2016 IEEE 22nd International Conference on Parallel and Distributed Systems

EHR: Routing Protocol for Energy Harvesting Wireless Sensor Networks

Yifeng Cao*, Xiao-Yang Liu*, Linghe Kong*, Min-You Wu*, Muhammad Khurram Khan†
*Shanghai Jiao Tong University, China
†King Saud University, Kingdom of Saudi Arabia
*{yifengcao, yanglet, linghe.kong, mwu}@sjtu.edu.cn, †mkhurram@ksu.edu.sa

***Abstract*—A well-designed energy-efficient routing protocol is an indispensable part for prolonging the lifetime of wireless sensor networks (WSNs) because a sensor node usually has limited energy. Many research efforts are contributed on routing design in WSNs. With the development of green technology, the energy harvesting technique is being applied to real WSNs. Therefore, existing routing protocols are not suitable for such new WSNs with energy harvesting. In this paper, we concentrate on designing a novel routing protocol, named energy harvesting routing (EHR), which takes energy harvesting as one major factor into routing design to improve the energy efficiency. First, we introduce a hybrid routing metric combining the effect of residual energy and energy harvesting rate. Then we propose an updating mechanism allowing every node to maintain dynamic energy information of its neighbors. Based on the hybrid metric and the neighbor information, EHR is able to locally select the optimal next hop. Extensive simulations are conducted to evaluate the performance of EHR. Results demonstrate that EHR outperforms existing routing protocols in energy harvesting WSNs in term of the energy efficiency.**

***Index Terms*—Energy-efficient routing protocol, energy harvesting**

I. INTRODUCTION

A wireless sensor network (WSN) is a distributed network system consisting of cooperative sensor nodes. Nowadays, WSNs have been in widespread use for environmental sensing, military applications, industrial monitoring and many other areas [1]. Researchers show great interest in many aspects of WSNs [2][3][4]. Generally, with limited transmission capability, a node cannot transmit data to a distant node. Therefore, a well-designed routing protocol is important. In most cases, making a guarantee on energy efficiency and time delay is critical for achieving high-quality routing service.

Previous research mostly focused on developing highly energy-efficient algorithms to reduce overhead of the network due to the restrict of the battery power supply mode. However, the energy level will drop gradually as the time passes by without a persistent external power source, leading to death of a sensor node. For large-scale wireless sensor networks, maintaining sensor nodes regularly results in a huge cost. One of probable approach to solving this problem is energy harvesting. Instead of dry cells, all of the sensor nodes are powered by an energy harvesting device which collects disperse energy (solar energy, wind energy and heat) from nature. Some products of energy harvesting such as in WISP [5][6], have come into application now.

Many research efforts have been paid on developing energy efficient and forward-aware routing protocols [7]. Low-Energy Adaptive Clustering Hierarchical (LEACH) [8] is a hierarchical routing protocol where some nodes are chosen to be cluster heads (CH) randomly. Their task is forwarding data packets to the base station. Based on it, CEEC [9] takes residual energy into consideration. Following, Distributed Hierarchical Agglomerative Clustering (DHAC) [10] uses the information of one hop neighbor to choose routes. A common drawback of these classic routing protocols is that the energy harvesting feature is not taken into consideration. Thus, these protocols cannot perform well if we directly apply them into advanced energy-harvesting WSNs. Motivated by this, it is necessary to design a new routing protocol customized for energy-harvesting WSNs.

However, there are two challenges remained. First, it is not easy to formulate a hybrid metric together with the residual energy and the energy harvesting rate naturally. They are both major factors influencing the selection. Second, the storage capability of a single node is limited. It is a challenge for nodes to judge which node is an optimal selection with limited information. Meanwhile, the process of updating energy information also needs an efficient mechanism. To ensure the system working normally, the information of each node should be as new as possible. It is important to find a solution to the information updating with less transmission cost.

To address these challenges, we propose a novel routing protocols, named EHR. EHR consists of two major components: a metric to tackle the first challenge and a method of maintaining energy information to tackle the second challenge. These two components are used for the selection of next hop. Traditional greedy algorithm works efficiently in a local range but it sometimes results in a sub-optimal selection. Our work aims to attain approximate overall optimization by modifying the greedy algorithm with the above two components.

Specifically, our major contributions are as follows:

- First, we introduce Energy-Harvesting Based Routing Protocol (EHR), which synthesizes energy harvesting rate and residual energy. This protocol will prolong the lifetime of the network.
- Second, we propose a method to update information with little overhead introduced into the network. The node will tell other nodes the state of itself by data packets to efficiently update the information.

1521-9097/16 $31.00 © 2016 IEEE
DOI 10.1109/ICPADS.2016.15

- Third, we conduct extensive simulations to evaluate the proposed EHR. The performance results demonstrate that EHR performs well in an energy harvesting WSN.

The rest of the paper is organized as follows. In Section II, we introduce related works in routing protocols and energy harvesting technology. In Section III, we present the model and provide details of the routing protocol. Algorithm procedures are described in Section IV. In Section V, we conduct the simulations. We conclude our work in Section VI.

