Adaptive Energy-Harvesting Aware Clustering Routing Protocol for Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSNs) are energy-constrained. However, recent advances in ambient energy harvesting technology have made it possible for sensor nodes to harvest energy from ambient environment and serve as a supplement or the only energy source. And most of current routing protocols are specially designed for battery-powered WSNs, may not be suitable for energy harvesting WSNs (EH-WSNs), especially for those entirely powered by harvesting energy. In this paper, we propose an Adaptive Energy Harvesting Aware Clustering (AEHAC) routing protocol for EH-WSNs, which takes node energy state into cluster head election algorithm and can adjust its parameter according to the network deploying environment. We analyze and evaluate the routing performance in terms of two metrics available node number and network throughput. Simulation results show that AEHAC maintains available nodes about 15% and networks throughput 19% more than traditional LEACH.**

Keywords- Routing Protocol; Clustering; Energy Harvesting; Wireless Sensor Networks; Adaptive

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have gained extensive attention from the public for their wide area of applications, especially in monitoring and tracking [1]. WSNs are significantly efficient for many civil and military applications, such security, disaster management and combat field surveillance.

Traditional wireless sensor nodes are usually powered by non-chargeable battery. Once battery power is exhausted, the nodes will die. Recently, researchers have resort to harvesting energy from the environment to power the sensor nodes. This technology can significant prolong the life span of WSNs, or even make WSNs running for perpetual. In this paper, we refer it as “Energy Harvesting Wireless Sensor Networks (EH-WSNs)” [2].

EH-WSNs are much more useful and economical in the long-term running. Energy such as light, vibration, thermal and wind are always available from the environment. The networks can operate perpetually without maintenance. Hence, EH-WSNs are useful for applications which the network once deployed and is hard to maintenance, such as environment monitoring, intrusion detection, structural health monitoring etc.

Compared to battery-powered WSNs, the EH-WSNs have some unique characteristics, therefore most of the existing WSNs routing protocols may not be efficient to be directly used in EH-WSNs. To the best of our knowledge, most of the EH-WSNs routing protocols assume that harvested energy serves as the secondary energy source as a supplement to the battery one and little effort has been devoted to address the issues related with routing protocol for perpetual-operated EH-WSNs.

The rest of the paper is organized as follows. The background and related work are introduced in Section II. We present AEHAC routing protocol with energy-aware clustering in Section III. Numerical results are given in Section IV. Finally, we summarize the conclusion in Section V.

II. BACKGROUND AND RELATED WORKS

In this section, we summarize the characteristics of EH-WSNs, and then study clustering routing protocols. At last, we give a brief review about the related routing protocols for EH-WSNs.

A. Unique characteristics for EH-WSNs

There are typically two types of EH-WSNs. One treats the harvested energy as a supplement to the chemical battery to maximize the lifetime of WSNs. The other is using the harvested energy as the only source to the WSNs for perpetual operation. Our work focuses on the second one.

Key differences of hardware structure between battery-powered WSNs node and EH-WSNs node is on the energy supplement module. The energy supplement module of EH-WSNs mainly consists of energy harvesting device and energy storage device while only battery in battery-powered WSNs node, as illustrated in Fig. 1 and Fig. 2 [3]. These differences introduce some unique characteristics for EH-WSNs.

1) Energy is potentially infinite, though there may be a limit on the rate at which it can be used [4]

For example, solar-powered WSNs collect solar power every day if there is sun light. Therefore, for long-term running, the network energy is unlimited. However, for a short term, the energy amount that can be provided to

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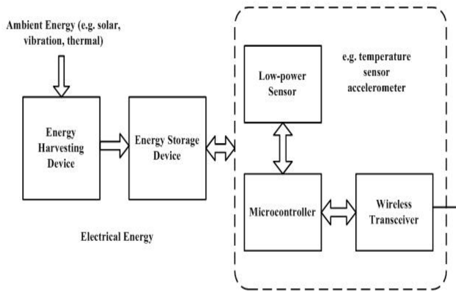

Figure 1. Hardware architecture of EH-WSNs node.

