An Energy Harvesting Aware Routing Algorithm for Hierarchical Clustering Wireless Sensor Networks

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Abstract

Recently, energy harvesting technology has been integrated into wireless sensor networks to ameliorate the nodes' energy limitation problem. In theory, the wireless sensor node equipped with an energy harvesting module can work permanently until hardware failures happen. However, due to the change of power supply, the traditional hierarchical network routing protocol can not be effectively adopted in energy harvesting wireless sensor networks. In this paper, we improve the Low-Energy Adaptive Clustering Hierarchy (LEACH) protocol to make it suitable for the energy harvesting wireless sensor networks. Specifically, the cluster heads are selected according to the estimation of nodes' harvested energy and consumed energy. Preference is given to the nodes with high harvested energy while taking the energy consumption rate into account. The utilization of harvested energy is mathematically formulated as a max-min optimization problem which maximizes the minimum energy conservation of each node. We have proved that maximizing the minimum energy conservation is an NP-hard problem theoretically. Thus, a polynomial time algorithm has been proposed to derive the near-optimal performance. Extensive simulation results show that our proposed routing scheme outperforms previous works in terms of energy conservation and balanced distribution.

Keywords: Energy harvesting, routing protocols, hierarchy, wireless sensor networks

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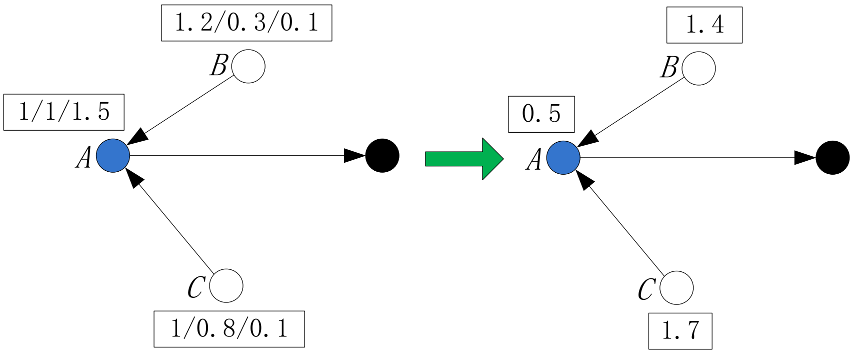
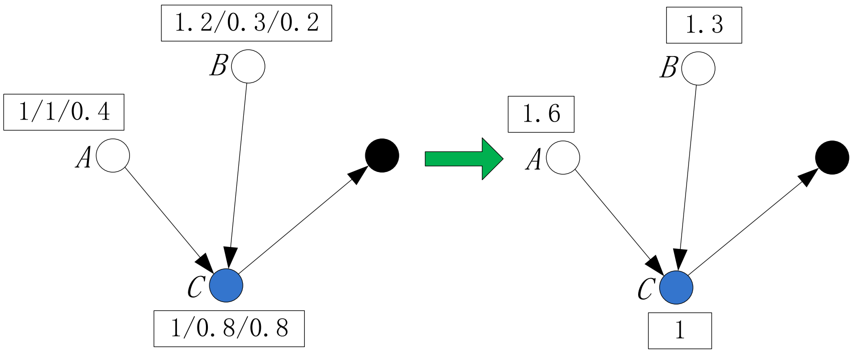
1. Introduction

Wireless sensor networks are typically made up of several battery-constrained nodes, which geographically disperses and cooperates to collect, process and transmit the data. Due to the complicated environment and diverse applications, it is difficult, or even infeasible, to provide an external power supply or to replace the exhausted batteries. Recently, the energy harvesting technology has ameliorated this problem because the node can be recharged due to its harvesting opportunity, by attaching an energy harvesting module. Numerous research works have been carried out on harvesting energy from environment, such as solar, wind and thermoelectricity [1], [2], [3]. The wireless sensor network powered by energy harvesting devices, which can scavenge energy from the surrounding environment and convert it to electrical energy, is called as an Energy Harvesting Wireless Sensor Network (EHWSN) [4]. However, in the EHWSNs, as the nodes are able to recharge their batteries, the traditional routing protocols can not be applied efficiently. Therefore, how to route the collected data packets efficiently using the harvested energy becomes a challenging task that greatly affects the overall performance of EHWSNs.

Consider the topology of an energy harvesting wireless sensor network shown in **Fig. 1(a)**. The numbers shown in the rectangles for the left subfigure of **Fig. 1(a)** are the current energy, harvested energy and consumed energy in a time period *T*, respectively. Under the energy aware routing algorithm [5], node *A* is selected as the cluster head, because the sum of its current energy and harvested energy is higher than those of the other nodes. Since the above scheme does not consider the energy consumption rate, in the following scenario we take the estimated consumed energy into account. As shown in the left subfigure of **Fig. 1(b)**, the cluster head is replaced by node *C* and the data transmission paths are changed accordingly. Thus, after data transmission, it can be derived that the sum of each node's energy in **Fig. 1(a)** is 3.6 units while that in **Fig. 1(b)** is 3.9 units and the variance of each node's energy is 0.39 in **Fig. 1(a)** while that in **Fig. 1(b)** is 0.09. Obviously, we conclude that the scheme shown in **Fig. 1(b)** is more efficient than that in **Fig. 1(a)** in terms of energy conservation and balanced distribution.



