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Clustering Routing Algorithm of Probabilistic for Energy-harvesting Wireless Sensor Networks

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Abstract: The technology of Energy harvesting seems to alleviate the problem of energy constrained in traditional Wireless Sensor Networks. This paper presents a clustering routing algorithm of probabilistic and energy balanced for energy harvesting wireless sensor network (EH-EBPR): Based on the residual energy and energy harvesting rate, each node execute the clustering with fully distributed, and then TDMA slot is allocated orderly according to the energy state of node. Consider that when cluster heads transmit data via single-hop or multi-hop in traditional clustering routing, there would be the problem of uneven energy consumption, EH-EBPR scheme combines single-hop with multi-hop probabilistically so that the energy consumption in the network is relatively uniform. Theory and simulation show that EH-EBPR routing algorithm works well in balancing the energy consumption of entire network as well as conserving the energy, and it is well suited for Energy-harvesting Wireless Sensor Network. *Copyright © 2013 IFSA.*

Keywords: Wireless sensor network, Energy harvesting, Probability routing, Clustering, Energy balance.

1. Introduction

As the small size of node and the special application environment, traditional wireless sensor network are usually powered by batteries and it is difficult to replace the power source, which makes the energy-constrained being a major problem in traditional wireless sensor network (WSN). A lot of previous research has therefore focused on the method to reduce energy consumption and extend the network lifetime [1]. With the development of technology, Energy harvesting has recently been introduced to overcome the problem of energy-constrained. Node in energy harvesting wireless sensor network (EH-WSN) can get energy from extern environment, such as wind, solar energy, temperature variation and so on [2]. However, the rate of energy-generating is random as the variable of extern environment. When energy harvesting rate of node is low, more attention should be paid to conserve the energy, we should also make use of the energy harvested as much as possible when the harvest rate is high, a good routing scheme in EH-WSN should adjust to the rate of energy harvesting. So traditional routing methods in WSN can not work well in energy harvesting wireless sensor network [3].

Related research about routing algorithm in EH-WSN has been done in recent years. Hyuntaek Kwon proposed Low-latency routing for energy-harvesting sensor networks [4], in which nodes can automatically adjust the duty cycle according to their energy state. Nodes in paper [5] are assumed to get energy only from extern environment, based on the energy state of all nodes, the whole network can turned into a flow network topology of link constrained, next hop can then be decided by remaining link capacity with greedy algorithm. Guojun. D proposed a EL-TPC strategy [6], different

energy harvesting rate were classified into different levels, and different levels has different priorities in routing, which leads a hierarchical routing scheme of three hops in maximum. Zhang Yu-Juan et have analysis the solar energy supply model in [7], then proposed an adaptive clustering routing algorithm based on LEACH [8], network in different energy states has different routing methods.

Consider the advantage of clustering routing algorithm in network scalability and reduction of data redundancy [9], we have designed a hierarchical clustering routing strategy: Energy balanced and Probability Routing for Energy-harvesting Wireless Sensor Networks (EH-EBPR). There are two stages in each round: clustering and inter-cluster communication. The rate of energy harvesting is taken into account when selecting the cluster heads. And in the stage of inter-cluster communication, each cluster head transmit its data to sink node via single-hop or multi-hop probabilistic. The combination of single-hop and multi-hop avoid the problem of uneven energy consumption caused by single-hop or multi-hop in traditional routing algorithm [10], it can balance the energy consumption in the whole network. Simulation results show that our routing algorithm can make good use of the energy harvested while balancing the energy consumption, therefore increasing the survival time of all nodes in EH-WSN.

The remainder of this paper is organized as follows: Section 1 gives the model of network and model of energy consumption, Section 2 describes the detail of EH-EBPR and make it analyzed, Section 3 presents the performance of the algorithm with the simulation results by Matlab, Finally, Section 4 gives concluding remarks and future work about the research.

2. System Model

2. 1. Network Model

Assume that N nodes randomly distributed in a square of a side length. The sink node is placed at an endpoint of the square and it has unlimited energy. Specific network model is as follows:

1. The energy subsystem of node in EH-WSN is constructed by storage batteries and solar harvester unit. And the harvest rate of every node in each round is different. The storage batteries can store a maximum energy of $E_{\max}$.

