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Research of Energy-Balanced Clustering Routing Algorithm Based on Distance Vector in WSN

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Abstract: Due to the restricted communication range and high network density, events forwarding in Wireless sensor networks is very challenging, and require multi-hop data forwarding. Improving network lifetime and network reliability are the main factors to consider in the research. In this paper, we propose an Energy-balanced Clustering Routing Algorithm based on Distance Vector, called ECRD. The operation of ECRD is divided into rounds and each round contains three phases: cluster formation phase, cluster-based routing establishment phase and data transmission phase. By calculating the appropriate number of clusters in advance, cluster head's energy consumption is balanced. In cluster head competition stage, clusters are formed by virtual cells, and energy-control factor helps to select the suited cluster heads to avoid the nodes with low residual energy becoming cluster heads. Energy-Distance Function plays important roles in cluster formation phase and cluster-based routing establishment phase. Experiment results show our method can effectively reduce and balance energy consumption and prolong the lifetime of Wireless sensor networks. *Copyright © 2013 IFSA.*

Keywords: Wireless sensor network, Routing, Energy-balanced, Cluster, Lifetime, Distance, Energy-distance function.

1. Introduction

A wireless sensor network (WSN) consists of thousands of low-cost, low-power and battery-powered sensor nodes [1, 2]. In WSN, sensor nodes are deployed in a desired area to monitor environmental parameters or to detect some specific events (e.g., forest fire, battlefield surveillance, and target moving) and send the observed data to the base station through single-hop or multiple-hop wireless routing [3]. As sensor nodes have limited and non-rechargeable energy resources, energy is a very scarce resource and has to be managed carefully in order to extend the lifetime of the sensor networks. In harsh and inaccessible deployment circumstances, sensors are necessarily powered by energy-constrained, often non-rechargeable batteries [4]. With time elapsing, some nodes will run out of battery and let the WSN in a disconnected state. This makes the energy consumption become a critical factor in the design of a WSN and calls for energy-efficient communication protocols that maximize the lifetime of the network.

In recent years, researchers have done a lot of studies and proved that clustering is an effective scheme in increasing the scalability and lifetime of wireless sensor networks [5]. In WSN, the sensor nodes are divided into several groups, called cluster. Every cluster would have a leader, often referred to as the cluster head. The cluster head nodes manage the network in the cluster, perform data fusion and send the processed data to the base station through other cluster head nodes or sensor nodes [6]. Each sensor node only belongs to one and only one cluster and communicates with its cluster head. This reduces energy consumption significantly; conserves communication bandwidth and improves the overall scalability of the network [7]. However, improper assignment of the sensor nodes for the formation of clusters can make some cluster head nodes overloaded with high number of sensor nodes. Such overload may increase latency in communication and degrade the overall performance of the WSN. Therefore, load balancing is also a crucial issue that must be taken care while clustering sensor nodes.

The nodes near the base station are more likely to use up their energy because they have to forward all the traffic generated by the nodes farther away to the base station [8, 9]. The uneven energy consumption results in network partitioning and limit the network lifetime. To this end, we propose an Energy-balanced Clustering Routing Algorithm based on Distance Vector (ECRD). In ECRD, we calculate the appropriate number k_{opt} of clusters for the value of kopt will impact the cluster head's energy consumption when cluster heads aggregate data from member nodes and transmit data to base station. In cluster head competition phase, clusters are formed by virtual cells of WSN, and energy-control factor helps to select the suited cluster heads to avoid the nodes with low residual energy becoming cluster heads. In cluster formation stage, Energy-Distance Function plays an important role. Using the value of energy-distance, each member node joins corresponding clusters. Also, energy-distance function helps to construct the multiple-hop routing in inter-cluster routing establishment phase. Experiment has been done and simulation results show ECRD can effectively reduce and balance energy consumption and prolong the lifetime of WSN.

The paper is organized as follows: The related work is presented in Section 2. The system module is described in Section 3. Section 4 introduces our proposed algorithm in detail. Simulation results are given in Section 5 followed by the conclusion in Section 6.