II. RELATED WORKS

We briefly review related works on energy-efficient routing protocols and energy harvesting technologies.

A. *Routing Protocol*

LEACH [8] protocol is a classical hierarchical routing protocol, where nodes are all grouped into clusters. Some nodes are chosen randomly as cluster heads for forwarding data packets while other nodes are in a sleeping state. Given that the WSN is modeled as a graph G, the probability of a node being a cluster head is given as:

$$P_i = \begin{cases} \dfrac{p}{1 - p(r \bmod \frac{1}{p})}, & \forall i \in G \\ 0, & \text{otherwise} \end{cases}, \tag{1}$$

where p is the proportion of CHs in the network system and r is the current round. After each round, nodes which are selected as CHs will be removed from G. An overall energy efficiency and consumption balance will be achieved with this protocol. The proposal of LEACH motivated other advancements in this field. In 2007, a sleep/wake routing protocol for multi-hops [11] was proposed to achieve higher energy efficiency. Each sensor schedules whether it will be in sleeping state or waking state within multiple hops. The scheduling is based on data delivery and synchronization error. The WSN will save energy from sleeping time. In DHAC [10], a node only needs to know information of one-hop neighbor. It builds a resemblance matrix with input data. When executing the algorithm, each cluster establishes its own resemblance matrix and determines the minimum cluster head for the future head choosing. It gains excellent performance in the network with light traffic.

B. *Energy Harvesting*

Replacing traditional batteries with energy harvesting devices is actively studied recently [12]. One of the first routing protocols which take use of solar energy for power is described in [13]. It classifies nodes into harvesting nodes and non-harvesting nodes, where non-harvesting ones should be avoided as possible. In [14], residual energy is taken into consideration as a negative factor. In [15], authors integrated wastage, harvesting and residual energy together with some other effects such as prediction errors and unequal harvesting opportunities. [16][17][18] respectively proposed algorithms which associated cost metrics of links with nodes available energy. In [19], a paradigm is proposed in an energy harvesting WSN. It introduces the energy sharing where nodes with lower energy can get powered from the nodes are high in residual energy. However, in these algorithms, a node determined its next hop only with the information of its neighbors, which may lead to low efficiency. What's more, most of them pay attention to the protocol itself without showing the details of the information exchanging process.

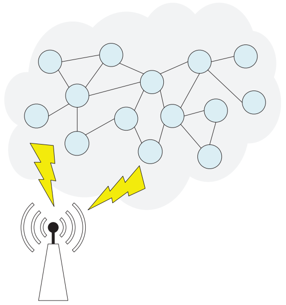


Fig. 1: A wireless sensor network.

III. SYSTEM MODEL

We model a WSN as a graph $G = (V,\ E)$ in a two-dimension plane as shown in Fig. 1, where V represents sensor nodes and E represents wireless links. If node i is in the communication range of node j, there exists an edge between i and j.

Each node in the WSN has three major attributes: residual energy (E_r), energy consumption per data packet transmisson (E_T) and energy harvesting rate (R). In addition, each node maintains two tables recording the above attributes of itself and its neighbors. We name them Self Table and Neighbor Table as TABLE I and II shows. We will explain another attribute energy harvesting density (D) in the table afterwards.

TABLE I: Self Table

E_r (Residual Energy)	R (EH Rate)	D (EH Density)

TABLE II: Neighbor Table

nodeID	E_r (Residual Energy)	R (EH rate)	D (EH Density)

For residual energy, it is divided into different levels as follows:

$$L_i = k + 1, \quad (\frac{k}{K} < \frac{E_{r_i}}{E_m} \leq \frac{k+1}{K}, k < K) \tag{2}$$

where K is the maximum energy level we have predetermined. The lifetime of a WSN is determined by the first dead node. Hence, a node cannot always be selected to forward data even if it has relatively high energy harvesting rate. To balance the energy consumption, energy is discretized into K levels. Nodes only transmit data to other nodes with the highest energy levels. When K = 1, the routing protocol totally depends on energy harvesting. When K is large enough, the residual energy determines the selection of next hop. A trade-off is

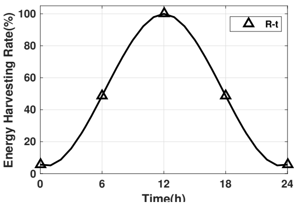


Fig. 2: Relatives between energy harvesting rate and time.

required for the practical application. Our simulations provide a range of suitable values for the selection of K. Compared with previous work with residual energy in consideration, we derive a discrete method which is simple and efficient.

To estimate energy consumption per data packet, we take the same energy model as in [20]:

$$E(l, d) = lE_0 + l\epsilon_s d^{\alpha}, \tag{3}$$

where E_0 is the energy consumption for one-bit data transmission, l represents the length of a data packet, ϵ_s is a constant, d represents the distance and α is a factor. We assume that the energy consumption of data packets for one node keeps invariant over a period of time. However, different nodes have various energy consumption.