2. Except the sink node, all nodes have the same function in whole network and each of them has a unique ID. They can also adjust the transmission power freely according to the distance to the receiver.

3. Links in the network are symmetric. The receiver can calculate an approximate distance to the transmitter with received signal strength indication (RSSI) [11].

4. The location of nodes in the network is relatively stable, the distance to sink node is almost unchanged.

5. Node will go to sleep and continue to get energy from solar when its energy is below 1 % of $E_{\max}$ (the maximum value of stored energy). Node in sleep state will also awake when its energy exceed $\lambda E_{\max}$.

2.2. Energy Model

The first order radio model that proposed by Heinzelman [12] is used to calculate the energy cost during communication in this paper. Assumes k data bits are to be transmitted d meters away from here, the energy cost of the transmitter can be calculated as follows:

$$E_{\mathrm{Tx}}(k,d)=\begin{cases} E_{\mathrm{elec}}\times k+\varepsilon_{\mathrm{first-amp}}\times k\times d^2 & d<d_0 \\ E_{\mathrm{elec}}\times k+\varepsilon_{\mathrm{two-ray-amp}}\times k\times d^4 & d\geq d_0 \end{cases}, \quad (1)$$

While E_{elec} denotes the energy consumed by transmitting or receiving circuit, $\varepsilon_{\mathrm{amp}}$ represents the energy consumed by transmission amplifier and it is different ($\varepsilon_{\mathrm{first-amp}}$ or $\varepsilon_{\mathrm{two-ray-amp}}$)when the distance d differs.

The energy cost by receiver is calculated by equation 2.

$$E_{\mathrm{Rx}}(k) = E_{\mathrm{elec}} \times k , \quad (2)$$

Consider that cluster head will make data fusion to reduce data redundancy, we set E_{Da} as the energy cost while data fusing, which has a typical value of 5 nJ/bit/signal [13].

We can see from equation 1 that the distance of transmission has a great impact on energy consumption. While there are traditional two ways (single-hop or multi-hop) to send the data form cluster head to sink node, both of them will cause uneven energy consumption of cluster heads. So it's also important to balance the energy cost of whole network.

3. EH-EBPR Scheme Description

There are two phase in the network: network initialization and cluster-rounding phase. During initialization process, the sink node broadcast message of Msg-dis all through the network and all the other nodes then calculate the approximate distance from themselves to the sink node. And during the phase of cluster-rounding, network will be clustered and data then will be transmitted through cluster heads every T_{round} seconds.

3.1. Clustering Algorithm

The clustering operation in this paper has similar idea of HEED [14]. Here is the mainly procedure :

1) According to the residual energy E_{residual} and harvest rate, each node can calculate its initial probability of being cluster head (CH_{pr}).

$$\text{CH}_{\text{pr}}(i)=\max\left\{C_{\text{pr}}\times\frac{E_{\text{residual}}(i)+P_{\text{r}}(i)\times T_{\text{round}}}{E_{\max}},P_{\min}\right\}, \quad (3)$$

C_{pr} denotes the initial proportion of cluster heads in the network. $P_{\text{r}}(i)$ is the average harvest rate of node i in current round. $P_{\min}$ is a const which is used to make the clustering process done in a limited number of iterations. Each node then send a message of Neighbor-search with a given power P_{intra} , Define $\text{N}(i)$ as the neighbor set of node i , which is given by equation 4.

$$\text{N}(i)=\left\{j|\text{D}(i,j)<=\text{R}_{\text{intra}}\right\}, \quad (4)$$

$\text{D}(i,j)$ represents the distance between node i and node j and R_{intra} is the range of intra-cluster communication which is decided by P_{intra} . Node can then receive Neighbor-ack messages replied by its neighbors, which can be used to calculate the cost value of each node. If a node has no neighbor, the cost will be set to infinity, otherwise it can be calculated as follows:

$$\begin{aligned}\text{cost}(i)=\alpha\times\min\left(\frac{N_{\text{nbo}}(i)\times E_{\text{rs}}(i)}{P_{\text{r}}(i)\times T_{\text{round}}},1\right)+\\(1-\alpha)\times\frac{\sum_{j\in N(i)}D(i,j)}{N_{\text{nbo}}(i)\times R_{\text{intra}}}\end{aligned}, \quad (5)$$

