption in WSNs. On the other hand, when the scale of clustering is large, the CHs is overburdened and the communication traffic between the member nodes is increased rapidly. Therefore, the mechanism of the energy-based cluster head selection in this paper is proposed. We design the threshold of CHs as

$$T'(n)=\begin{cases}\frac{P}{1-P*\left(r \bmod \frac{1}{P}\right)}W(resi_{energy},init_{energy}), n\in G,\\ 0,\quad \text{otherwise}\end{cases} \tag{11}$$

where P is the percentage of CHs, G is the set of nodes which are not selected as CHs in the nearest $\frac{1}{p}$ round, r is the current rounds. $W(resi_{energy},init_{energy})=\sqrt{\frac{resi_{energy}}{init_{energy}}}$ is a weight factor which is related to the initial and residual energy of each node. $init_{energy}$ is the initial energy of each node, and $resi_{energy}$ is the residual energy of each node.

C. Algorithm Description

The algorithm performs cyclic reconstruction of clustering during execution, and it is still carried out in the same round as the conventional LEACH. Each round is still divided into the phase of clustering formation and the phase of transmitting data stably.

Among them, the phase of clustering formation is divided into four stages in details:

- WSNs select the CHs,
- the CHs broadcast the clustering message,
- the ONs join into the clustering,
- the ONs generate a scheduling mechanism.

In the phase of transmitting data stably, the ONs transfer collected data to the CHs. Then the CHs perform the data

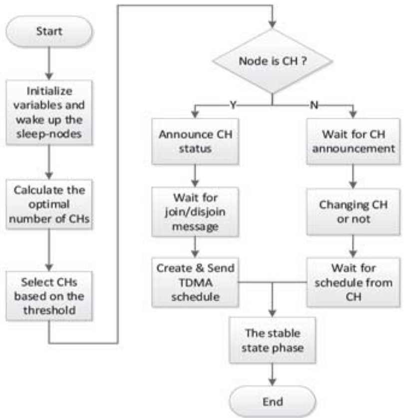

Fig. 2. The setup phase of the proposed LEACH algorithm.

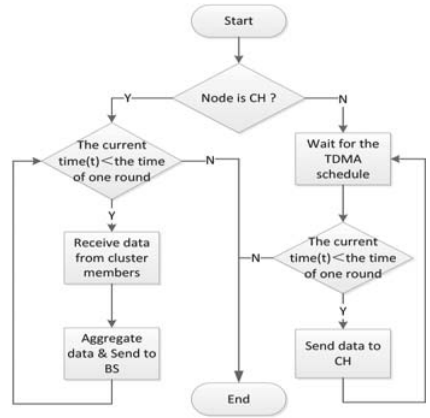

Fig. 3. The stable state phase of the proposed LEACH algorithm.

fusion and relay to the BS. The exact details of the residual-energy aware LEACH algorithm are outlined in **Algorithm 1**. Fig. 2 and Fig. 3 show the algorithm flowchart of clustering formation and the phase of transmitting data stably.

The specific steps are given as follows:

Step 1: Distributing N sensor nodes in the M m $\times$ M m monitoring area randomly, and deploying a sink node or a base station in the center of the monitoring area. Its structure diagram is shown in Fig. 1.

Step 2: The sensor nodes broadcast their information to the WSNs.

Step 3: Determining the optimal number of CHs K_{opt} according to Eq. (10).

Step 4: The CH is determined according to K_{opt} and the times that the cluster has already become CHs. The specific selection method is as follows: each node generates a random number (between 0 and 1) and compares the number with the threshold shown in Eq. (11). If the number is less than the threshold, it is selected as CHs.

Step 5: The clustering message is broadcasted to the whole networks, then the remaining nodes receive the message and send a joining message to the closest CH to complete the clustering formation.

Step 6: The CHs use TDMA to allocate time slots to member nodes for exchanging data.

Step 7: During the phase of transmitting data stably, the member nodes transfer the collected data to the corresponding cluster and the CHs send the fused data to the BS.