For energy harvesting rate, we assume that different nodes have different rates which are determined by device and solar energy. Meanwhile, the rate changes with time. Approximately, the energy harvesting rate reaches a peak at noon and drops to the lowest point at midnight as shown in Fig. 2. To get the value of R, each node makes predictions to estimate its current energy harvesting rate [21]. We use Gaussian function to model the curve between energy harvesting rate and time of a given node i:

$$R_i(t) = a_i e^{-\frac{(t-b_i)^2}{2{c_i}^2}}, \tag{4}$$

where a_i, b_i, c_i are factors influenced by luminous intensity.

However, energy harvesting rate cannot show the characteristics of energy harvesting in an area. To quantify an area's average energy harvesting rate, we propose the concept of energy harvesting density (D):

Definition 1. *The energy harvesting density of node i is defined as:*

$$D_i = \frac{\sum\limits_{j \in N(i) \bigcup \{i\}} (R_j t_T - E_{T_j})}{|N(i)| + 1}. \tag{5}$$

For the information tables, Self Table records residual energy, energy harvesting rate and energy harvesting density while Neighbor Table records the same attributes of neighbors as shown in TABLE I and II. They need to be dynamically updated. To reduce the updating overhead, we propose a time-slot based information-updating mechanism (TI mechanism) without extra transmission. In this mechanism, an approximate estimation is conducted to update information.

Besides characteristics listed above, each node has the knowledge of the network's topology. The distance d_{ij} between any node i and j can be known by any node.

To make our descriptions clearer, we list notations in TABLE III.

IV. PROTOCOL DESIGN

In this section, we study the single-vertex shortest path problem with weight assigned to each vertice in a distributed WSN system. We illustrate the formulation of weight and adopt a greedy approach.

A. Overview

We provide an overview of the EHR algorithm. There are four phases in the EHR algorithm. The phases are as follows:

- Information initialization. When a WSN begins to work, each node initializes its information in routing table. Information in Neighbor Table is attained by transmission and computed with (2)(3)(4)(5).
- Dividing energy levels. In this phase, the EHR algorithm uses (3) to compute each node's level. The source node only transmits data to nodes with $L_i = L_{max}$.
- Next hop selection. Each source node selects the node to forward data in this phase. All its neighbors will receive the data packet. Hovewer, only the selected node will accept and decode it.
- Updating information. We propose a time-slot based information-updating mechanism to update the table efficiently with little overhead.

B. Improved Greedy Algorithm

We modify the Greedy Algorithm based on energy harvesting density in next hop selection. Traditional greedy algorithm is based on energy harvesting rate, which will choose a suboptimal path. In [22], the concept of density motivates us to consider the average energy harvesting rate in an area. Furthermore, nodes clustered in an area usually share the similar energy harvesting rate. A simple comparison can show the advantages of this method over common Greedy Algorithm. As shown in Fig. 3, the algorithm will finally choose path $A \rightarrow B \rightarrow E \rightarrow F$ instead of $A \rightarrow C \rightarrow D \rightarrow F$ which is chosen by Greedy Algorithm, because the energy harvesting density of area R_1 is larger than R_2.

TABLE III: NOTATIONS

E_{r_i}	residual energy of node i
E_m	the largest energy of node i
L_i	the energy level of node i
K	the maximum energy level
$N(i)$	the set of neighbor nodes of node i
E_{T_i}	energy consumption of sending a data packet
R_i	energy harvesting rate of node i
D_i	energy harvesting density of node i
t_T	time for transmitting data packets
d_{ij}	distance between node i and j

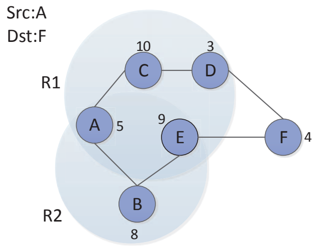


Fig. 3: The greedy algorithm based on density will select a better path than the traditional greedy algorithm.

C. Time-slot based Information-updating Mechanism

Residual energy and energy harvesting rate in Self Table should be periodically updated to make the correct selection with the algorithm. To do this with little transmission overhead, we propose a time-slot based information-updating mechanism (TI).

There are three major parts for the mechanism: packing information, setting time slot and updating table.

Packing information: When node i tries to send a data packet to a certain destination, it adds information in Self Table into some segment of the packet. All the neighbors will receive the data packet though only the destination node accepts it. The time for one-hop transmission is t_T.

Setting time slot: There are two probable cases in each time slot. In the first case, a data packet from node i comes to node j in a time slot. The neighbor nodes of i simply replace i's information in their Neighbor Table with the data packet. After that, all the nodes except j simply discard the packet. The destination node j accepts it and tries to forward it with EHR. In the second case, no data packet is received by node j within a time slot. The solution to it will be specified in the next part.

