An Effective Routing Protocol for Energy Harvesting Wireless Sensor Networks

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***Abstract*—In traditional wireless sensor networks (WSNs), the power supply is a limiting factor on the lifetime of sensor nodes. Recently, energy harvesting technology has made it possible to develop autonomous WSNs with theoretical unlimited lifetimes. However, the change of power supply calls for a different version of network protocol. In this paper, we introduce Energy Potential Function which is utilized to measure the node's capability of enery harvesting and extend the traditional protocol LEACH to Energy Potential LEACH which is suitable for energy harvesting WSNs. Energy Potential LEACH can not only extend network lifetimes, but also improve the network throughput in energy harvesting WSNs. We evaluate the proposed protocol analytically and numerically, and find that it exhibits a better performance than previous work in terms of lifetimes and throughput.**

***Index Terms*—Wireless Sensor Networks, Routing Protocol, Cluster Head Selection, Energy Harvesting**

I. Introduction

Wireless sensor networks (WSNs) are widely used in various fields such as environmental monitoring, security monitoring, industrial control and military affairs [1].

Traditionally, sensor nodes in WSNs are powered by non-chargeable battery. Once a node's battery power is exhausted, it will die. Until now, energy consumption remains a key challenge during the design of battery-powered WSNs even though significant research efforts [2] have been taken on this subject.

Recently, researchers have resorted to harvesting energy from the environment to power sensor nodes. This technology can significantly prolong the life span of WSNs, and even make sensor nodes run perpetually. In this paper, we refer it as Energy Harvesting Wireless Sensor Networks (EH-WSNs) [3].

When a network is large enough to require multiple hops, routing will be involved. In WSNs, routing is also used to prolong the network lifetime since wireless sensor nodes are power-constrained devices [4]. The routing protocol for WSNs has been a hot area of research for many years due to its importance.

The main contribution of this paper is to extend the traditional routing protocol Low-energy adaptive clustering hierarchy (LEACH) [5] to Energy Potential LEACH (EP-LEACH). EP-LEACH adopts a new metric Energy Potential Function to measure the node's capability of enery harvesting. EP-LEACH not only inherits the advantage of LEACH, but also extends network lifetimes and improves the network throughput in EH-WSNs.

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The paper is organized as follows. Section II presents the state of the art. Then we explain Energy Potential Function and Energy Potential LEACH in details in Section III and Section IV. Section V evaluates the performance of Energy Potential LEACH through computer simulations. Finally, we conclude the paper and summarize our future work in Section VI.

II. Background and Related Works

A. Energy Harvesting Wireless Sensor Networks

EH-WSNs have been deployed in many fields such as structural health monitoring [6], active volcano monitoring [7], habitat monitoring [8] and fire hazard detection [9]. These applications can be classified into two categories: event-driven application and monitoring application. In event-driven application, sensors are generally in low power mode and may be activated by emergencies (active volcano monitoring and fire hazard detection). In monitoring applications, sensor nodes are in extremely low power mode or sleep mode and wake up at regular time (habitat monitoring and structural health monitoring).

B. The prediction of power supply in EH-WSNs

The prediction of future energy harvesting is a key issue for the design of routing protocol in EH-WSNs. One kind of prediction models is based on historical data: Kansal proposed a simple model based on an exponentially weighted moving-average (EWMA) filter [10]. Another kind of prediction models is based on weather forecasts: Sharma *et al.* figured out the relationship between several weather metrics and solar intensity [11].

C. Routing Protocol

A proper routing protocol can greatly improve the performance of networks. For WSNs, a series of energy-efficient routing protocol were proposed in order to reduce the energy consumption. LEACH is a well-known clustering-based routing protocol that tries to minimize energy dissipation in WSNs. Some protocols were derived from LEACH and adapted for the different situation in EH-WSNs [12], [13].

In recent years, there has been much research on the routing protocols for EH-WSNs. Thiemo Voigt *et al.* proposed a solar-aware version of LEACH [14] and a solar-aware version of Directed Diffusion [15].

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III. Energy Potential Function

In order to prolong the overall lifetime and the throughput of WSNs, high-energy dissipation in communicating with the base station should be spread to all sensor nodes in the WSNs. LEACH tries to achieve this goal by randomly selecting sensor nodes as cluster-heads, this method is effective in battery-powered WSNs because sensor nodes are nearly homogeneous and each node's potential of becoming cluster head is roughly equal. However, in EH-WSNs, the variation of energy harvesting makes the assumption of homogeneity invalid. Therefore, Energy Potential Function (EP-Function) is introduced to measure a node's capability of energy harvesting. EP-Function is also a measurement of a node's continuous operation ability.