Step 8: When completing the current round, going to the next round and repeating step 3−7.

IV. Evaluations and Analysis

In order to analyze the residual-energy aware LEACH approach over the conventional LEACH approach, the wireless sensor nodes are located as the same distribution in the following simulations [20].

TABLE I
Simulation parameters

Variables	Value
The number of sensor nodes	N =100
The width of monitoring area	M=100m
Initial energy	E_0=0.4 J
BS location	(50m,50m)
Energy consumed for transmitting and receiving 1-bit data	$E_{elec} = 5 \times 10^{-8}$ J/bit
Amplifier energy of free space	$\varepsilon_{fs} = 10\text{pJ/bit/m}^2$
Amplifier energy of multi-path	$\varepsilon_{amp} = 0.0013\text{pJ/bit/m}^4$
Energy consumed in data fusion for 1-bit	$E_{DA} = 5 \times 10^{-9}$ J
Number of data package	DM=4000 bits
Number of control package	CM=32 bits

A. Simulation Parameters

The wireless sensor nodes are randomly deployed in an area of 100 m $\times$ 100 m. The sink node or base station is located at the center of the area. Other simulation parameters are listed in TABLE I.

B. Analysis of Simulation Results

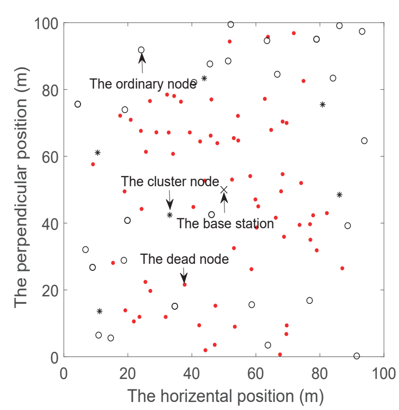

Fig. 4. Distribution of death nodes in the 100th round in the conventional LEACH.

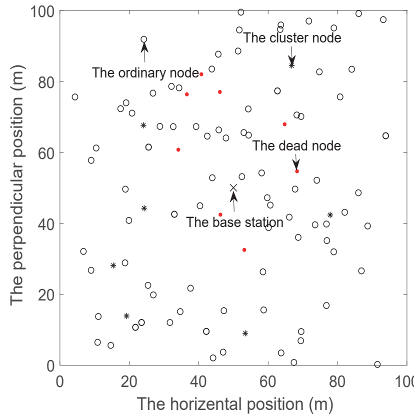

Fig. 5. Distribution of death nodes in the 100th round in the residual-energy aware LEACH.

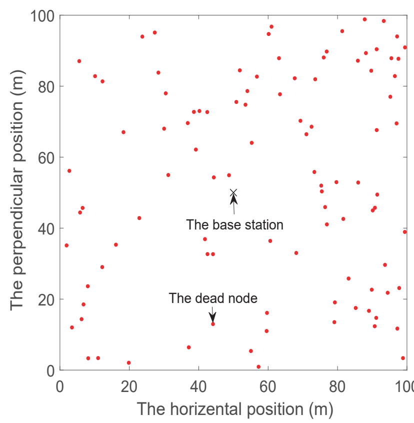

Fig. 6. Distribution of death nodes in the 200th round in the conventional LEACH.

In order to analyze whether the energy consumption in WSNs is equalized or not, the number of dead nodes and survived nodes in each round is compared. Fig. 4 and Fig. 5 show the distribution of dead nodes and survived nodes in the 100th round between the residual-energy aware LEACH approach and the conventional LEACH approach. Fig. 6 and Fig. 7 show the distribution in the 200th round. We observe that both the residual-energy aware LEACH approach and the conventional LEACH approach have already appeared dead nodes in 100 and 200 rounds. Meanwhile, it is clearly seen that the number of dead nodes in the proposed approach is far less than the other because of the using of the optimal number of CHs and the energy-based CH selection threshold. The large area of dead nodes means that the WSNs are about to fail to work properly.