2. Related Work

Many clustering algorithms and cluster-based routing protocols have been proposed for wireless sensor networks in recent years. The main goals of them are to efficiently maintain the energy consumption of sensor nodes, decrease the number of transmitted data to the base station, and prolong the lifetime of network. These protocols differ in many ways such as the basis on which the cluster head nodes are selected, the used method for cluster formation, the inter-cluster routing algorithm etc.

In Low-Energy Adaptive Clustering Hierarchy (LEACH) [10]: a predefined percentage of nodes are selected as cluster head nodes randomly and randomly rotated – with no probability of a cluster head to become again cluster head up to certain number of rounds. Each node selects the closest head as cluster head and sends data to it using TDMA schedule. LEACH may result in bad cluster head selection, bad cluster head nodes distribution, and instability in clusters number and size; this increases the load on cluster head nodes as well as on members, sometimes the distance between the cluster head and its member may be long, this leads to a long time for data to reach the cluster head which implies widening the time slot of the TDMA schedule, also sometimes the whole network formed in one cluster, this implies the lengthening of the TDMA schedule itself to be enough for all existing nodes minus one (the alone cluster head). This long TDMA schedule with its wide time slots increases the data latency.

HEED [11] extends LEACH by incorporating communication range limits and intra-cluster communication cost information. The initial probability for each node to become a tentative cluster head depends on its residual energy, and the final head is selected according to the cost. In HEED, the cluster heads are well-distributed over the sensor field. However, HEED does not consider the balanced energy consumption among cluster head nodes. Consequently, the cluster head nodes around the base station would deplete their energy faster, leading to what is known as an energy hole around the base station.

In Ref. [12], Kim etc. proposed a probability-driven unequal clustering mechanism for wireless sensor networks (PRODUCE). It organizes the network with unequal-sized clustering determined with localized probabilities and multi-hop routing based on stochastic geometry. Far clusters from the base station are made to have larger cluster sizes that allow focusing more on intra-cluster data processing rather than inter-cluster processing. It results in energy consumption balancing, increasing lifetime, and improving coverage.

In Ref. [13], a new clustering and data-gathering method, named clustering algorithm based on base station meshing (CABSM), is presented. In this algorithm, clusters are formed by virtual grids, which are carved up by base station through transmitting discrete signals in two perpendicular directions. The first Level Cluster Head is chosen by the residual energy, which collects and fuses the data in a cluster, and transmits the result to the second Level Cluster Head based on the inter-cluster data-gathering method. Finally data of the entire network is sent to the base station by the second Level Cluster Head. Although CABSM takes a simple method to select cluster head nodes considering node' s residual energy, but the distance between cluster head nodes and base station is an important factor to effect the efficiency of communication, that will lead to cluster head nodes located far way from base station die faster and arise energy holes adjacent the base station.

The energy-efficient multi-level clustering (EEMC) approach [14] is a centralized and top-down clustering scheme wherein the network topology is constructed from the base station. The base station first collects the location and energy information of all the sensors and then determines the cluster heads on the level next to it and the members of each cluster head. Each cluster head then collects the information of its members and determines the cluster heads on the level next to it again. This process is repeated until the number of levels equals the optimal expected value.

The distributed hierarchical agglomerative clustering (DHAC) approach [15] is a bottom-up network construction scheme wherein some nearby sensors are first grouped into a cluster and a sensor with the smallest identification number is elected as the cluster head. Then, the neighboring clusters are grouped into a larger cluster also with the smallest identification number as the cluster head. This process is repeated until the cluster size reaches a given threshold.

3. System Module

3.1. Energy Module

Single sensor node energy dissipation can be divided into two parts: receiving and sending. According to wireless transmission theory, the energy consumption for a transmitter to send and receive an L-bit message over a distance d, energy expanded by the radio is given by:

$$E_{Tx}(L,d)=\begin{cases} L*E_{elec}+L*\varepsilon_{fs}*d^2 & if \quad d\le d_0 \\ L*E_{elec}+L*\varepsilon_{mp}*d^4 & if \quad d\ge d_0 \end{cases}, \quad (1)$$

where E_{elec} is the energy dissipated per bit to run the transmitter or the receiver circuit. ε_{fs} and ε_{mp} depend on the transmitter amplifier model, and d is the distance between the sender and the receiver. By equating the two expressions at d=d_0. To receive an L-bit message the radio expends E_{Rx}=L×E_{elec}.