(a) Node *A* is selected as the cluster head under existing routing protocol



(b) Node *C* is selected as the cluster head so as to improve the network performance

Fig. 1. An example illustrating how to route the data packets using the harvested energy so as to improve the network performance, where the numbers in the rectangles for the left subfigures denote the current available energy, harvested energy and consumed energy in a time period *T*, respectively.

Numerous research works have been focused on the hierarchical routing protocols for WSNs. The LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol [6] proposed by Wendi et al. is one of the first clustering-based protocols utilizing randomized rotation of local cluster heads to evenly distribute the load among the sensor nodes in the network. After that, a variety of clustering protocols have been proposed to enhance the network performance from many aspects, such as communication mode [7], [8], network security [9], [10], connected area coverage [11] and node's mobility [12], [13], [14]. In [15], the authors proposed a low complexity cooperative protocol based on LEACH for wireless sensor networks. In this protocol, *M* cluster heads instead of a single cluster head are selected for each cluster to aggregate and forward the data packets. They also presented an analytical model to evaluate the energy consumption based on Bit Error Rate (BER) curve. Wu et al. proposed a dynamic gradient-aware hierarchical packet forwarding mechanism based on the relative positions of nodes. And the cluster heads are selected according to the energy conservation efficiency and relative distance [16]. Guo et al. considered applying simultaneous wireless information and power transfer technique to cooperative clustered energy-harvesting wireless sensor networks [17]. In [18], the authors proposed a novel two layer heterogeneous architecture for wireless sensor networks, combining energy harvesting and mobile data gathering technologies. The cluster heads change their positions in each data gathering cycle.

Topology control approach is also developed to improve the network performance. Dahnil et al. [19] proposed an adaptive clustering algorithm to increase the lifetime of network while maintaining the required connectivity. The optimal degree of a cluster head is achieved by adjusting its transmitting power level and this value is preserved during the whole network operations. In [5], the authors presented a novel routing scheme called Energy-Potential-LEACH (EP-LEACH) [5] based on LEACH for EHWSNs considering the harvested energy of each node. The threshold value is obtained according to the energy of each node, instead of randomly generated as that in [6]. Thus, the high energy conservation nodes are selected as the cluster heads in preference to the other nodes.

Although numerous works has been done, no work refers to the issue of improving the network performance by maximizing the minimum energy conservation considering both the harvested energy and consumed energy for each node in the EHWSNs [20], [21]. Aiming at this, we propose a low-complexity hierarchical routing scheme for the EHWSNs considering nodes' harvested energy and consumed energy. The node with high energy conservation has priority to be a cluster head. Maximizing the minimum energy conservation for each node has been proved to be an NP-hard (Non-deterministic Polynomial hard) problem and we propose a polynomial time protocol called Energy Harvesting Aware LEACH (EHA-LEACH) to achieve the approximate solution. Extensive experiments have been done to verify the performance enhancement of our proposed scheme.

The remainder of this paper is organized as follows. Section 2 introduces the system model. In Section 3, we mathematically formulate the problem and give the proof of its NP-hardness. Then, we design a low-complexity algorithm to achieve the near-optimal solution in Section 4. Simulation results are given in Section 5. Finally, we conclude the paper in Section 6.

2. System Model

In the EHWSNs, each node is typically equipped with an energy buffer or an ultracapacitor for storing the harvested energy. Such an energy storage system is practically not ideal: the energy capacity is limited, the charging efficiency, β, is strictly less than 1 and some energy is lost through leakage. The charging efficiency means that the energy buffer is not 100% efficient at storing electricity, i.e., more energy is always used to charge the battery than that can be recovered from it [22]. Therefore, we adopt the harvesting system with nonideal energy buffer to model the behavior of a load and describe the physical condition on energy conservation [23].

Let $p_h(v, t)$ denote the harvesting rate of node v from ambient environment at time t. Then, we calculate the harvested energy of node v during the time interval $[0, T]$ as

$$E_h(v, 0 \le t \le T) = \beta \cdot \int_0^T p_h(v,t)dt - \int_0^T p_{leak}(v,t)dt \tag{1}$$

where $p_{leak}(v, t)$ is the leakage power of node v at time t for the energy buffer. Note that T here can be one hour, one day or any other nonnegative time scale.

As for the energy consumption, both the free space (d^2 power loss) and multipath fading (d^4 power loss) channel propagation models have been adopted, depending on the distance between the transmitter and receiver [24]. If the distance is larger than a threshold d_0, the multipath fading model is used; otherwise, the free space model is used instead. Hence, the consumed energy for transmitting an $l - bit$ data packet a distance d during the time period $[0, T]$ can be calculated as

$$E_{tx}(l,d) = \begin{cases} l \cdot E_{elec} + l \cdot \varepsilon_{fs} \cdot d^2, & d < d_0 \\ l \cdot E_{elec} + l \cdot \varepsilon_{mp} \cdot d^4, & d \ge d_0 \end{cases} \tag{2}$$

where E_{elec} is the electronics energy, $\mathcal{E}_{fs}$ or $\mathcal{E}_{mp}$ is the amplifier energy depending on the distance to the receiver and its acceptable bit error rate. Here, for a cluster head, d denotes the distance to the base station, whereas for a non-cluster head node, d denotes the distance to its cluster head.