The size of a time slot is actually dependent on practical application. They should meet two basic requirements: dividing time into homogeneous slots and promising at least one data packet transmission in one time slot. In this problem, the size of time slot is t_T.

Table updating without data packets: In this case, the routing table will be updated periodically at time $t_0+kt_T(k=1,2,...)$ until a new data packet comes. The updating process of different attributes for node j is described as follows.

First, it updates E_r and R in Neighbor Table. Since node j doesn't send or receive the data packet during a time slot, the residual energy will only increase by harvesting energy. Thus, we have:

$$E'_{r_i} = E_{r_i} + R_i t_T, \tag{6}$$

where R_i is i's energy harvesting rate in j's Neighbor Table. To estimate the energy harvesting rate of a certain neighbor node, we assume the proportion of two nodes won't change. With R'_i and R'_j generated previously, we get the ratio:

$$\epsilon_{ij} = \frac{R'_i}{R'_j}, \tag{7}$$

where R_i is i's energy harvesting rate in j's Neighbor Table and R_j is j's energy harvesting rate in j's Self Table. Given R_j the current energy harvesting rate of j in Self Table, we have the following equation:

$$\epsilon_{ij} = \frac{R_i}{R_j}. \tag{8}$$

Hence, we have:

$$R_i = \frac{R'_i R_j}{R'_j}. \tag{9}$$

By this way, E_r and R of j's neighbors have been updated successfully.

Then, it updates D in Self Table. With the formulations above, we get current energy harvesting rate of j's neighbors $\{R'_{N_1}, R'_{N_2}, ..., R'_{N_n}\}$ and j's energy harvesting rate R'_j. Hence, D'_j can be formulated as:

$$D_j = \frac{R_j + \sum_{i=1}^{n} R_{N_i}}{n+1}. \tag{10}$$

Finally, it updates D in Neighbor Table. We take the same action to update the information of energy harvesting density in Neighbor Table. Similarly, the proportion won't change. With the previous information, we can get the proportion:

$$\gamma_{ij} = \frac{D'_i}{D'_j}. \tag{11}$$

Similarly, we have:

$$\gamma_{ij} = \frac{D_i}{D_j}. \tag{12}$$

Finally, the updated D_i is formulated as:

$$D_i = \frac{D'_i D_j}{D'_j}. \tag{13}$$

Algorithm 1 Updating Mechanism

```
Require:
    $ST_j$: Self Table of j.
    $NT_j(i)$: i's attributes in j's Neighbor Table.
    $Pac_i$: The coming data packet from i in $t_T$.
if $Pac_i \neq \emptyset$ then
    $NT_j(i).E_r \leftarrow Pac_i.E_r$;
    $NT_j(i).R \leftarrow Pac_i.R$;
    $ST_j.D \leftarrow \frac{ST_j.R+\sum_{k=1}^{n} NT_j(k).R}{n+1}$;
    $NT_j(i).D \leftarrow Pac_i.D$;
else
    $NT_j(i).E_r \leftarrow NT_j(i).E'_r + NT_j(i).R \times t_T$;
    $NT_j(i).R \leftarrow \frac{NT_j(i).R' \times ST_j.R}{ST_j.R'}$;
    $ST_j.D \leftarrow \frac{ST_j.R+\sum_{k=1}^{n} NT_j(k).R}{n+1}$;
    $NT_j(i).D \leftarrow \frac{NT_j(i).D' \times ST_j.D}{ST_j.D'}$;
end if
return
```

To conclude TI mechanism, it is actually an approximate estimation of nodes' current state. Based on the characteristic of the solar energy, such an estimation attains a relatively precise result in average sense.

D. The Next Hop Selection Algorithm

Given that we have all the necessary information for the routing protocol, we present the specific forwarding algorithm procedures for selection of the next hop, as shown in Algorithm 2.

When a WSN begins to work, each node will initialize its routing table with $(3)(4)(5)$. When some event occurs and node S needs to transmit data to a certain destination node $Target$, it will first index its Neighbor Table to group its neighbors by residual energy. Then it selects the node with the largest energy density value from the nodes which are highest in energy levels. To avoid the case of ring, we rule that the node can only transmit data to those who are closer to the destination node. All the neighbor nodes will receive the data packet but only the selected next hop will accept it. The nodes which have received the data from the source node update its routing table by data packets at the same time. Other nodes will update the routing table by estimating the information with $(6)(9)(10)(13)$. After that, the algorithm will repeat EHR until the current node find $Target$ in its neighbors at some time.

Algorithm 2 EHR Algorithm

```
Input:
    $S$: The current node
    $Target$: The destination node
    $N(S)$: The neighbor set of $S$
$A \leftarrow \emptyset$;
if $(Target \in N(S))$ then
    return $Target$
else
    for all $i \in N(S)$ do
        if $d(i, Target) < d(S, Target)$ then
            $A \leftarrow A \cup \{i\}$;
        end if
    end for
    compute each $L_i \in A$ and find $L_{max}$;
    for all $i \in A$ do
        if $L_i = L_{max}$ and $(\forall j \in A/\{i\},\ D_i < D_j)$ then
            $Relay \leftarrow i$;
        end if
    end for
end if
update the routing table;
return $Relay$;
```

We now analyze the complexity of the algorithm. Suppose the maximum degree of one single node in this graph is M. In the worst case, the network is a one-dimension linear network. The process will be repeated for $N-1$ times. Therefore, the overall time complexity is $O(MN)$.