Fig. 8 shows the tendency of the number of dead nodes in both the residual-energy aware LEACH approach and the conventional LEACH approach under the same random distribution. Due to the uncertain number of CHs and without consideration of the residual energy of every node, we observe

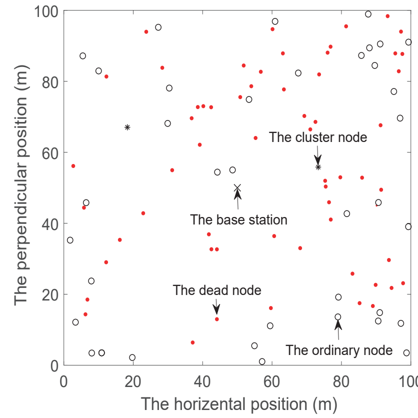

Fig. 7. Distribution of death nodes in the 200th round in the residual-energy aware LEACH.

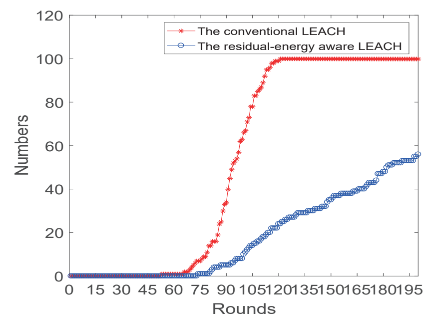

Fig. 8. Trend of death nodes.

that it appears the first dead node around 65 rounds and the number of dead nodes increases sharply which means the WSNs nodes have died in a large scale in the conventional LEACH approach. In contrast, the first dead node in the residual-energy aware LEACH approach can be found around 70 rounds and the number of dead nodes increases gently in working rounds. This indicates that the proposed approach delays the round of first dead node and the energy consumption is more equalized.

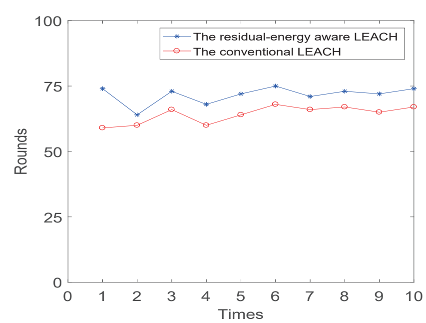

Fig. 9. N=100,the rounds of the first died node.

In order to avoid the contingency of a single simulation,

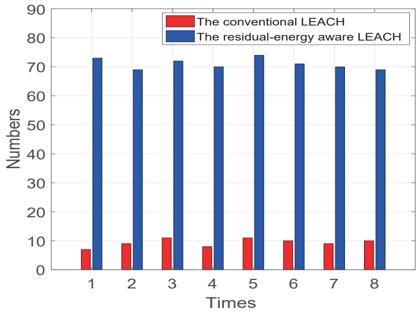

Fig. 10. Number of dead nodes in the 100th round.

Fig. 9 shows the rounds of the first dead node between the two approaches in multiple simulations and the same random distribution. We observe that the round of first dead node in the residual-energy aware LEACH approach are always later than that in the conventional LEACH approach. Fig. 10 shows the number of dead nodes in the 100th round in multiple simulations. It is obvious that the number of dead nodes in the 100th round in the proposed approach is far less than the other. When comparing the conventional LEACH and the residual-energy aware LEACH approach, we show that the proposed approach consumes less energy than LEACH and the energy consumption is more balanced, this is due the optimal number of CHs and the the threshold of selecting CHs.

V. Conclusions

In this paper, we develop a residual-energy aware LEACH approach to equalize the energy consumption of the nodes and prolong the system lifetime. In particular, the optimal number of CHs is determined by optimizing the energy consumption of the whole networks, and the threshold of selecting CHs is obtained according to the balance of energy consumption. The proposed residual-energy aware LEACH approach performs better than the conventional LEACH approach in terms of energy consumption, the number of surviving nodes and sensing areas, respectively.

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