Also, on the receiving side, the amount of consumed energy for capturing this incoming data packet can be computed as

$$E_{rx}(l) = l \cdot E_{elec} \tag{3}$$

In this paper, the base station is supposed to be equipped with much more energy compared with the sensing nodes, which is the same as that used in other similar works [25], [26].

3. Problem Formulation

The EHWSN can be modeled as a directed graph $G(\mathbb{V}, \mathbb{E})$ with node set $\mathbb{V}$ and link set $\mathbb{E}$, where $u \in \mathbb{V}$ represents a node within the network, and a link $(u, v) \in \mathbb{E}$ means the fact that node u can communicate with node v directly. We also define $D(u, v)$ as the distance from node u to node v and D as the transmission range for each node. In other words, the link (u, v) exists while $D(u, v) < D$. Under the Energy-Potential LEACH (EP-LEACH) routing protocol [5], the network operation is broken up into rounds and the sensor nodes are separated into different clusters each round. Each round consists of the set-up clustering and the steady data transmission phases. As the data transmission paths are identified by the clustering topology, we focus on the set-up clustering phase in this paper. In the EHWSNs, the harvesting capability of every node varies from each other due to their different locations. Also, each node consumes the harvested energy with a nonuniform rate [27]. Thus, we introduce the energy potential function to measure a node's energy harvesting and consuming status. First, we define the energy potential function of node u as the following

$$F(u) = \frac{e^{(E(u,0)+E_h(u,0<t<T)-M)/A}}{1+e^{(E(u,0)+E_h(u,0<t<T)-M)/A}} \tag{4}$$

where M and A denote the mean and variance values for the energy of each node in the network and can be computed as

$$\begin{cases} M = \sum\limits_{u\in\mathbb{V}} (E(u,0)+E_h(u,0<t<T))/\,|\,\mathbb{V}\,| \\ A = \sum\limits_{u\in\mathbb{V}} (E(u,0)+E_h(u,0<t<T)-M)^2/\,|\,\mathbb{V}\,| \end{cases} \tag{5}$$

In the Eq. (5), M denotes the general energy distribution situation within the network and reflects the central tendency in statistics. It makes sense to compare individual energy status to the overall group of energy status. A denotes the variation for the energy of each node, which measures the node's energy deviation from the mean energy for the network [28].

Next, for node u, the neighboring nodes set $L(u) \leftarrow \{v \mid D(u, v) < D\}$ can be determined. Each node decides whether to be a cluster head or not by randomly generating a number between 0 and 1. If the number generated of node u is less than a pre-determined threshold $T(u)$, it becomes a cluster head in this round. Otherwise, it is not a cluster head in this round. The threshold $T(u)$ is written as

$$T(u) = \frac{F(u)}{\sum\limits_{v\in L(u)} F(v)} \cdot p \cdot |\,L(u)\,| \tag{6}$$

where p is the desired percentage of cluster heads. From this threshold expression, it can be figured out that the nodes with high energy conservation have more probability to be selected as the cluster heads, which also acts in conformity with our design principles. Because the energy potential function behaves exactly the same as the high pass filter [29].

The cluster head is responsible for forwarding the data collected from the sensing nodes belonging to the cluster head to the base station. Assume that the available energy of node v at time t is represented as $E(v, t)$. Then we denote by $E(v, t + T)$ the energy of node v after operation for a round, where a round is set as the time scale T. In this time period T, a node either plays a role in collecting the information as a non-cluster head node or aggregates and forwards the data packets as a cluster head. From Eqs. (2) and (3), we derive that the cluster heads consume more energy compared with the other nodes in a round.

Suppose the network nodes are divided into m clusters at the start of a round during the network operation. Denote by $C_i (i = 1, 2, ..., m)$ the different cluster nodes set. Thus, we have $\bigcup_{i=1}^{m} C_i = \mathbb{V}$ and $\sum_{i=1}^{m} |C_i| = |\mathbb{V}|$. Also, each sensor node is supposed to generate one $l - bit$ data packet in a round. Then, the consumed energy for node v can be described as

$$E_c(v, 0 < t < T) = \begin{cases} E_{tx}(l \cdot |C_v|, d) + |C_v| \cdot E_{rx}(l), & \text{if } v \text{ is a cluster head} \\ E_{tx}(l, d), & \text{otherwise} \end{cases} \tag{7}$$

Our aim is to evenly distribute the load among the nodes, maximize the minimal energy conservation of each node, and therefore enable more operation rounds with the limited harvested energy. Then we can mathematically formulate this optimization problem as

$$\max \min_{v \in \mathbb{V}} Y_v$$

$$s.\,t.: \;\; Y(v) = E(v, T) = E(v, 0) + E_h(v, 0 < t < T) - E_c(v, 0 < t < T) \tag{8}$$

where $Y(v)$ denotes the energy conservation of node v after the operation round.

Theorem 1. *The problem that maximizes the minimal energy conservation is NP-hard.*
Proof: Consider a case of the problem with only two clusters: C_1 and C_2. Each node $u \in \mathbb{V}$ can directly communicate with both cluster heads, represented as $\mathfrak{C}_1$ and $\mathfrak{C}_2$, respectively. If node u associates with $\mathfrak{C}_1$, the consumed energy for $\mathfrak{C}_1$ is $y_1(u)$; if the node attaches to $\mathfrak{C}_2$, the consumed energy for $\mathfrak{C}_2$ is $y_2(u)$. For brevity, we assume $\mathfrak{C}_1$ and $\mathfrak{C}_2$ have the same energy storage [30]. Thus, maximizing the minimal energy conservation equals to finding a subset $\mathbb{V}' \subset \mathbb{V}$ that satisfies

$$\sum_{u \in \mathbb{V}'} y_1(u) = \sum_{u \in \mathbb{V} - \mathbb{V}'} y_2(u) \tag{9}$$

Let $y_1(u) = y_2(u)$ and assume that $\sum_{u \in \mathbb{V}} y_1(u)$ can be evenly divisible by 2. Then this problem reduces to the partition problem [31], which is a known Non-deterministic Polynomial-time hard (i.e. NP-hard) problem.