3.2. Network Module

We make some assumptions about the sensor nodes and the network model, which are as:

- There are n nodes uniformly dispersed within a square field;
- Base station can move before cluster head nodes competition, and be stationary when cluster formation phase begins;
- All nodes are stationary after deployment;
- All nodes are location-aware;
- All nodes have the same initial energy;
- All sensor nodes are of equal significance;
- Data in adjacent monitoring area are interrelated and can be aggregated;
- Cluster head nodes play the central role of data aggregation;
- Base station locates outside the detection area and is not energy limited in comparison to energy of other nodes in the network;
- All nodes have enough energy to complete the data transmission and routing formation.

4. ECRD Algorithm

The operation of ECRD is divided into rounds and each round contains three phases: cluster formation phase, cluster-based routing establishment phase and data transmission phase. Fig. 1 shows the flow chart of ECRD algorithm.

In cluster formation phase, the procedures of calculate appropriate number of cluster, cluster head nodes competition and cluster formation are introduced in detail. With the help of Energy-Distance Function, we establish the cluster-based routing algorithm in single-hop and multiple-hop. The data transmission phase includes inter-cluster data transmission and intra-cluster data transmission.

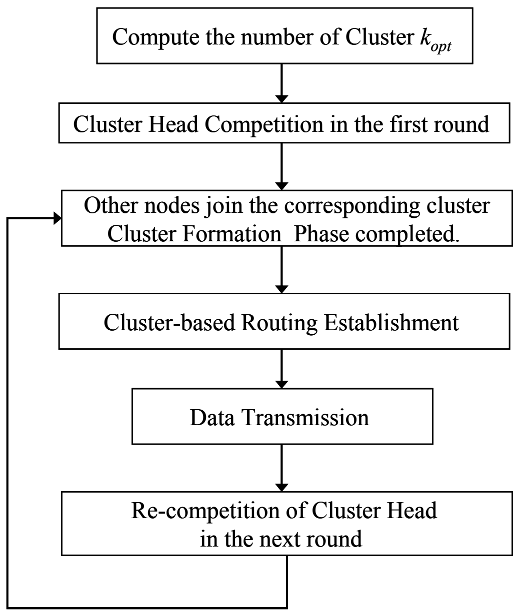

Fig. 1. Flow char of ECRD algorithm.

4.1. Cluster Formation Phase

There are a large number of nodes distributed in WSN. For clustering, if the number of clusters is large, then the amount of cluster head nodes will be more, and the communication between cluster head nodes will be more complex and lead to some cluster head nodes runs out of their energy and make the network die in advance [16]. But if the number of cluster is small, then there are more non-cluster head nodes in one cluster. That will make the cluster head node assume more responsibility of inter-cluster communication and data aggregation. That also will lead to energy load imbalance and impact on the network lifetime. So, appropriate number of cluster will balance energy consumption and prolong network lifetime.

1) Calculate the appropriate number of cluster

We assume an area $S=M*M$ m^2 over which n nodes are uniformly distributed. The distance between any node and base station is$\leq d_0$. Thus, the energy dissipated by the cluster head nodes during one round is given by the following formula [17]:

$$E_{ch}=(\frac{n}{k}-1)\times L\times E_{elec}+\frac{n}{k}\times L\times E_{DA}+L\times E_{elec}+L\times\varepsilon_{fs}\times d_{BS}^2 \tag{2}$$

where k is the number of clusters, E_{DA} is the processing cost of a bit report to the BS, and d_{BS} is the average distance between a cluster head node and base station. The energy used in a non-cluster-head node is equal to:

$$E_{nonch}=L\times E_{elec}+L\times\varepsilon_{fs}\times d_{CH}^2, \tag{3}$$

where d_{CH} is the average distance between cluster member and its cluster head node.

The total energy dissipated in the network per round is given by:

$$E_t=L\times(2\times n\times E_{elec}+n\times E_{DA}+\varepsilon_{fs}\times(k\times d_{BS}^2+n\times d_{CH}^2)) \tag{4}$$

Then, the optimal number of clusters can be computed by (5).

$$k_{opt}=\sqrt{\frac{n}{2\pi}}\sqrt{\frac{\varepsilon_{fs}}{\varepsilon_{mp}}}\frac{M}{d_{BS}^2} \tag{5}$$

2) Cluster head nodes competition in first round

Because all the nodes in WSN have equal initial energy before working, we initially divide the network into a series of clusters by geographic location [13].