E. Special Cases

Some special cases should be considered to ensure the robustness of EHR. We have special measures for them.

For almost every network system, congestion must be taken into consideration because it degrades overall performance. When the transmission frequency is too high, one node harvesting energy more will receive large amounts of packets in a time as shown in the figure. Congestion brings may problems including higher packet loss, queueing delay and low efficiency. Packet loss occurs when received packets are larger than the limited cache of a node.

An extra flag indicating the cache state can be added to avoid packet loss. When the utilization of cache reaches a certain threshold(less than 100%), the node will send a tiny packet to its neighbors indicating they should not continue to send packets to it any more. Similarly, when the used cache reduces to another threshold, the node also sends a tiny packet to neighbors indicating it has enough cache for receiving packets.

Algorithm 3 Indicating cache state

```
Input:
    $c$: Utilized cache size.
    $Flag$: Current state of cache;
if $c \geq \delta_{upper}$ && $Flag = true$ then
    $Flag \leftarrow false$;
    Send state packet;
else
    if $c \leq \delta_{lower}$ && $Flag = false$ then
        $Flag \leftarrow true$;
        Send state packet;
    else
        do nothing;
    end if
end if
return
```

Another problem brought by congestion is queueing time. One node can only deal with one forwarding request at a time. Two or more packets in cache will prolong the transmission time of a packet. We propose a general approach without specifying in detail to in our paper. For most application cases, requirements on energy efficiency and on-time delivery are different. Sensors supervising forest-fire require more on time while sensors for air-pollution detection require less on it relatively. We define a new variable W which indicating demand of the special application for time and efficiency:

Definition 2. *Demand for time and efficiency*

$$W = \frac{\omega_1}{T_{delay}} + \omega_2 D. \tag{14}$$

To balance the time delay, we can modify the algorithm by replacing D by W and using W to judge which node to select as next hop.

F. Performance Analysis

1) Basic Analysis: We present a theoretical analysis for EHR. Traditionally, energy consumption in an autonomous

WSN system consists of two parts: packet transmission, information exchanging. The energy consumption from generating a packet to the destination node receiving this packet can be formulated as:

$$E^* = \sum_{i\in\Omega}(E_{P\_i} + E_{I\_i}), \tag{15}$$

where Ω is the set of the nodes on routing path. With TI mechanism, energy on information exchanging is almost removed. Energy on packet transmission increases a bit due to a larger packet size. Since it is negligible compared with the overall energy consumption of packet transmission, the formulation is modified as follows:

$$E^*_{TI} = \sum_{i\in\Omega} E_{P\_i} + \epsilon. \tag{16}$$

As a result, the WSN system's improvement on energy efficiency can be represented as:

$$\Delta E^* = \sum_{i\in\Omega} E_{I\_i} - \epsilon \approx \sum_{i\in\Omega} E_{I\_i}. \tag{17}$$

Division of energy levels and the improved greedy algorithm helps maximizing the lifetime of WSN. To make it specific, we suppose there are N nodes in all in the system and each node has n neighbors on average. In a certain time slot, net increase in energy for a node is:

$$\Delta E = \begin{cases} R_i t - E_{P\_i} - E_{power\_on}, & \forall i \in \Theta \\ R_i t - E_{power\_on}, & \text{otherwise} \end{cases}, \tag{18}$$

where Θ is the set of all nodes which are sending a packet. In a time slot, a node has a possibility of p to generate a packet and each packet will pass k nodes in an average sense. A node's net increase in energy is:

$$\begin{aligned} \Delta \overline{E} = pk(R_i t - E_{P\_i} - E_{power\_on}) \\ +(1-pk)(R_i t - E_{power\_on}), \end{aligned} \tag{19}$$

To simply the analysis, the average energy harvesting rate and packet transmission energy are set as $\overline{R}$ and $\overline{E_P}$ respectively. Hence, the formulation in (18) can be substitute as follows:

$$\Delta \overline{E} = \overline{R}t - pk\overline{E_P} - E_{power\_on}. \tag{20}$$

For a system without dividing residual energy into different levels, the lifetime is

$$T = \frac{E_{max}}{\overline{R}t - pk\overline{E} - E_{power\_on}} \tag{21}$$

on average. However, with EHR, a node dies only when all of the neighbor nodes of the packet source are in the lowest level. If battery is divided into L levels, the lifetime will be prolonged to

$$\begin{aligned} T^* = \frac{n(L-1)}{L} \cdot \frac{E_{max}}{\overline{R}t - pk\overline{E} - E_{power\_on}} \\ + \frac{1}{L} \cdot \frac{E_{max}}{\overline{R}t - pk\overline{E} - E_{power\_on}}. \end{aligned} \tag{22}$$

Hence, the ratio between the lifetime of EHR wireless sensor networks and non-EHR ones is

$$\nu = \frac{T^*}{T} = \frac{nL - n + 1}{L}. \tag{23}$$

From the formulation, a larger value of L and a smaller value of n contributes to prolonging the lifetime of the system.