4. Solution Method

We have included a glossary of terms that have been used in this section in **Table 1**.

Table 1. A glossary of terms used in this section

Notation	Definition
$\mathbb{H}$	The set of nodes storing the cluster head nodes
$E_h(i, 0 < t < T)$	The harvested energy of Node v_i in the time period T
$\mathbb{V}$	The set of nodes within the network
M	The mean value for the energy of each node within the network
A	The variance value for the energy of each node within the network
$L(i)$	The set of node i's neighbors, $L(i) \longleftarrow \{j \mid D(j, i) < D\}$
$D(u, v)$	The distance from node u to node v
$F(i)$	The energy potential function of node i
$T(i)$	The pre-determined threshold value of node i
$R(z)$	The remaining energy after data transmission for node z
C_i	The i_{th} cluster node set

Considering that maximizing the minimal energy conservation is NP-hard, we develop an approximation algorithm for deriving the near optimal solution. In this section, we will elaborate our polynomial-time EHA-LEACH scheme in detail.

We follow the main principles of the classical LEACH protocol and improve the cluster head selection procedures to make it more suitable for the energy harvesting wireless sensor networks. The operation of our proposed EHA-LEACH protocol is separated into rounds. Each round begins with a set-up phase while the cluster heads are determined and the network structure is organized. After that, the data are transmitted to the base station in a steady-state phase.

In the EHWSNs, each harvesting node consumes the collected energy under different policies. For instance, one node consumes different amount of energy as a cluster head, compared to being a non-cluster sensing node. Thus, we take the energy harvesting and consuming rates into account to complete the cluster heads selection process collaboratively.

First, $\mathbb{H}$ is initialized as $\emptyset$ for storing the cluster head nodes set and the harvested energy $E_h(i, 0 < t < T)$ in the following time period T is computed for each node $i \in \mathbb{V}$. M and A are determined according to Eqs. (4) an (5), respectively. Then, for each node $i \in \mathbb{V}$, the neighboring nodes set $L(i) \longleftarrow \{j \mid D(j, i) < D\}$ is derived. $F(i)$ and $T(i)$ can be computed according to Eqs. (6) and (7), respectively. γ is generated randomly ranging from 0 to 1. If $\gamma < T(i)$, i is selected as a cluster head. Given the cluster heads, the network is initially divided into m clusters (lines 1-12).

Lines 13-17 show the cluster heads re-selection phase. $R(z)$ is defined as the remaining energy after this operation round for node z, under the condition that z is selected as the cluster head of C_i. Then, node k with the largest remaining energy, $k \leftarrow \arg\max_{j \in C_i}\{R(j)\}$, is re-selected as the cluster head of C_i. After that, each node in C_i updates its cluster head. The other clusters run the same steps.

Algorithm 1 The pseudo-code of cluster formation under EHA-LEACH scheme

```
1: H ← Ø and Compute $E_h(i, 0 < t < T)$ for each node $i \in \mathbb{V}$
2: Calculate $M$ and $A$ according to Eqs. (5) and (6)
3: for each node $i \in \mathbb{V}$ do
4: $L(i) \leftarrow \{j \mid D(j, i) < D\}$
5: Calculate $F(i)$ and $T(i)$
6: Generate a random value $\gamma$ between [0, 1]
7:   if $\gamma < T(i)$ then
8:     $i$ is selected as a cluster head
9:     $\mathbb{H} \leftarrow \mathbb{H} \cup \{i\}$
10:   end if
11: end for
12: $m \leftarrow |\mathbb{H}|$ and $C_j$ is constructed, $j = 1, 2, ..., m$
13: for $i = 1 : m$ do
14: Compute $R(j)$ for each $j \in C_i$
15: $k \leftarrow \arg\max_{j \in C_i} \{R(j)\}$
16: Update $k$ as the cluster head for each $j \in C_i$
17: end for
18: for each node i ∈ 𝕍 do
19:   if $i$ is a cluster head then
20:     $E_c(i, 0 < t < T) = E_{tx}(l \cdot |C_i|, d) + |C_i| \cdot E_{rx}(l)$
21:   else
22:     $E_c(i, 0 < t < T) = E_{tx}(l, d)$
23:   end if
24: end for
```

Lines 18-24 show the data transmission phase. If a node is a cluster head, its consumed energy includes receiving the data packets from the nodes belonging to this cluster and forwarding the collected data to the base station. Otherwise, the node's consumed energy includes transmitting the collected data packets to its corresponding cluster head. The details of the pseudo-code for the above procedures are shown in Algorithm 1.

The cluster head selection phase of our EHA-LEACH scheme introduces the same order of computational complexity as the EP-LEACH scheme, which is $O(|\mathbb{V}|^2)$. In the following data communication phase, it takes $O(|\mathbb{V}|)$ time. Therefore, the overall computational complexity of our EHA-LEACH scheme is $O(|\mathbb{V}|^2)$.