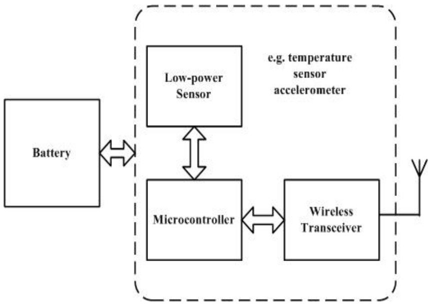

Figure 2. Hardware architecture of battery-powered WSNs node.

network is limited. This characteristic is the key distinction from battery-powered WSNs.

2) The energy distibution is not even.

Most sensor networks have to be deployed randomly in a hostile environment, such as military and disaster area. Many modern approaches have been used on WSNs deployment, i.e. from aircraft or launched via artillery, and sensor nodes are therefore distributed with a certain stochastic description.

When solar harvesting WSNs nodes are deployed by above means, different solar panel angles and surroundings may cause different energy harvesting rate.

3) EH-WSNs are sensitive to the environment

For the long term, the energy of EH-WSNs is all from the environment though some start energy may be from the energy storage device. Therefore, environment changes, e.g. Temperature, humidity etc., may affect the node energy harvesting rate significantly. The energy in EH-WSNs may not sustain without a battery to backup which may cause network nodes die and relive frequently and therefore change the network topology frequently.

B. Cluster Routing Protocol

Noted in previous analysis, the routing protocols in EH-WSNs, especially in perpetual-operated EH-WSNs have a strictly requirement to the scalability, fault tolerance and topology control. Most of the existing routing protocols are hard to be directly used in EH-WSNs. However, the merit of the clustering in these conventional protocols can meet the requirement of EH-WSNs.

Grouping sensor nodes into clusters has been widely pursued to achieve the network scalability. Each cluster has a leader, often referred to as cluster head. Clustering technique has numerous advantages such as localizing the route, cutting topology maintenance overhead, reducing the rate of energy consumption, decreasing the number of relayed packets and etc. [5].

LEACH[6][7] is the most popular energy-efficient hierarchical clustering algorithm for WSNs. LEACH randomly selects a few nodes as cluster heads and rotates this role to even distribute the energy load among the sensors in the network. For each node, the probability of being chosen as a cluster head can be formulate by

$$p_i(r) = \begin{cases} \dfrac{p}{1 - p \times (r \bmod \frac{1}{p})} & \text{if} \quad i \in G(r) \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

Where $p_i(r)$ denotes the probability that node i can be cluster head, p denotes the percentage of the node number that can be cluster heads in a round. r denotes the index of current round. $G(r)$ denotes the set of the nodes have not been a cluster head in the most recent $r \bmod (1/p)$ round.

Bench of routing protocols were proposed based on LEACH for the purpose of simplicity, scalability, distributed calculation and good performance to balance to the energy dissipation of the network, such as PEGASIS [8], HEED [9], TEEN [10] and so on.

C. Energy harvesting routings review

Voigt et al. [11] first proposed a solar aware routing protocol similar to directed diffusion, which prefers to route data package via solar-powered nodes. After that, they developed LEACH for sLEACH (solar-aware LEACH). Islam et al. [12] proposed A-sLEACH which is an extension to sLEACH. However, in both of sLEACH and A-sLEACH, they treated solar energy as a supplement to node's energy source to extend the life span of WSNs, and when the nodes in WSNs exhausted their battery energy, the WSNs will end at last.

Lin et al. [13] proposed a distribute algorithm that considers energy replenishment to get the optimal multihop path. Kandasamy and Krishnan [4] developed a multipath routing scheme that based on an estimated energy budget, including current energy, the predicted energy consumption and the energy expected from solar cell, to attained energy optimization and reducing congestion in the network. Zeng et al. [14]

proposed routing protocols which combine geographic routing and energy efficient routing techniques, which takes the realistic wireless channel condition and environmental energy supply into account when making routing decisions. On the base of the tradition opportunistic routing protocols and taking into account energy constrains, Eu et al. [15] introduced EHRO for EH-WSNs. In the paper, after analyzed and compared three state-of-the-art routing algorithms, Hasenfratz proposed R-MPRT-mod which uses solely the stored energy in cost function. Jaggi et al. [16] designed an online and adaptive activation algorithm which is not depending on global system parameters. However, none of these works pays attention to hierarchy routings in EH-WSNs.

To the best of our knowledge, there is no related work on the clustering routing protocol for EH-WSNs.