The EP-Function of a node should be a function of hardware characteristics (transmission power, battery capacity) and ambient conditions around the node (temperature, humidity, illumination intensity). Therefore, to determine the exact formula of EP-Function is not a simple task. In this paper, we introduce a basic version of EP-Function. The time is divided into the same length of duration ΔT and some energy profile variables of a node are defined as follows:

- T_w, the time interval during which energy harvesting can be predicted, i.e. sensor node can exactly know how much energy can be gained in the next Tw slots.
- $R_k(i)$, the remaining battery power of node k at the beginning of slot i.
- $S_k(i)$, the gained power from the harvesting source of node k during slot i.

Given the above variables, a basic version of EP-Function suitable for EH-WSNs is defined as follows:

$$F_k(i) = \frac{e^{\lambda_k(i)[R_k(i)-\mu_k(i)+\sum_{j=i}^{i+T_w} S_k(j)]}}{1+e^{\lambda_k(i)[R_k(i)-\mu_k(i)+\sum_{j=i}^{i+T_w} S_k(j)]}} \tag{1}$$

In Eq.(1),$(R_k(i) + \sum_{j=i}^{i+T_w} S_k(j))$ is used to represent the energy potential of a node. $\mu_k(i)$ and $\lambda_k(i)$ are parameters used to standardize this variable where $\mu_k(i)$ is the mean value and $\frac{1}{\lambda_k(i)}$ is the variance. Both of them can be estimated based on the historical data.The definations of $\mu_k(i)$ and $\lambda_k(i)$ are as follow:

$$\mu_k(i) = E[R_k(i) + \sum_{j=i}^{i+T_w} S_k(j)] \tag{2}$$

$$\lambda_k(i) = \frac{1}{\sqrt{Var[R_k(i) + \sum_{j=i}^{i+T_w} S_k(j)]}} \tag{3}$$

Note that the basic form of Eq.(1) is $\frac{e^{a(x-\mu)}}{1+e^{a(x-\mu)}}$ which is a smoothed step function and can be referred as a high pass filter. Using this function, nodes with extremely low energy potential will never be chosen as cluster heads and nodes with energy potential above a certain threshold will be chosen as cluster heads with nearly equal probability. a and μ are parameters control the shape of this function.

The value of $F_k(i)$ ranges from 0 to 1. $Zero$ means the sensor node will run out of energy and die in the next slot, while One means the sensor node has sufficient power to keep working as the cluster head. It is easy to see that $F_k(i)$ in Eq.(1) highly depends on the prediction accuracy of $S_k(j)$ where $j \in [i, i + T_w]$. We will discuss this issue in Section V.

IV. Energy Potential LEACH

In this section, we extend the well known routing protocol LEACH to Energy Potential LEACH by introducing the EP-Function to the cluster head selection strategy.

A. Cluster Head Selection Strategy of Energy Potential LEACH

The operation of LEACH is seperated into rounds with $\frac{1}{P}$ slots, where each slot begins with a set-up phase when the cluster heads are selected and the structure of network is organized, followed by a steady-state phase when data are transferred to the base station. At set-up phase of slot i, the node k chooses itself to be cluster head by the probability $T_k(i)$ defined as Eq.(4) if it hasn't been selected as cluster head in a round. Otherwise, the probability is 0. P is the expected ratio of the number of cluster heads to the total number of nodes in the network. Each node will be a cluster head only once within $\frac{1}{P}$ slots.

$$T_k(i) = \frac{P}{1 - P \times (i \ mod \ \frac{1}{P})} \tag{4}$$

Due to the characteristics of EH-WSNs, the cluster head selection strategy must be modified in at least two ways:

1) At slot i, nodes with more potential energy should be more likely selected as cluster head.
2) There should be no limitation of times that a node can be the cluster head.

Based on the above considerations, our reformulation of Eq.(4) is as follows, in which $T_k(i)$ represents the probability that node k elect itself to be the cluster head at slot i:

$$T_k(i) = \frac{F_k(i)}{\sum_{r\in\mathscr{N}_k} F_r(i)} \times P \times |\mathscr{N}_k| \tag{5}$$

where

$$\mathscr{N}_k = \{r | D(r, k) < D_t\}. \tag{6}$$

In Eq.(5), $F_k(i)$ is calculated according to Eq.(1), and P is the optimal proportion of clusters in the network. In Eq.(6), $D(r, k)$ is a measurement of geographical distance between node r and node k. $\mathscr{N}_k$ is denoted as the set of node k's neighbors which are less than D_t from node k, and $|\mathscr{N}_k|$ is the size of $\mathscr{N}_k$. D_t is an important distance threshold under which two nodes are neighbors and can be interpreted as the node's familiarity to the network. $D_t \to +\infty$ means the node knows all the nodes' EP-Functions in the network while $D_t \to 0$ means the node knows nothing about the network.