5. Performance Evaluation

In this section, extensive experiments are carried out to validate the developed EHA-LEACH hierarchical routing protocol and evaluate the performance improvement. To illustrate the effectiveness of our proposed protocol (EHA-LEACH), we compare it with LEACH [6] and Energy-Potential LEACH (EP-LEACH) [5] protocols. Among the well-cited algorithms, we include them in this comparative analysis based on the following criteria: (1) the reference algorithms can be applied in an unidirectional planar communication environment; (2) the reference algorithms have the same or lower computational complexity of $O(|\mathbb{V}|^2)$ each round similar to our proposed EHA-LEACH algorithm.

5.1 Simulation setup

The simulation was implemented with the following parameters and assumptions. 100 homogeneous nodes with 0.5 J initial energy are randomly scattered within a square region. For the purpose of illustration, we show the network topology in **Fig. 2**. This instance shows a network with 100 nodes randomly scattered over a 100 × 100 m^2 region, where harvested energy of each node is normalized and displayed from low (blue) to high (red).

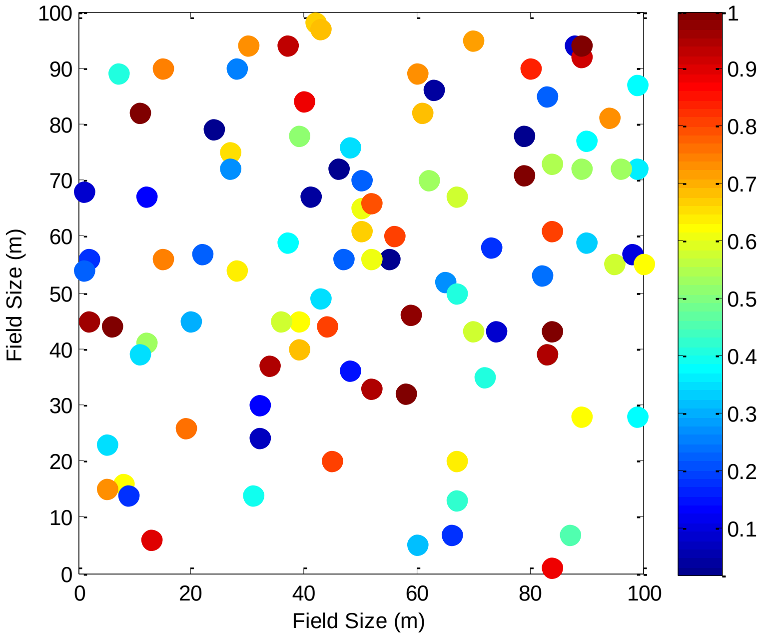


Fig. 2. Illustration of the network topology, where 100 nodes are randomly scattered over a 100 × 100 m^2 region with the harvested energy is not uniformly distributed.

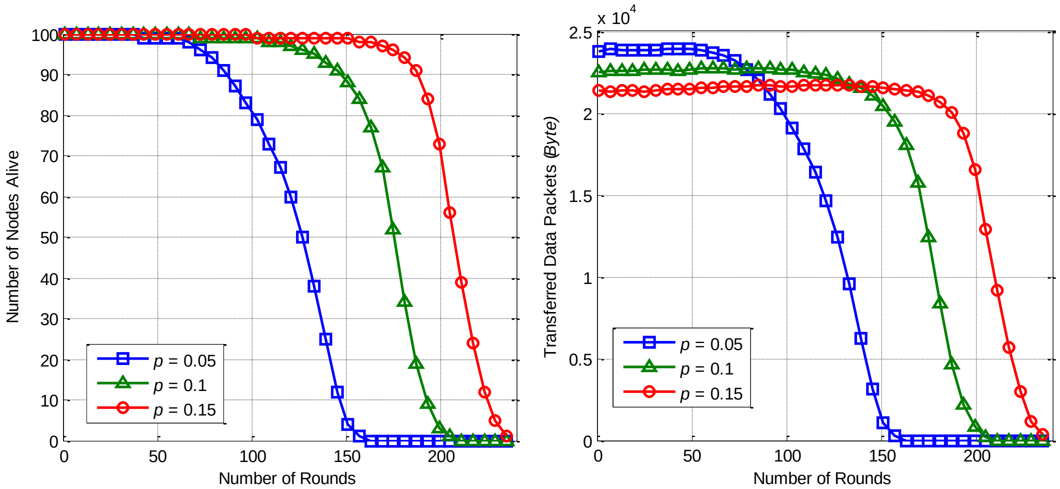
The algorithm works in rounds to offer a dynamic environment where each node adjusts its transmission power periodically. We suppose that each sensor node generates a $2000 - bit$ data packet in a round to be transmitted to its corresponding cluster head. And the MAC layer protocol is assumed to be ideal the same as that used in other studies [32], [33]. The electronics energy E_{elec}, the amplifier energy ε_{fs} and ε_{mp} are 50×10^{-9} nJ/bit, 100×10^{-12} $J/bit/m^2$ and 0.0013×10^{-12} $J/bit/m^4$, respectively [17]. The nodes are recharged hourly and the time period in which nodes harvest energy is chosen at the daytime from 9:00 am to 4:00 pm. The reason not to use the solar data in the other time is that it makes it hard to see the effects of the energy harvesting aware algorithm. The network operation rounds are measured until the first node ends its lifetime, i.e., the network dies until the first node runs out of energy [34]. **Table 2** summarizes the energy harvesting profile used in simulation [23]. We suppose the energy harvesting information can be obtained or predicted in advance [35]. Each curve shows the average results over 500 independent simulation runs.