N_{nbo} is the number of the neighbors of node i . E_{rs} is a const which means the energy cost when node i send the data generated by one cluster member in a round to the sink node, so that $N_{\text{nbo}}(i)\times E_{\text{rs}}(i)/(P_{\text{r}}(i)\times T_{\text{round}})$ means the approximate ratio of energy cost and energy harvested. When the harvest rate is low, the value of the first part in equation 5 will be α , energy conservation is a major factor in this case; while the harvest rate is high, the value of the first part in equation 5 will be lower than α , the value of cost is a combination of energy conversation and harvesting energy utilization. we can also adjust α to the harvest rate so that we can get better utilization of harvested energy while reducing the energy consumption of whole network.

2) Iterative stage. Define the set of candidate cluster heads of each node as S_{CH} . If S_{CH} is empty, the node will compete as cluster head with a probability of CH_{pr} in current iterations. If S_{CH} is not empty, the node will select a node with minimum cost as its tentative cluster head among S_{CH} . If a node is selected as a cluster head, it will broadcast the message to its neighbors, and the status of it will be final-CH or tentative-CH if the value of CH_{pr} equals 1 or not. Nodes who receive the message then update their S_{CH} . At the end of each iteration, every node will double the value of its CH_{pr} , when CH_{pr} equals 1, the iteration will end.

3) Termination stage: each node will select the node that has minimum cost among nodes whose status is final-CH as its cluster head from its neighbors. If there is not any node whose status is final-CH, node will select itself as the cluster head and then broadcast the message.

3.2. TDMA Slot Allocation

After the network is clustered, the method of Time Division Multiple Access is used to allocate the time slot for the members of a cluster to transmit the data to their cluster head. Node will awake and transmit its data during its time slot, and turn into sleep on the other time. Considering the characteristics of energy harvesting wireless sensor network, the time allocated to each node is based on their energy state. One has a larger value of ($E_{\text{residual}}+P_{\text{r}}\times T_{\text{round}}$) will transmit its data earlier, which can lower the probability that nodes turn into sleep as well as making better use of the energy harvested.

3.3. Inter Cluster Communication

Each cluster head received the data of all nodes in its cluster and make the data fusion, and then transmit the data to sink node. Define the distance from node i to sink node as $D_{i-\text{sink}}$, the next hop is decided by following cases.

A. If $D_{i-\text{sink}}\le \text{S}$, the cluster head will transmit the data to sink node directly. S is a constant distance. To avoid unnecessary energy cost by excessive data relay, if the cluster head is close to sink node, the data can be transmitted by single hop.

B. If $D_{i-\text{sink}}>\text{S}$, R_{co} is defined as the routing coefficient of the cluster head. And if $Random(0,1)<R_{\text{co}}$, the data will also be transmitted to sink node directly. Considering the relation

between distance and energy cost in the first order radio model, R_{co} is defined as follows:

$$R_{co}(i)=\beta\times\frac{S^2}{D^2_{i-\text{sink}}}+(1-\beta)\times\frac{E_{\text{residual}}(i)+P_r(i)\times T_{\text{round}}}{E_{\max}}, \quad (6)$$

so node that has more energy and closer to the sink node will has a great chance transmitting its data directly.

C. If $D_{i-\text{sink}} > S$ and $Random(0,1) >= R_{co}$, the cluster head will transmit the data by multi-hop. Node who has minimum value of C_{cost} from N_{CH} will be the next hop. C_{cost} can be calculated by following equation.

$$C_{\text{cost}}(i)=\gamma\times\frac{D_{i-\text{sink}}}{D_{\max}}+(1-\gamma)\times(1-\frac{E_{\text{residual}}(i)}{E_{\max}}), \quad (7)$$

where $D_{\max}$ is the maximum value of the distance from one node to sink node. Define the neighbor cluster heads of node i as $N_{CH}(i)$:

$$N_{CH}(i)=\left\{\begin{matrix} j \mid D(i,j)\le R_{\text{inter}} \cap D_{i-\text{sink}} \\ > D_{j-\text{sink}} \cap j\in clusterhead \end{matrix}\right\}, \quad (8)$$

where R_{inter} represents the range of inter-cluster communication, so the cluster head which is selected as the next hop should be closer to the sink node as well as having more energy, it will also then transmit the data received by the way above. And if there is not any neighbor, the cluster head will transmit the date to sink node directly.