2) Special Cases: Congestion will degrade the performance in two aspects. Firstly, it brings extra energy consumption by sending each node's state packet. In most cases, it is negligible. However, in a rather high-frequency wireless sensor network, the cost it brings out cannot be ignored. Secondly, a node cannot select the best candidate next hop if the candidate has almost full cache. It both decreases system's lifetime and degrades the energy efficiency.

V. SIMULATION RESULTS

In this section, we give a simulation of the EHR Algorithm. Our simulations include two parts:

- To demonstrate the advantages of EHR over previous routing protocols.
- To study variables' effects on a WSN's overall performance, including energy levels, data transmission frequency and energy harvesting rate.

A. Simulation Settings

We take energy consumption based routing protocols [7] as a benchmark because it is the most common routing protocol for WSNs without energy harvesting. To highlight the advantages of EHR, we conduct the contrast test in a special scene, where each node with a higher energy harvesting rate has a higher transmission consumption.

As shown in Fig. 4, a wireless sensor network is a large system with links connecting each node. In our simulation, all n sensors are distributed randomly in a 200m × 200m field. All the packets range from 256 bytes to 512 bytes. The transmission energy between two nodes with a link ranges from 1J to 10J. Since energy sustaining the system is quite small compared with the transmission consumption, we simply neglect it. The transmission delay t_T and time slot Δ are set to 1 time unit. Some parameters will be in deep study for their effects on overall performance including energy harvesting rate, possibility of generating a packet and max energy levels.

For clarity, the simulation settings are summarized in TABLE IV.

TABLE IV: SIMULATION SETTINGS

Notations	Defination	Value
n	Number of nodes	50
m	Number of neighbors of a node	1-10
s	Packet size	256 bytes-512 bytes
E_{ij}	Energy consumption between i and j	1-10J
R	Energy harvesting rate	0-8 Wh/s
p	Possibility of generating a packet	4%-50%
K	Max energy levels	1-100
Δ	Time slot size	1 time unit
t_T	Transmission delay	1 time unit

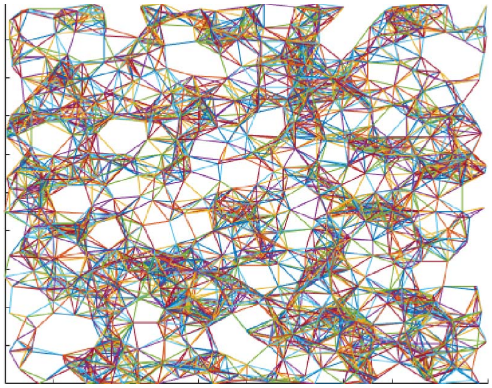


Fig. 4: A large complex wireless sensor network.

B. Energy Mode

The energy harvesting rate changes with time. Since EHR is based on harvesting solar energy, the harvesting rate usually reaches its peak at noon. A Gaussian distribution is applied to our simulation where all the three parameters in (4) is changeable.

For energy consumption, we have the suppose that all the packets are good packets without being corrupted or lost, which makes the transmission energy a constant.

C. Result Analysis

The size of a wireless sensor network can be very large as shown in Fig. 4. Limited to the computer performance, we do our simulation in a small WSN with only 50 nodes.

1) Basic performance: EHR has a better performance than traditional routing protocols without energy harvesting. As shown in Fig. 5a, they share similar decreasing gradient in the evening or before dawn. During the time, next hop selection is determined by energy consumption totally due to a low harvesting rate. However, EHR has a better increasing gradient over the other protocol when nodes are in a state of being powered. After 48 hours, the energy in WSNs using EHR is about 20% more than WSNs using the energy consumption based routing protocols.

2) Traffic load: Fig. 5b shows the relation between transmission frequency and residual energy at a certain time when $n = 50$ and $K = 5$. When a node has a higher probability to generate a packet, there are more packets in the system, which brings out a higher frequency in transmitting packets. Congestion will occur if the frequency is too high. As we can see from (20), when p is too large, pk can be larger than 1, which means one node has more than one packet waited to be delt with in its cache on average.

Frequency affects the WSN's lifetime by energy consumption. When transmission frequency increases, the WSN will have a shorter lifetime. We simulate the situation that each node generates a data packet with a probability of 4%, 10%, 25% and 50% within one time slot. When the probability is larger than 25%, the WSN dies quickly. In addition, how much the performance can be optimized is influenced by transmission frequency. Using E_r and $\bar{E_r}$ to represent the average residual energy under EHR and the contrast algorithm, we define a variable μ to represent the optimization effect:

$$\mu = \frac{E_r - \bar{E_r}}{\bar{E_r}}. \tag{24}$$

From Fig. 5c, the value of μ increases as the WSN transmits data more frequently. Generally, a higher transmission frequency will achieve a larger optimization.