Table 2. Energy harvesting profile

Time	Harvesting power (mW)	Time	Harvesting power (mW)
9:00-10:00	60	13:00-14:00	140
10:00-11:00	120	14:00-15:00	140
11:00-12:00	140	15:00-16:00	120
12:00-13:00	140	16:00-17:00	60

5.2 Validation of our proposed scheme

We first vary the probability of becoming a cluster head (p) for each node from 0.05 to 0.15 with the increment of 0.05. The performance evaluation of our EHA-LEACH algorithm in terms of the number of nodes alive and the amount of data transmission has been reported. As shown in **Fig. 3(a)**, the network with high probability p preserves more nodes alive after running for a period of time (about 55 rounds). That is because before 55 rounds, each node has enough energy to maintain the data collection and data transmission. After that, some nodes with high energy consumption rates start to run out of energy. Notice that higher p means more nodes would be selected as the cluster heads in each round. This results in that the node collecting information would have chance to choose a more suitable node as its cluster head, compared with the same network environment with lower p. As a result, the node consumes less energy transmitting the same amount of data packets each round, resulting in operating for a longer period of time before it drains out of energy.



(a) Number of nodes alive for different p plotted against time

(b) The amount of data transmission for different p plotted against time

Fig. 3. Performance evaluation on the number of nodes alive and transferred data packets under different p, where each node begins with 0.5 J energy.

Fig. 3(b) plots the amount of data transmission each round under different p. Notice that the curve with p = 0.05 behaves best until about 80 rounds, i.e., it transmits most data packets during these rounds. After about 150 rounds, the curve with p = 0.15 behaves the best. The reason the curve with p = 0.05 transmits more data in the beginning is that less nodes are selected as the cluster heads. Thus, more nodes are used to collect the information and more data packets are transmitted. But it's worth to be mentioned that the data transmission would consume more energy as the sensor nodes have less cluster heads to be selected. This explains that as time progresses, it behaves worse and worse whereas the curve with $p = 0.15$ achieves more data transmission gradually.

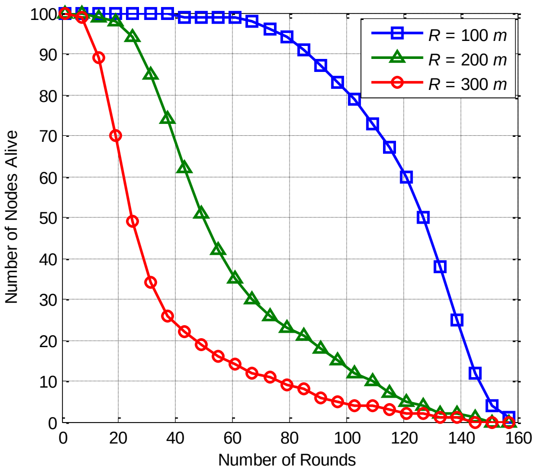


Fig. 4. Number of nodes alive for different region size plotted against time

Next we fix the probability of becoming a cluster head for each node to be 0.05 and vary the side length (S) of the square region from 100 *m* to 300 *m*. Also, the performance evaluation of our EHA-LEACH algorithm with respect to the number of nodes alive and the amount of data transmission has been presented. As shown in **Fig. 4**, the number of nodes alive decreases with the increase of square region. This can be explained as follows. With the increase of the square region, the distance between two nodes increases. As a result, the energy for transmitting the same size data packet increases, both from the sensor nodes to the cluster heads and from the cluster heads to the base station. Thus, the number of nodes alive decreases after the same number of operation rounds. As for the amount of data transmission, it behaves the same trend shown in **Fig. 4**. Different from that in **Fig. 3**, here the probability of being a cluster head for each node is fixed as $p = 0.05$. Hence, more nodes alive mean that more non-cluster head nodes are used to collect information, leading more data transmission during each round of operation. We do not show the figure of the amount of data transmission under various region size against time in order to save space in the context.

5.3 Comparison with other routing schemes

Since the optimal solution is hard to compute (NP-hard), which has been proved theoretically in the above, we do not compare the outcomes derived by our scheme with the optimal solution. In the following, we show the simulation results of comparing various routing schemes.

To illustrate the re-selection process of new heads, we present the cluster heads derived from the EP-LEACH and EHA-LEACH schemes, respectively in **Fig. 5**. The network consists of 100 nodes randomly scattered in a $100 \times 100\ m^2$ area and the probability of becoming a cluster head for each node is set as 0.05. The node selected as a cluster head is surrounded by a black circle. For the purpose of illustration, the numbers next to the nodes represent different routing protocols. Specifically, the nodes imposed by Number 1 mean the cluster heads derived by EP-LEACH scheme and the nodes imposed by Number 2 mean the cluster heads derived by our proposed EHA-LEACH scheme. The arrow denotes the re-selection process of cluster head within the same cluster. It is observable that our proposed EHA-LEACH scheme replaces the cluster head while there exist one node which harvests more energy in the cluster. Notice that if the result derived by EP-LEACH scheme keeps the same as that derived by our EHA-LEACH scheme, the cluster head keeps unchanged.