The main purpose of our reformulation is to assign more forwarding tasks to the nodes with more potential energy. Meanwhile, the procedure of the cluster head selection should be distributed without the involvement of the base station.

In Eq.(5), P, D_t and $F_k(i)$ are all tunable. They will be given some initial values before the establishment of network, and then adjusted by the sensor nodes. In our network model, P is fixed to 0.05 and $F_k(i)$ is defined as Eq.(1). D_t has a initial value and each node refines its own D_t based on the ambient condition.

B. Analysis of Energy Potential LEACH

In this sub-section, we prove that the expectation of the number of cluster heads in the network ($N_{ch}(i)$) at slot i is equal to $N \times P$, *i.e.*

$$E[N_{ch}(i)] = E[\sum_{k=1}^{N} T_k(i)] = N \times P \tag{7}$$

This is important because the number of cluster head in the network should be a controllable parameter and not vary widely.

In extreme cases, we can get

$$\lim_{D_t \to 0} T_k(i) = P \tag{8}$$

$$\lim_{D_t \to +\infty} T_k(i) = \frac{F_k(i)}{\frac{1}{|\mathcal{N}_k|}\sum_{r \in \mathcal{N}_k} F_r(i)} \times P \tag{9}$$

Eq.(8) is established when D_t approaches zero, and then the only neighbor of node k is itself. Therefore, we get $|\mathcal{N}_k| = 1$ and $\sum_{r \in \mathcal{N}_k} F_r(i) = F_k(i)$.

Then

$$\begin{aligned}\lim_{D_t \to 0} E[N_{ch}(i)] &= E[\lim_{D_t \to 0} N_{ch}(i)] \\ &= E[\sum_{k=1}^{N} \lim_{D_t \to 0} T_k(i)] \\ &= N \times P\end{aligned} \tag{10}$$

$$\begin{aligned}\lim_{D_t \to +\infty} E(N_{ch}(i)) &= E(\lim_{D_t \to +\infty} \sum_{k=1}^{N} T_k(i)) \\ &= \sum_{k=1}^{N} \lim_{D_t \to +\infty} \frac{E(F_k(i))}{\frac{1}{|\mathcal{N}_k|}\sum_{r \in \mathcal{N}_k} F_r(i)} \times P \\ &= N \times P\end{aligned} \tag{11}$$

Eq.(11) is established because $\frac{1}{N}\sum_{r=0}^{N} F_r(i)$ is a unbiased estimation of $E[F_k(i)]$.

However, in common cases when $D_t \in (0, +\infty)$, the proof will be tricky. In this paper, we only present the numerical result given that $N = 1000$, $P = 0.05$, $F_k(i)$ obeys the exponential distribution. We run the simulation for 1000 times and show the statistical results in the form of Box plot shown in Fig.1. We can see that even though D_t varies from 0 to 100, the average number of cluster heads stays close to $N \times P$.

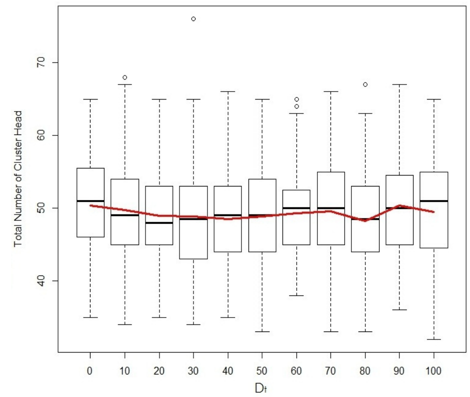

Fig. 1: The relationship between D_t and the total number of cluster heads

V. Performance Evaluation

A. Simulation Setup

In our simulations, we use a network with 1000 solar-powered nodes which are placed uniformly within a 100×100 square area. Fig.2 shows harvested energy of all nodes in the network during a single day. We can see that peaks of these curves usually appear at noon and there is hardly any energy harvesting during night. The base station located in at the center of the square area. We use the same assumption as in [5] where the percentage of nodes that are cluster heads $P = 0.05$, the communication paraments $E_{elec} = 50nJ/bit$, $\varepsilon_{amp} = 100pJ/bit/m^2$, each node sends a $2000 - bit$ data packet to the base station during each time slot, and the data aggregation rate is 0.5. LEACH[5] and TEEN[16] are simulated for comparison. The simulations for all the protocols are implemented in Matlab and the simulation results are averaged over 500 runs.