Before cluster head nodes competition, base station broadcast with different radius in two direction perpendicular to each other, and divides the network into multiple virtual cells with the shape of similar to square. The area of virtual cell is approximately equal and each cell is defined as a cluster.

Firstly, base station broadcasts with radius r outside the network. Radius r can be compute as follows:

$$r=\frac{M}{\sqrt{k_{opt}}}+d_{toBS}, \tag{6}$$

where M is the side length of network, and d_{toBS} is the vertical distance form base station to network boundary.

Those nodes located in the area of broadcast-radius r will receive the broadcast signal and define themselves as layer 1 in this direction. After that, nodes in layer 1 will close their communication section and fall into sleep. Base station increases the transmission radius r and broadcast. The new radius can be calculated as:

$$r=\frac{2M}{\sqrt{k_{opt}}}+d_{toBS} \tag{7}$$

All the nodes received the second broadcast will be defined into layer 2. In this way, base station broadcast $\sqrt{k_{opt}}$ times, and all nodes will be defined into corresponding layers. Fig. 2 shows the results of partition.

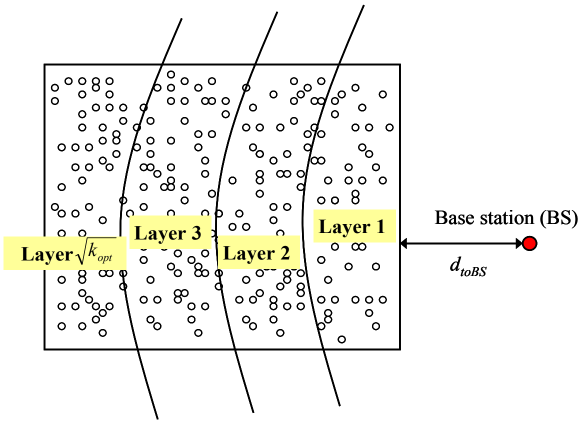

Fig. 2. Partition result of network (in the right direction).

In the same way, base station moves to another direction of network and repeats the broadcast to partition the nodes into corresponding layers. As shown in Fig. 3.

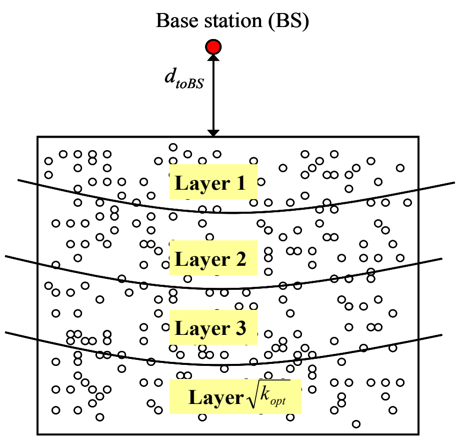

Fig. 3. Partition result of network (in the top direction).

After two partitions of base station in different direction, each node is divided into corresponding cell, which is defined as a cluster. Fig. 4 shows the results of cluster partition.

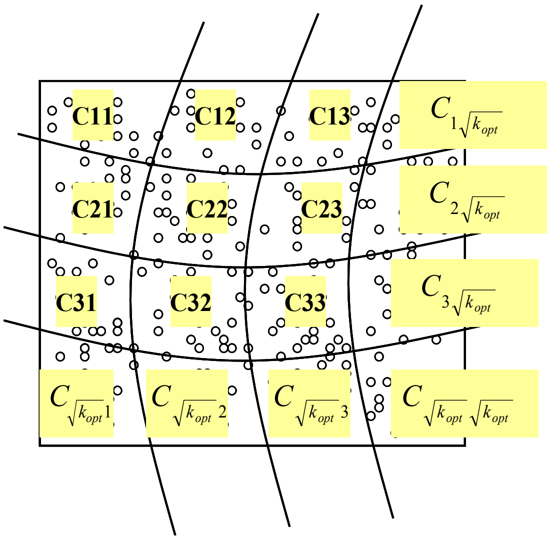

Fig. 4. Partition results of cluster.