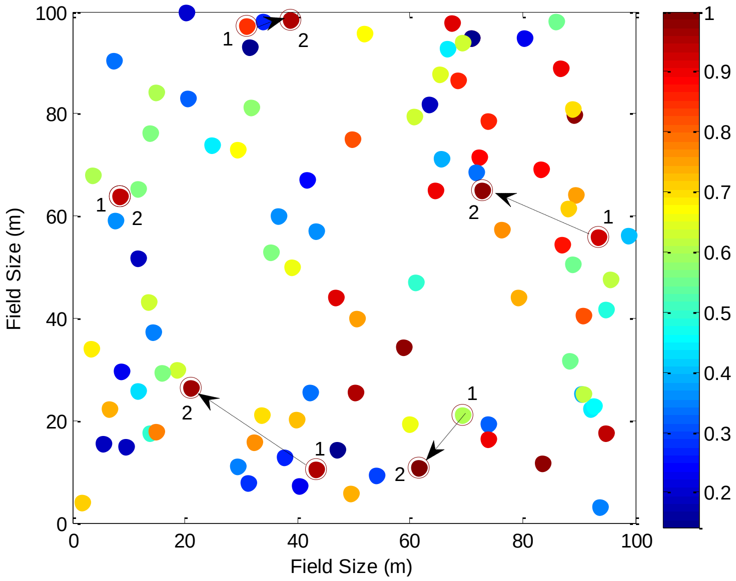
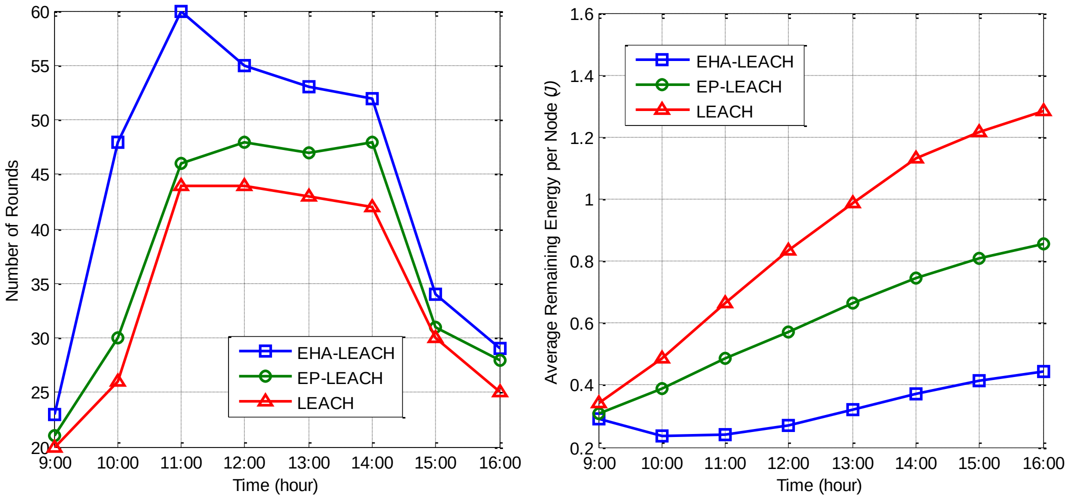


Fig. 5. Illustration of the re-selection process of cluster heads.

Fig. 6(a) illustrates the number of operation rounds under different routing protocols in 8 hours. Each curve in this figure behaves the similar trend with the energy harvesting profile. In other words, the network operates for longer durations while harvesting more energy from the ambient environment, and vice versa. It can be seen that our EHA-LEACH scheme maintains more operation rounds by achieving 18.41% and 29.19% performance improvements at average, respectively, compared with the EP-LEACH and LEACH schemes. This is because our EHA-LEACH scheme considers not only the harvested energy but also the energy consumption rates of different nodes. The cluster head would be replaced with some other node belonging to its cluster with the same available energy, but with lower energy consumption rate. Also, EP-LEACH performs better than LEACH as it considers the harvested energy during the cluster head selection phase. The node with high energy has more opportunity to be a cluster head, regardless of whether it has been a cluster head in the past rounds.

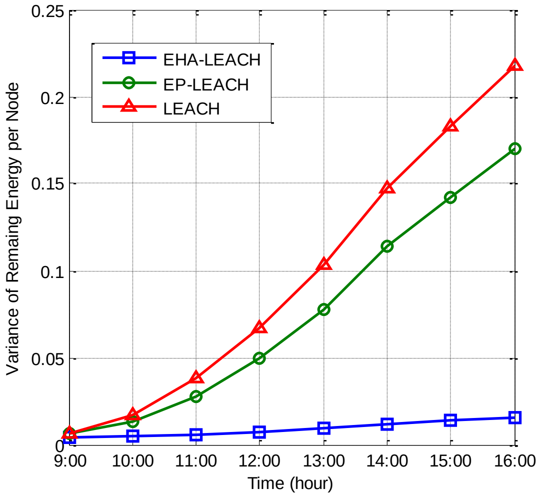
Fig. 6(b) depicts the average remaining energy per node under different routing schemes in 8 hours. It is observable that the results derived by our EHA-LEACH scheme keep lower than those of the other two routing schemes. Because the network dies once one of the network nodes runs out of energy, regardless of the other nodes' remaining energy. And the networks derived by LEACH and EP-LEACH schemes die earlier than the network derived by our proposed EHA-LEACH scheme. This indicates that our scheme can exploit the harvested energy more efficiently to transmit the collected information before the network dies.