B. Evaluation Metric

We choose three metrics to analyze the performance of three protocols: number of dead nodes, throughput and data failure rate. Number of dead nodes indicates the overall lifetime of nodes in the network. Throughput indicates the average transmission rate of data packets from sensor nodes to the base station. Data failure rate measures the ratio of failed data packets to the total data packets.

C. Simulation Results and Analysis

1) Number of Dead Nodes: Fig.3 represents the number of dead nodes during 24 hours. We note that Energy Potential LEACH greatly reduces the likelihood of nodes' death since Energy Potential LEACH can elect competent nodes to be the cluster head according to EP-Functions.

2) Throughput: Fig.4 represents the average throughput in the network during 24 hours. We can see that the variance of throughput of Energy Potential LEACH is the smallest among these three protocols since the nodes can arrange theirs workloads according to future energy harvesting conditions.

3) Data Failure Rate: Fig.5 represents the data failure rate of EP-LEACH with different parameters. The prediction accuracy represents the data accuracy of gained power $S_k(i)$ in the next T_w slots. We can see that the data failure rate is highly related to the prediction accuracy while we can reduce the data failure rate by half by increasing D_t from $100m$ to $250m$ when the prediction accuracy is higher than 60%.

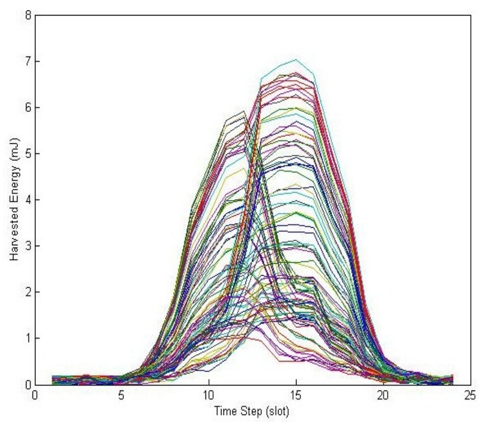

Fig. 2: Power supply of 1000 nodes. Power supply represents how much energy a node can harvest from environment

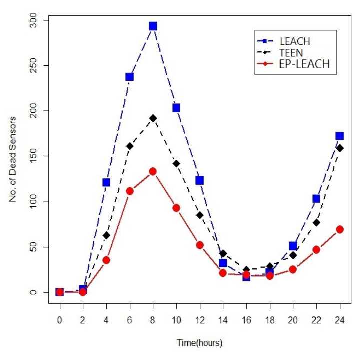

Fig. 3: Number of dead nodes variation of different routing protocol in 24 hours

VI. Conclusion and Future Work

In this paper, we proposed the routing protocol EP-LEACH by introducing EP-Function. We evaluated our protocol analytically and numerically and showed that it exhibits better performance than existing protocols.

As future works, we plan to apply the proposed algorithm in our practical project. In this case, the influence of the battery capacity and the limitation of computing power should be carefully considered. Furthermore, we are trying to make EP-LEACH more smarter by introducing machine learning algorithms to select optimal parameters for Energy Potential LEACH.

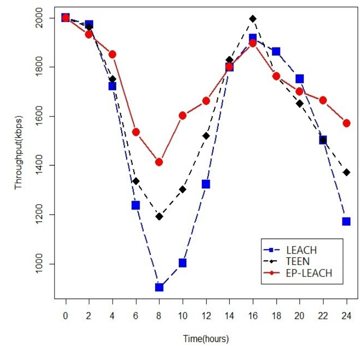

Fig. 4: Throughput variation of different routing protocol in 24 hours

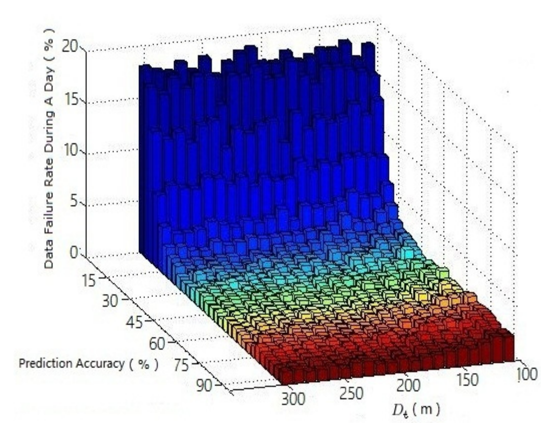

Fig. 5: The Relationship among data failure rate, prediction accuracy and D_t

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