After partition, each node computes their approximate coordinate according to the two broadcast message. Broadcast message includes {broadcast radius r, distance from base station to network, etc.}.

Nodes in each cluster compete for the cluster head node follows the same scheme in LEACH protocol.

3) Cluster formation

In this phase, cluster head node sends a broadcast message, which includes it's ID, residual energy, location etc. That is $\{ID_{CH}, E_{CH\_residual}, (x_{CH}, y_{CH}),$ etc.$\}$. When non-cluster-head nodes receive the message, they calculate the value of Energy-Distance function.

$$f(CH_i, j) = \frac{d(CH_i, j)}{E_{CH_i\_residual}} \tag{8}$$

In formula (8), $d(CH_i, j)$ is the distance between non-cluster-head node j and cluster head node CH_i, $E_{CHi\_residual}$ is the residual energy of CH_i. Each non-cluster-head nodes, especially nodes located in the boundary of cluster, will receive several broadcast message. Node j select the cluster i with a minimum value of $f(CH_i, j)$ to join it. Because the value of $f(CH_i, j)$ is less, the distance between CH_i and node j is closer, and the residual energy of CH_i is larger. Node j joins to cluster i will reduce the inter-cluster energy consumption and prolong the lifetime of network.

Node j sends back a message to CH_i, which include $\{ID_j, E_{j\_RES}\}$.

$$E_{j\_RES} = E_{j\_residual} - E_{send} - E_{trans} \tag{9}$$

E_{send} is the energy consumption of send back this message to CH_i, and E_{trans} is the energy consumption of transmit aggregation data to CH_i in data transmission phase. The value of E_{j_RES} represents the residual energy of node j when accomplishing a whole round, this will help to select cluster head node in next round.

When receiving all the back-message, cluster head nodes identify all their member nodes and cluster formation completed.

4) Cluster head nodes competition in next round

Cluster head competition scheme in LEACH protocol randomly select the cluster head nodes, this will lead to fractional nodes consume energy too fast and cause network system expire in advance. In the following rounds, we choose residual energy of node as an energy-control factor to balance the energy consumption in WSN. In our approach, the ratio of residual energy and initial energy will affect the value of threshold $T(n)$, Node with high residual energy will have more probabilities to be selected as a cluster head. Threshold $T(n)$ is calculated as follows:

$$T(n) = \frac{p}{1 - p(r \times \bmod \frac{1}{p})} \times [r_m p + (1 - r_m p)\frac{E_{i\_residual}}{E_{i\_init}}] \tag{10}$$

E_{i_init} is the initial energy of node i, r_m represent the number of node i can't be selected as cluster head. When node i is selected as cluster head, set $r_m = 0$; otherwise, set $r_m{+}{+}$.

Energy-control factor in cluster head competition will decrease the randomness of the nodes to be selected as cluster head, hence nodes with more residual energy have more chance to be selected than nodes with low residual energy. So our approach uses the residual energy as much as possible, effectively prevents nodes' energy expire too fast, and balances energy consumption in the whole network.

4.2. Cluster-based Routing Establishment Phase

Because in LEACH protocol cluster head nodes communicate with base station in single-hop manner, it is energy consuming and its expandability is limited so that it could not adapt to large network. But in multiple-hop communication, cluster head nodes near the base station will become the "hot node" in WSN for it will forward a large number of data, thus this will results in these cluster head nodes failure in advance, and shorten the lifetime of network. In order to solve the unbalanced energy consumption between cluster head nodes with different distance, we use a mixed scheme with single-hop and multiple-hop routing solution.

For each cluster head node *i*, calculate it's Energy-Distance value as follows:

$$f(CH_i, BS) = \frac{d(CH_i, BS)}{E_{CH_i\_residual}} \quad (11)$$

$d(CH_i, BS)$ is the distance between base station and cluster head node CH_i. The cluster head nodes with more residual energy and less distance to base station will calculate a smaller value of Energy-Distance. So we choose *num* cluster head nodes to be the single-hop communication node with base station. Where *num* is the number of single-hop communication node and $num \le \sqrt{k_{opt}}$.