3.3. Node Maintenance and Exception Processing

Considering the case that node run out of energy while transmitting the data. If the node that runs out of energy is a cluster head, it will broadcast a message of Cluster-disband to disband the cluster and then turn into sleep. The members of this cluster will not transmit data until next round. And if the node that runs out of energy is the member of a cluster, it will send a message of Energy-exhaust and then turn into sleep. Nodes in the status of sleep continue to replenish their energy from outside. When the energy reaches a certain level ($\lambda E_{\max}$) they will then awake.

4. Simulation and Performance Evaluation

Matlab7. 0 is used as a simulation tool to evaluate the performance of EH-EBPR scheme. Assume that 400 nodes randomly distributed in an area of 150 m×150 m. All nodes have same original state of energy and they can harvest energy from sunshine outside. The main parameters are shown in Table 1.

Table 1. Main parameters used in this paper.

Parameter	Value	Parameter	Value
Range of network	$150m\times150m$	E_{elec}	50 nJ/bit
N (Number of nodes)	400	$\varepsilon_{\text{first}-\text{amp}}$	10 pJ/(bit·m^2)
Location of sink node	（0 m, 0 m）	$\varepsilon_{\text{two}-\text{ray}-\text{amp}}$	0. 0013 pJ/(bit·m^4)
E_{init} (Initial energy of node)	2J	E_{Da}	5 nJ/(bit·signal)
Data packet size	4000 bits	α	0.5
Broadcast packet size	200 bits	β	0.8
S	50 m	γ	0.3
R_{intra}	20 m	R_{inter}	60 m
T_{round}	10 s	C_{pr}	0.05
λ	0.4	$P_{\min}$	$10^{(-4)}$

In order to verify the performance of EH-EBPR, we will make a comparison of EH-EBPR, HEED, and HEED-M [15]. The process of clustering in HEED and HEED-M are the same. While cluster heads in HEED transmit their data to sink node directly, cluster heads in HEED-M transmit their data with multi-hop according to the distance to sink node and their residual energy.

4.1. Energy Efficiency

At first, the total energy consumption of the network in one round is considered. As the rate of energy harvesting is affected by external environment, we can set the harvest rate of all nodes uniformly distributed between (0 mW, 0.1 mW). The

energy consumption of top 20 rounds nodes with three different routing schemes are shown in Fig. 1.

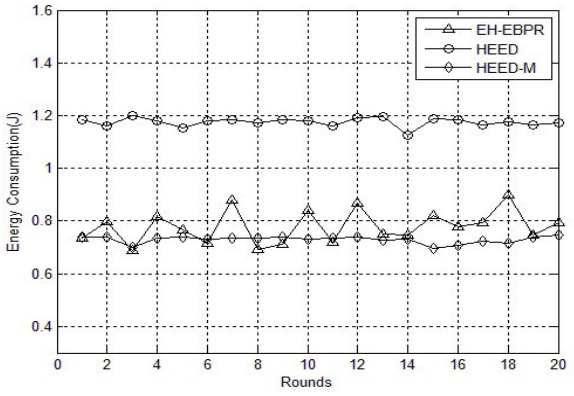

Fig. 1. Energy consumption of the network in one round.

We can find that network with HEED has higher energy consumption, the reason is that the cluster heads transmit their data directly to sink node, as energy consumption is growing rapidly with the change of distance, therefore the energy consumption is high. Network with HEED-M transmit the data via multi-hop, which can reduce serious energy loss due to the data transmission of long distance, so the energy consumption is relatively low. And EH-EBPR combines single-hop with multi-hop, node that is far away from sink node will likely transmit the data to next hop while node that is closer to sink node will probably transmit the data directly to sink node. That can avoid transmission of long-distance as much as possible, and it can also reduce unnecessary energy cost caused by excessive data reception in multi-hop routing schemes. So the energy consumption with EH-EBPR is also relatively low.