3) Harvesting rate: Fig. 5d shows the effect of energy harvesting rate. A WSN harvesting energy more efficiently has a longer lifetime. Given (3) as a formulation, we simulate with different value of coefficient a. When a increases from 0.001 to 0.008, the overall performance achieves a little improvement about 10%.

4) Max energy levels: Theoretically, larger levels contribute to prolonging the lifetime of the WSN as shown in (23). Hovewer, it may also lead EHR to making suboptimal selections. Value selection's effects of K are tested with the condition where $a = 1$ and the probability of generating data packets is 50%. As shown in Fig. 5e, when K is too small, the time of first node to death (FNDT) is shorter. When $K \geq 10$, the changes in FNDT are small. When K becomes larger, the next hop selection mainly depends on the residual energy. As shown in Fig. 5f, the WSN with a larger K has a higher energy consumption because it neglects the characteristics of energy harvesting. According to the simulation, K ranging within $[10, 20]$ has a relatively good performance.

VI. CONCLUSION AND FUTURE WORK

Most of the existing energy-efficient routing protocols concentrate on the improvement of distributed algorithms. Their work is based on the residual energy and transmission power. In this paper, we propose the EHR routing protocol which takes energy harvesting as a major factor. To efficiently select the next hop, we present the TI mechanism to update the routing table periodically without extra overhead.

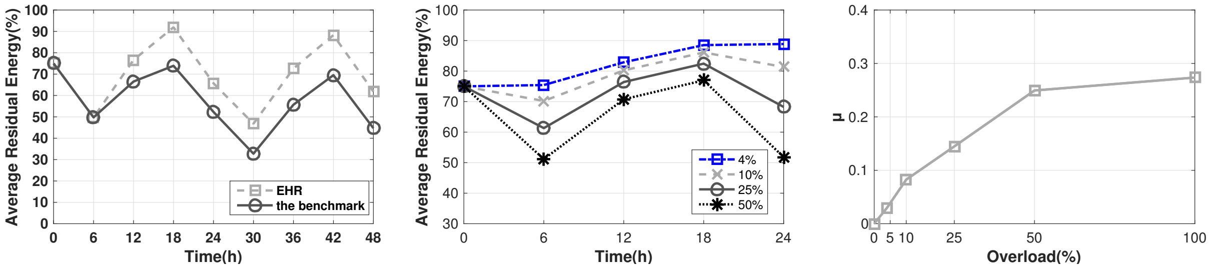
There are still some works remained to be improved. First, though we have made modifications on greedy algorithm, the selection of next hop will still result in a shorter lifetime than the optimal approach. A more sufficient algorithm for the selection is one of our future work. Second, since time delay will decrease the performance of a WSN, a trade-off between time delay and energy harvesting rate is an important future work.

ACKNOWLEDGEMENT

This research was supported by NSFC grant 61672349, 61303202, and China Postdoctoral Science Foundation grant 2014M560334, 2015T80433. The authors would also like to thank Mr. Yao Xie for his valuable comments.

REFERENCES

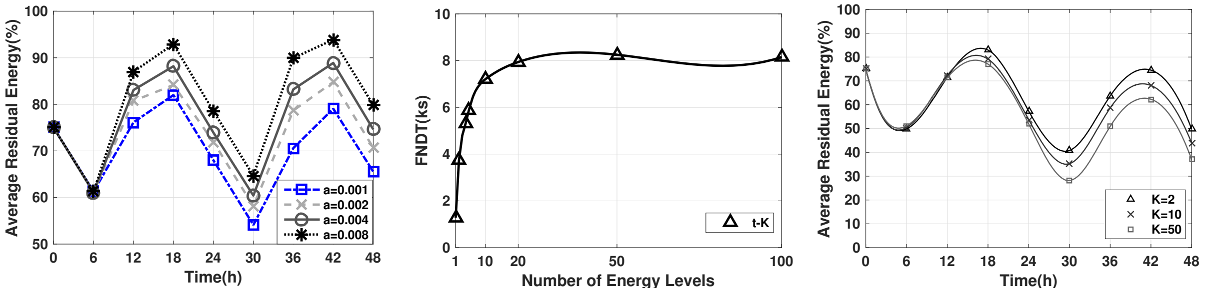
[1] A. Argyriou. "Data collection from resource-limited wireless sensors for cloud-based applications". *IEEE Globecom*, 2015.



(a) Performance comparison between EHR and contrast algorithm in 48 hours.

(b) Effects of data transmission frequency on overall performance.

(c) The relation between the performance of optimization(μ) and transmission frequency (overload).



(d) Effects of energy harvesting rate on overall performance.