As for the other nodes, they communicate with base station in multiple-hop routing. Before that, every cluster head nodes broadcast their ID, location to each other. Multiple-hop cluster head nodes establish their candidate relay node set by calculate the value of Energy-Distance. The candidate relay set $Cand\_CH_i$ of cluster head node *i* is defined as follows:

$$Cand\_CH_i = \{CH_k \mid f(CH_k, BS) + \frac{d(CH_i, CH_k)}{E_{CH_i\_residual}} < f(CH_i, BS)\} \quad (12)$$

As is shown in Fig. 5, $f(CH_i, BS)$ is the Energy-Distance value transmitted date from CH_i to base station in single-hop routing. $\frac{d(CH_i, CH_k)}{E_{CH_i\_residual}}$ is the Energy-Distance value from CH_i to CH_k. $f(CH_{ki}, BS)$ is the Energy-Distance value from CH_{ki} to base station.

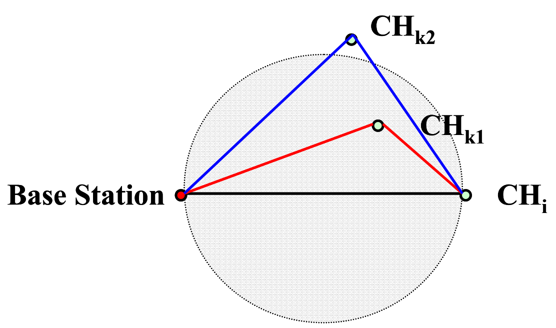

Fig. 5. Selection of relay nodes.

Fig. 5 shows that if cluster head node CH_i transmits data to base station directly will take more Energy-Distance value than indirectly communication through node CH_k, then cluster head node CH_k is added into the candidate relay nodes set. That means, when communicating with base station in multiple-hop routing through the nodes in candidate relay set, cluster head node CH_i will save more energy, thus can balance the energy load in the whole network and prolong the lifetime of network.

When transmitting data from cluster head node to base station, each CH_i chooses a relay node with minimum value of Energy-Distance consumption in candidate relay set, and constructs the multiple-hop communication routing.

4.3. Data Transmission Phase

The data transmission phase includes inter-cluster data transmission and intra-cluster data transmission.

Once the clusters are formed and the TDMA schedule is fixed, the data transmission phase can begin. The active nodes periodically collect the data and transmit it during their allocated transmission time to their cluster head node. The radio of each non-cluster-head node or member node can be turned off until the node's allocated transmission time which minimizes the energy consumption in these nodes. The cluster head node must keep its receiver on to receive all the data from the member nodes in the cluster. When all the data has been received, the cluster head nodes aggregate the data and route the same data via multiple-hop or single-hop communication approach to the base station.

In this phase, the *num* cluster head nodes with lower value of Energy-Distance transmit data to base station directly. Other cluster nodes choose the appropriate node as relay in their candidate relay set and communicate with base station through relay node in multiple-hop routing.

5. Simulation Results

In the simulation test, we compare some indicators such as the network lifetime, the number of nodes alive and the network energy consumption in protocol of LEACH and ECRD. The parameters used in the simulation are listed in Table 1.

Table 1. Parameter list of this simulation test.

Parameters	Value
Network field	(0,0)~(200,200)
Number of nodes	400
Base station position	(100, 230)
Initial energy	3 J
E_{elec}	50nJ/bit
E_{DA}	5 nJ/bit/signal
Length of data message	4000 bits

The simulation has been done by NS2 software. Fig. 6 and Fig. 7 show the comparison of network lifetime and network overload with protocol of LEACH and ECRD.

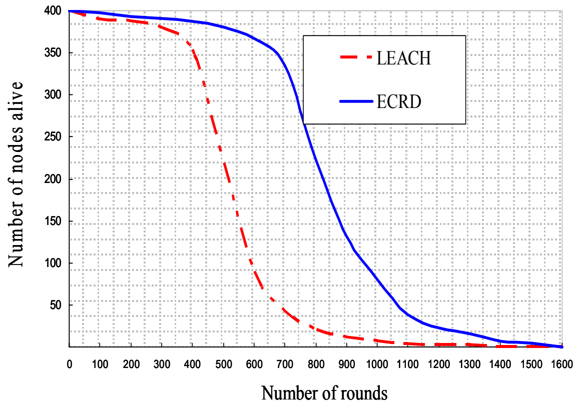

Fig. 6. Comparison of Network Lifetime.