III. ADAPTIVE ENERGY-HARVESTING AWARE CLUSTERING ROUTING PROTOCOL

A. The EH-WSNs model

Some assumptions are made for the EH-WSNs as follows. We assume that all nodes can communicate with the sink node if needed. We suppose nodes always have data to send to the sink node and have correlated data. Each node can use power control to change its transmit power and therefore communication distance. All nodes have the same hardware architecture and are randomly deployed in the field. Each node can harvest energy from the environment without backup chemical battery and can evaluate its short term energy harvesting rate. The energy harvesting rate is between *[0,* $\mu_{\max}$ *]*. The operation of the EH-WSNs model is divided into rounds *r*. In the paper, we assume that the total node number in the EH-WSNs is N .

We assume that, once node energy falls below $E_{threshold-down}$, it will quit the network and switch to the sleep mode. The nodes with energy close to the threshold may join and quit the network frequently, which would introduce a large cost to the network. We take this effect into account. When a node is in sleep mode, only if the node energy above $E_{Threshold-up}$ then it can woke up and try to join the network. Obviously, $E_{Threshold-up}$ > $E_{Threshold-down}$. This threshold scheme can reduce the overhead of the topology control.

B. Energy-Harvesting Aware Clustering Algorithm

From the reference [7], there is optimum number of cluster heads, which can minimize the whole network energy consumption during a round. It also applies to EH-WSNs for it only concerns with the topology and the node number of the network. We assume that the number of node in networks $n(r)$ fluctuates near n_0 and the optimum cluster head for node number n_0 is k_0 , then the cluster head rate in the networks can be express by:

$$p = \frac{k_0}{n_0} \tag{2}$$

Compared to the battery-powered WSNs, the current round cluster heads election is far less depended on the former round election for the whole networks energy changed little. Therefore, we can take the election as independence. For simplicity, we directly use the p as the probability of the node becoming the cluster head and it doesn't change with the round *r*:

$$p_i(r) = p \tag{3}$$

But it's hard to get the optimal p in actual application for the diversity of the environment and uncertainty of the network deployment. So we wish the network can search its optimum number of cluster heads by itself during operation.

LEACH is designed especially for the battery-powered WSNs. Cluster heads selecting scheme makes the nodes to be cluster heads in turns, it can make the power consuming evenly distributed among nodes. In EH-WSNs, energy is infinite and the energy harvesting rates are usually various between nodes. Therefore, it is impropriate to still use the cluster head selecting algorithm. We expect that the nodes with a faster energy harvesting rate should have higher probability to be cluster heads.

For above reasons, we propose AEHAC. The operation of EHAC is divided into rounds and each round has mainly two phases: set-up phase and steady-state phase. Following, we focus on the differences between our routing protocol and LEACH. In AEHAC, we improved cluster heads election algorithm of LEACH:

$$p_i(r) = \rho(r)\frac{\alpha \cdot E_{i\text{-Residual}}(r) + \beta \cdot E_{i-\text{Harvest}}(r-1) + \mathrm{C_B}}{E_{i-\text{Capacity}}} \tag{4}$$

Where $p_i(r)$ is the probability of node *i* be cluster heads during the round *r*. $\rho(r)$ is the regulation factor of cluster heads. α is the residual energy coefficient. $E_{i\text{-Residual}}(r)$ is the residual energy of node *i*. β is the harvest energy coefficient, $E_{i-\text{Harvest}}(r-1)$ is the harvested energy during round *r* of the node *i*, $E_{i-\text{Capacity}}$ is the capacity of the node *i*. $\mathrm{C_B}$ is the energy equilibrium constant, which can stable the network when the node the variation of the energy harvesting rate in the networks. So while the energy harvesting rate change fast with the time, C_B should be relative big number, otherwise C_B should be a small number.

$\rho(r)$ is determined by sink node, sink node use searching algorithm to get the optimum ρ .when the searching algorithm works, sink node change ρ for each *m* round, meanwhile sink node check whether the step length λ bigger than the threshold δ. If λ is bigger than δ, the sink will compare $D_C(m)$ and $D_L(m)$, which $D_C(m)$ is the current *m* round sink average data and $D_L(m)$ is the last sink average data. If $D_L(m) > D_C(m)$, then $\lambda = -0.614\lambda$ $\rho(r) = \rho(r\text{-}1) + \lambda$; if $D_L(m) < D_C(m)$,then $\lambda=\lambda$ $\rho(r) = \rho(r\text{-}1) + \lambda$; until $|\lambda|<\delta$, then searching algorithm end, and the ρ is the optimum ρ . At the beginning of each round sink will broadcast its ρ to the networks, the nodes in the networks will update its ρ before the cluster heads election algorithm works.