4.2. Energy Balance

In the network with EH-EBPR, a cluster head transmit its data via single-hop or multi-hop with a certain probability, which can balance the energy cost of whole network. Fig. 2 shows the residual energy of all nodes after 500 rounds when the harvest rate equals 0. Fig. 3 shows the residual energy of all nodes after 500 rounds when the harvest rate uniformly distributed between (0 mW, 0.1 mW).

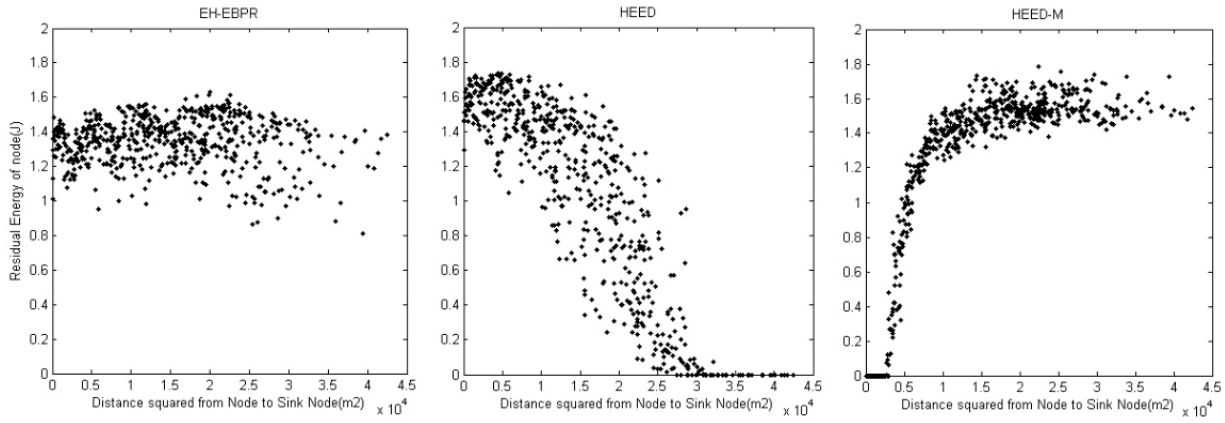

Fig. 2. Residual energy of all nodes after 500 rounds when harvest rate equals 0.

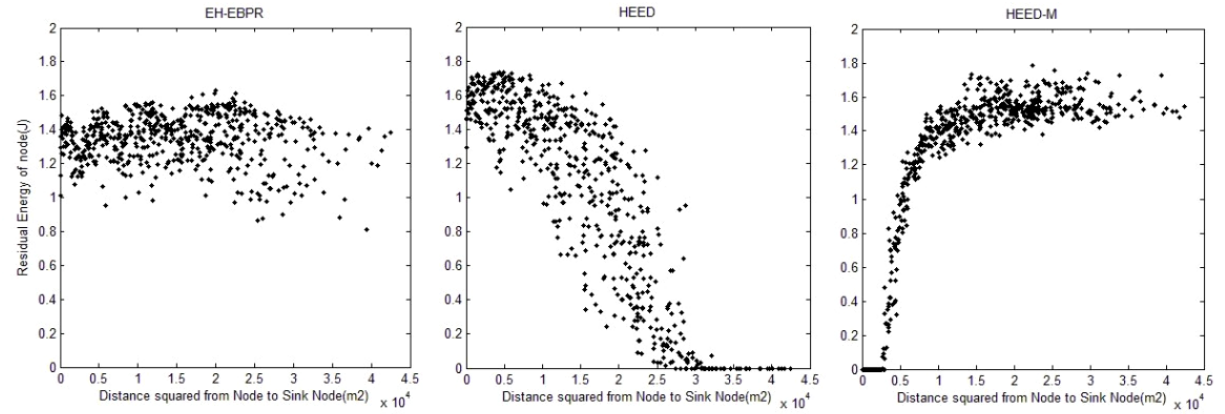

Fig. 3. Residual energy of all nodes after 500 rounds when harvest rate uniformly distributed between (0 mW, 0.1 mW).

We can see from Fig. 2 that the residual energy of nodes in the network with EH-EBPR is approximately uniform after 500 rounds. While in the network with HEED, as the distance of data transmission is too long, nodes that far away from sink node run out of their energy prematurely. And in the network with HEED-M, on the contrary, nodes that are close to sink node exhaust their energy early because they need to relay the data of whole network.