The results of Fig. 6 show that in 800 rounds, 44.5 % nodes run out of their energy, and in 1100 rounds, 90 % nodes exhaust their energy in ECRD. In contrast, in 500 rounds, 45.25 % nodes consume all their energy, and in 700 rounds, 89 % nodes die in LEACH.

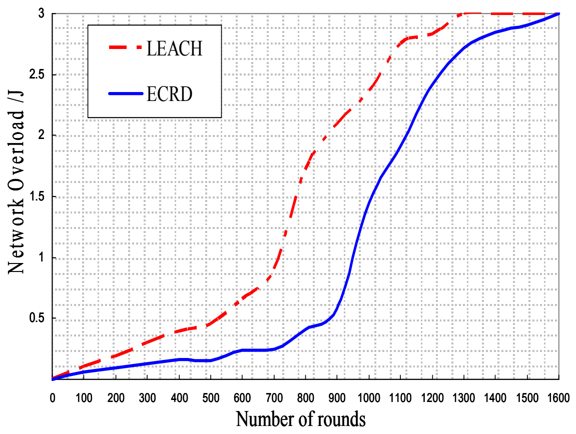

Fig. 7. Comparison of Network Overload.

Results in Fig. 7 show that energy consumption of ECRD is less than that of LEACH protocol. In ECRD, the whole network consumes about 48.3 % energy in 1000 rounds. While about 57.3 % energy exhausts in 800 rounds in LEACH. When the simulation test runs in 1300 rounds, LEACH runs out of it's energy, but ECRD still has about 10 % energy left to support network communications.

According to the definitions given in [18], the lifetime of a WSN can be quantified using the following three kinds of metrics: (1) time from the deployment of the network to the death of the first node (First Node Dies, FND); (2) time when a certain percent of nodes alive (Percentage Nodes Alive, PNA); (3) time when all the nodes are dead in the network (Last Node Dies, LND). Here, we define the network lifetime as Half Node Alive (HNA) and Last Node Dies (LND).

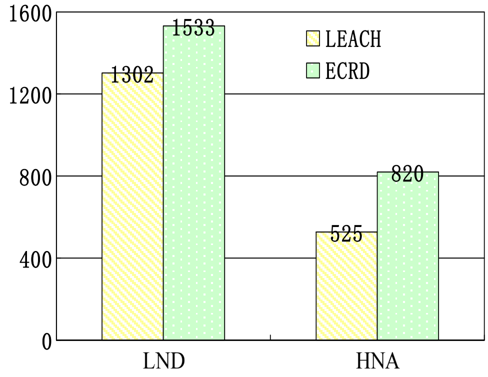

Fig. 8. Comparison of Number of Node Alive.

Fig. 8 shows that, for the parameter of LND, ECRD prolongs about 15 % network lifetime compared with LEACH protocol; for parameter HNA, there are about 56 % more nodes alive in ECRD than LEACH. The simulation results show that ECRD, compared with LEACH, is more efficient to reduce and balance energy consumption and hence prolong the network lifetime.

6. Conclusion

Power-aware routing in wireless sensor networks focuses on the crucial problem of extending the network lifetime of WSN, which are limited by low-capacity batteries. Aiming at the problem of limited energy of sensors in WSN, based on the classic clustering routing algorithm LEACH, an Energy-balanced Clustering Routing Algorithm, called ECRD, considering both the distance and residual energy of nodes is presented in this paper. Firstly, we calculate the appropriate number k_{opt} of clusters, because the value of k_{opt} will impact the cluster head's energy consumption when cluster heads aggregate data from member nodes and transmit data to base station. In cluster head competition phase, clusters are formed by virtual cells of WSN, and energy-control factor helps to select the suited cluster heads to avoid the nodes with low residual energy becoming cluster heads. In cluster formation stage, Energy-Distance Function plays an important role. Using the value of energy-distance, each member node joins corresponding clusters. Also, energy-distance function helps to construct the multiple-hop routing in inter-cluster routing establishment phase. Experiment has been done and simulation results show our method can effectively reduce and balance energy consumption and prolong the lifetime of WSN.

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