Algorithm1. Sink node searching algorithm

if mod(r,m)==0&&$|\lambda|>\delta$
  if $D_L(m) > D_C(m)$
    $\lambda=-0.614\lambda$;
    $\rho(r) = \rho(r\text{-}1) + \lambda$
  else
    $\rho(r) = \rho(r\text{-}1) + \lambda$;
  end
else
  $\rho(r) = \rho(r\text{-}1)$;
end
broadcast ρ to the networks

In the setup stage, when a node received the sink broadcast, it synchronizes with the sink, and then gets the ρ from the broadcast packet. After that, sink node use formulation (6) to calculate the cluster head probability $p_i(r)$, After the node calculates the probability of being cluster heads, it will generate a random number σ between [0, 1]. If $p_i(r) > \sigma$, it will be cluster head, otherwise it will be non-cluster head nodes. Then the cluster head broadcast message and the non-cluster head nodes choose the nearest cluster head to join in, then cluster head allot TDMA schedule to its members.

Algorithm2. Cluster head selection algorithm

if node *i* received sink broadcast packet **then**
  synchronizes with the sink and update ρ;
    calculate $p_i(r)$ and generate a random number σ;
  if $p_i(r) > \sigma$ **then**
      node *i* be cluster head and broadcast message;
  else
      listening to the network;
  end
else
  listening to the network;
end

In steady-state phase, the biggest difference between AEHAC and LEACH is: in AEHAC, some node may lack of energy (when the energy lower than $E_{Threshold-down}$), turn into sleep mode, while some node wake up (when the energy is higher than $E_{Threshold-up}$) trying to join the network again.

When a node wakes up, the node will do nothing but listening to the network: whether there is a message send by the sink to start a new round. If the node received that message in one frame, the node will synchronized with the network and participate the cluster heads election. If the node did not receive that message in one frame, the node will prefer to synchronized with the TDMA schedule by receiving the packets of a cluster head (which contain the message the round sustain information) to know when is the end of the round, then it goes to sleep and will wake up at the end of the round.

IV. Performance Evaluation

A. Simulation Setup

In our experiments, we used a 200-node network where nodes were randomly distributed between (x=0, y=0) and (x=200, y=200) with the sink node at location (x=100, y=100). Each data message packet is 500 bits long. Each round the node will produce 16 such packets. The control packet is 100 bits long. We use the same radio energy dissipate model in LEACH. The communication energy parameters are set as: E_{elec} = 50nJ/bit, ε_{fs} = 10pJ/bit/m^2, ε_{mp} = 0.0013pJ/bit/m^4, and the energy for data aggregation EDA=5nJ/bit/signal. The node maximum energy harvesting rate $\mu_{\max}$ = 0.008J/hour, and energy harvesting rate of the node in the network is random distribute between 0 and $\mu_{\max}$ .We set the round duration 0.1hour. The capacity of the node is 0.3J, the initial energy is equal to the node capacity, $E_{\text{Threshold-down}}$=1/10 E_{Capacity} , $E_{\text{Threshold-up}}$ =3/10 E_{Capacity} . $\alpha=\beta=1$, C_B =0，m=10, the initial ρ=0.3, λ=0.2, the searching threshold δ=0.01, and we set the searching algorithm start at 20 hour of the network operation.

B. Evaluation Metrics

The common metric to evaluate the performance of a routing protocol is to calculate the throughput in WSNs. But to perpetual operated EH-WSNs, we also should emphasize the percentage of available nodes in the whole network nodes. The more available nodes at the same time, the more information about sensed object, thus brings the observer more details, deep and comprehensive understanding of the sensed object. Therefore, maximizing the number of available nodes under given workload and environmental constrain should be the major task for perpetual operated EH-WSNs.

C. Simulation results and Analysis

We give a simulation to the available node number and throughput of LEACH and AEHAC in our EH-WSNs model. As are shown in Fig.3 and Fig.4. From the line of LEACH in the two figures, we observe that the available node number and network throughput fall at beginning with the initial energy consume, and then they reached a relative steady stage as the time increasing.