The emerge of energy harvesting have alleviated the problem of energy constraint in traditional wireless sensor network. By the comparison between Fig. 2 and Fig. 3, we can see that EH-EBPR routing scheme can also made good use of the energy harvested as well as balancing the energy cost.

During the stage of network clustering, the node will select a cluster head with minimum cost as its cluster head. As is shown in equation 5, if a node have a high harvest rate and its neighbors are close to it, the value of cost will be small. The consideration of harvest rate is to make good use of the energy harvested, and the consideration of the average distance from node to its neighbors is to conserve the energy cost caused by intra-cluster communication when harvest rate is low.

4.3. Network Lifetime

At first, if node can't get energy from outside, we define the network lifetime as the rounds when the first node turns into sleep in the network. Fig. 4 shows the minimum residual energy of nodes in the network with different routing strategy. While in the network with HEED, as the residual energy in the network is unbalanced, after 250 rounds, there will be one node who exhaust the energy and turn into sleep, so is the network with HEED-M after about 270 rounds. And in the network with EH-EBPR, node will not turn into sleep until about 1350 rounds.

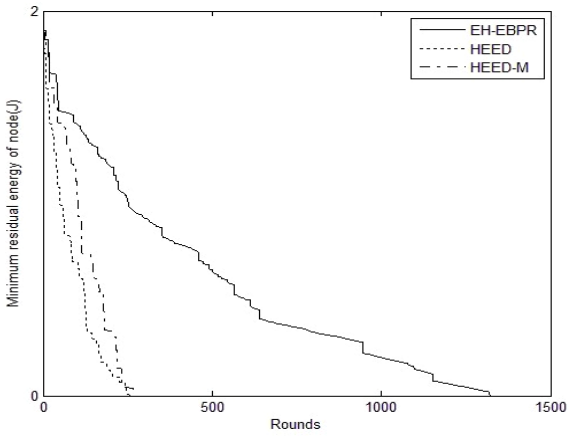

Fig. 4. The minimum residual energy of nodes in the network.

Consider the situation when the harvest rate of all nodes uniformly distributed between (0 mW, 0.1 mW). Node will go to sleep when its energy is below 1 % of $E_{\max}$ and then awake when its energy exceed $\lambda E_{\max}$. The lifetime of the node seems to be infinite. But if the average rate of energy harvesting in the network is lower than the rate of energy consumption, the number of survival nodes in the network will continue to decline until the energy harvested can afford the energy cost in the network. Fig. 5 shows the number of survival nodes in the network in different round.

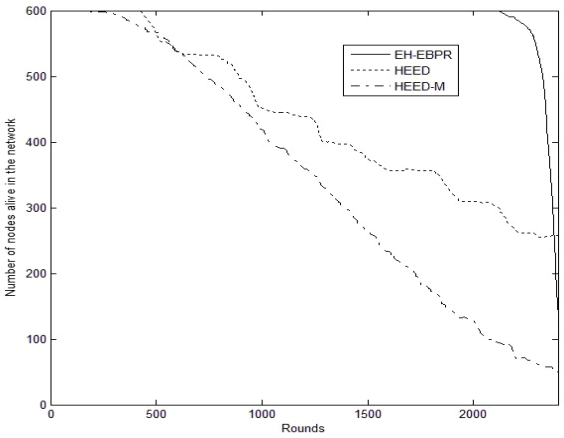

Fig. 5. Number of nodes alive in the network.

As we can see from Fig. 5, the number of nodes alive doesn't decrease until about 2200 rounds. And because of the character of energy balance in EH-EBPR, the residual energy of all nodes are almost not far-off, so nodes in the network will die rapidly after about 2200 rounds.

5. Conclusions and Future Work

In this paper, we have presented a clustering routing algorithm of probabilistic for energy-harvesting wireless sensor network. Nodes can transmit the data via single-hop or multi-hop with a certain probability. Simulation results show that the combination of single-hop and multi-hop can not only make good use of energy harvested but also balance the energy consumption of whole network. As the value of α , β , γ , λ have great impact on the performance of network, we will discuss how to set proper value of the parameters according to the average harvest rate in the future. With proper parameters, we believe that EH-EBPR routing algorithm can work well in EH-WSN of different harvest rate.

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