Also, the variance of remaining energy per node has been analyzed, which illustrates the energy equilibrium distribution among the sensor nodes. From **Fig. 6(c)**, we can see that the results derived by our EHA-LEACH scheme behave more smoothly and keep lower than those of LEACH and EP-LEACH schemes. This demonstrates that our proposed scheme distributes the load more evenly, which is in accordance with our above theoretical analysis. Also, as expected, the LEACH scheme performs worst because it does not consider the harvested energy in the cluster head selection phase.



(a) Number of rounds for different routing protocols in 8 hours

(b) Average remaining energy per node for different routing protocols in 8 hours

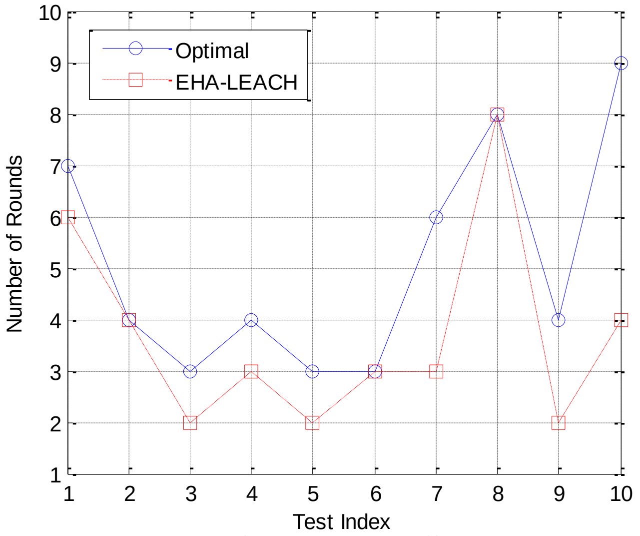


(c) Variance of remaing energy per node for different routing protocols in 8 hours

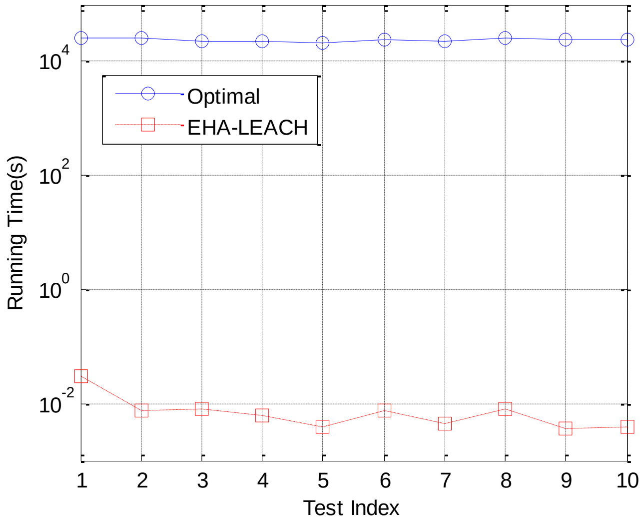
Fig. 6. A comparative analysis of different algorithms

Also, to verify our proposed algorithm's effectiveness, we downsize the network scale to complete the performance comparison with the optimal solution. We get the exact maximum operation rounds by the enumerating method. The experiment is carried out on a $100 \times 100\ m^2$ field where 5 nodes are randomly scattered. Each round the nodes are constructed into 1 cluster, which indicates the probability of becoming a cluster head (p) for each node is 0.2.

Fig. 7 reports the results of 10 experiments. As indicated in Fig. 7(a), the results derived by our proposed EHA-LEACH scheme behaves almost the same trend as the optimal results, while our algorithm decreases the computational complexity greatly which was illustrated in Fig. 7(b). We derive that our proposed scheme reaches 72.55% of the optimal operation rounds at a pretty low cost. In another words, our algorithm sacrifice little accuracy to achieve the polynomial-time computability. It was in line with our front computational complexity analysis.



(a) Number of rounds under different algorithms



(b) Running time under different algorithms

Fig. 7. Performance evaluation on the operation rounds and running time derived by our proposed EHA-LEACH scheme and the enumerating scheme.

6. Conclusion

In this paper, we have studied the hierarchical routing protocol of utilizing the harvested energy efficiently for the energy harvesting wireless sensor networks. The problem of maximizing the minimum energy conservation among the sensor nodes is analyzed and we prove its computational NP-hardness. To find the near-optimal solution effectively, we develop a polynomial time algorithm. The cluster head is determined according to the estimation of harvested energy and consumed energy for each node, besides considering the distance to the base station. Extensive experiments have been carried out for evaluating the performance of our proposed scheme. The simulation results have shown that our proposed scheme achieves significant performance improvement over existing schemes. In our future work, we will focus on using real-life solar irradiance traces with an energy prediction model to evaluate the robustness of our proposed scheme.

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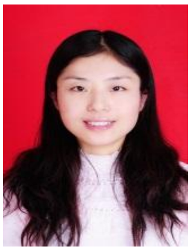

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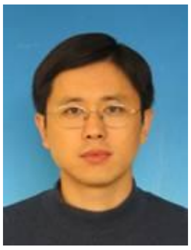

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