(e) The relation between FNTD and the number of energy levels.

(f) The differences in residual energy with various selection of K.

Fig. 5: Simulation results

[2] L. Kong, M. Xia, X. Y. Liu, G. Chen, Y. Gu, M. Y. Wu, and X. Liu. "Data loss and reconstruction in wireless sensor networks". *IEEE Transactions on Parallel and Distributed Systems*, 25(11), 2014.

[3] L. Kong and X. Liu. "mzig: Enabling multi-packet reception in zigbee". In *Proceedings of the 21st Annual International Conference on Mobile Computing and Networking*, MobiCom '15, 2015.

[4] X. Y. Liu, Y. Zhu, L. Kong, C. Liu, Y. Gu, A. V. Vasilakos, and M. Y. Wu. "CDC: Compressive data collection for wireless sensor networks". *IEEE Transactions on Parallel and Distributed Systems*, 26(8), 2015.

[5] Y. Zhao, J. R. Smith, and A. Sample. "NFC-WISP: A sensing and computationally enhanced near-field RFID platform". *IEEE RFID*, 2015.

[6] Y. Zhao, A. LaMarca, and J. R. Smith. "A battery-free object localization and motion sensing platform". *ACM UbiComp*, 2014.

[7] N. A. Pantazis, S. A. Nikolidakis, and D. D. Vergados. "Energy-efficient routing protocols in wireless sensor networks: A survey". *IEEE Communications Surveys and Tutorials*, 15:551–591, 2013.

[8] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan. "Energy-efficient communication protocol for wireless microsensor networks". *Proceedings of the 33rd Hawaii International Conference on System Sciences*, 2000.

[9] M. Aslam, T. Shah, N. Javaid, Z. Rahman A. Rahim, and Z. A. Khan. "CEEC: Centralized energy efficient clustering a new routing protocol for WSNs". *IEEE Secon*, 2012.

[10] C. H. Lung and C. Zhou. "Using hierarchical agglomerative clustering in wireless sensor networks: An energy-efficient and flexible approach". *Ad Hoc Networks*, 8:328–344, 2010.

[11] Y. Wu, S. Fahmy, and N. B. Shroff. "Energy efficient sleep/wake scheduling for multi-hop sensor networks: Non-convexity and approximation algorithm". *IEEE INFOCOM*, 2007.

[12] W. K. G. Seah, Z. A. Eu, and H. P. Tan. "Wireless sensor networks powered by ambient energy harvesting (WSN-HEAP) survey and challenges". *Wireless Communication, Vehicular Technology, Information Theory and Aerospace and Electronic Systems Technology*, 2009.

[13] T. Voigt, H. Ritter, and J. Schiller. "Utilizing solar power in wireless sensor networks". In *Local Computer Networks, 2003. LCN '03. Proceedings. 28th Annual IEEE International Conference on*, pages 416–422, Oct 2003.

[14] A. Kansal and M. B. Srivastava. "An environmental energy harvesting framework for sensor networks". In *Proceedings of the 2003 International Symposium on Low Power Electronics and Design*, ISLPED '03. ACM, 2003.

[15] G. Martinez, S. Li, and C. Zhou. "Wastage-aware routing in energy-harvesting wireless sensor networks". *IEEE Sensors Journal*, 14(9):2967–2974, Sept 2014.

[16] K. Zeng, W. Lou, K. Ren, and P. J. Moran. "Energy-efficient geographic routing in environmentally powered wireless sensor networks". In *MILCOM IEEE Military Communications conference*, Oct 2006.

[17] M. K. Jakobsen, J. Madsen, and M. R. Hansen. "DEHAR: A distributed energy harvesting aware routing algorithm for ad-hoc multi-hop wireless sensor networks". In *World of Wireless Mobile and Multimedia Networks (WoWMoM), 2010 IEEE International Symposium on a*, June 2010.

[18] X. Lin, N. B. Shroff, and R. Srikant. "Asymptotically optimal power-aware routing for multihop wireless networks with renewable energy sources". In *Proceedings IEEE 24th Annual Joint Conference of the IEEE Computer and Communications Societies.*, 2005.

[19] H. Li, J. Xu, R. Zhang, and S. Cui. "A general utility optimization framework for energy harvesting based wireless communications". *IEEE Communications Magazine*, 53, 4, 2015.

[20] D. Wei, Y. Jin, S. Vural, K. Moessner, and R. Tafazolli. "An energy-efficient clustering solution for wireless sensor networks". *IEEE Transactions on Wireless Communications*, 40:3973 – 3983, 2011.

[21] S. Guo, C. He, and Y. Yang. "ResAll: Energy efficiency maximization for wireless energy harvesting sensor networks.". *IEEE SECON*, 2015.

[22] D. Zhang, K. Zheng G. Li, X. Ming, and Z. Pan. "An energy-balanced routing method based on forward-aware factor for wireless sensor networks". *IEEE Transactions on Industrial Informatics*, 10:766 – 773, 2014.