We name the stage: *dynamic balanced stage*. The network in this stage, the quitting network nodes is approximately equal to the joining network nodes; the whole network harvested energy is approximately equal to the consumed energy.

From the line AEHAC in Fig. 4, we observe the when the searching algorithm works, the network throughput changed rapidly, when the searching algorithm finished and get the optimum cluster head regulation factor, it reached the dynamic balanced stage.

To verify the stability of the searching algorithm, we give a simulation of AEHAC with different initial cluster head regulation factor ρ and searching step length λ (ρ=0.3, λ=0.2; ρ=0.4, λ=0.2; ρ=0.3, λ=0.1). We trace the regulation factor ρ changing process and have the Fig. 5. From the Fig. 5, we conclude, though with the different initial cluster head regulation factor ρ and searching step length λ, the optimum cluster head regulation factor ρ can reached near the same value. This demonstrates the stability of the searching algorithm.

From Fig. 3 and Fig. 4, we can conclude that AEHAC can increase the available node number by about 15% and the throughput 19% than LEACH on the dynamic balanced stage. The improvement of available node number and network throughput is mainly brought in by the cluster head selection algorithm for it increase the probability of the energy rich node being cluster heads, meanwhile decrease the probability of the energy poor node being cluster heads. Thus the network can make the best of the harvested energy, lower the packet loss rate which is brought by cluster head lack power and have better efficiency to extract energy from the environment.

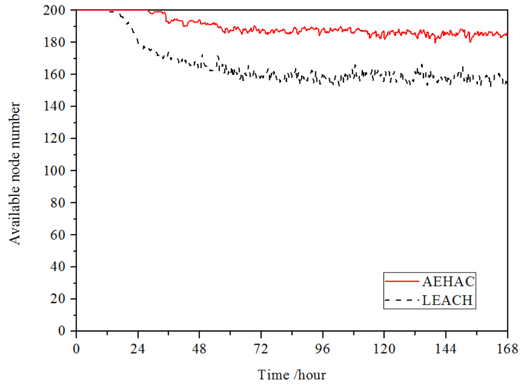

Figure 3. Available node in EH-WSNs

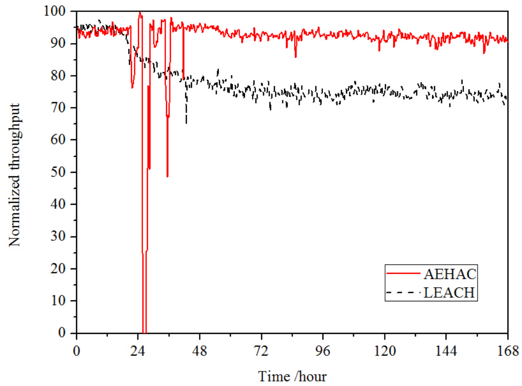

Figure 4. Throughput in EH-WSNs

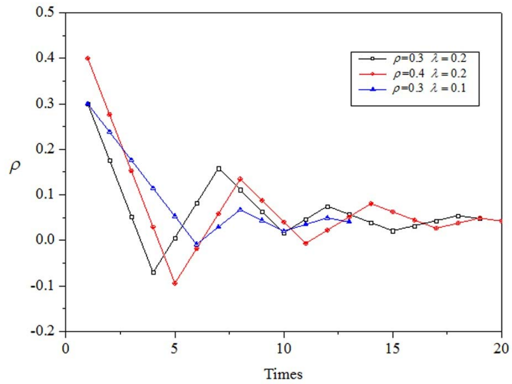

Figure 5. Regulation factor ρ changing process

V. CONCLUSION

In this paper, we summarized the unique characteristics of energy-harvesting WSNs, studied clustering scheme routing protocols especial LEACH. Base on it, we build the energy harvesting WSNs model, then we propose Adaptive Energy-Harvesting Aware Clustering (AEHAC) routing protocol for perpetual-operated EH-WSNs. The protocol elects cluster head distributed and combines with energy harvesting rate and the node residual energy making it more efficient for EH-WSNs. The AEHAC can adjust its parameter according to the network deploying environment. Simulation has shown, compared with LEACH, AEHAC not only increase the available node number, but also increase the network throughput on the dynamic balanced stage. Simulation also has shown the AEHAC has a good stability.

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