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Energy Balanced Non-Uniform Distribution Node Scheduling Algorithm for Wireless Sensor Networks

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Abstract: Node sleep scheduling is one of the most important methods to improve energy-constrained wireless sensor networks. Most existing approaches to solve this problem require sensors' location information, which may be impractical considering high positioning costs. In this paper, an energy balanced non-uniform distribution node scheduling algorithm (EBNDNS) is proposed and evaluated. This method needs distance between sensors instead of location information. A simple non-uniform distribution strategy is also proposed. Combined with this strategy, simulation results show that EBNDNS can relieve the "energy-hole" problem for the multi-hop communication and significantly prolong the lifetime of networks.

Keywords: wireless sensor networks, node scheduling, location-unaware, non-uniform distribution

1 Introduction

Wireless sensor networks consist of a large number of tiny sensors to observe and influence the physical world. Each sensor is usually powered by battery and expected to work for several months without recharging. Therefore one of the important issues is to achieve higher energy efficiency and increase the lifetime of network as well as sufficient sensing area. A broadly used method is to turn off redundant sensors by scheduling sensor nodes to work alternatively. But selecting the optimal sensing ranges for all the sensors is a well-known NP-hard problem [1]. Existing algorithms[2,3,4] to determine redundant nodes mostly require exact location of nodes with the help of Global Positioning System (*GPS*) or the directional antenna technology. However, the energy costs and system complexity involved in obtaining geography information may offset the effectiveness of the proposed solutions as a whole since GPS and other complicated-hardware devices consume too much energy and the costs are too high for tiny sensors. Furthermore, it is sometimes not suitable for the application settings to be equipped with GPS, such as underground, etc. Nodes sleep scheduling algorithm without location information is more valuable in practice.

Although schemes which require no accurate geography information may generate blind points that cannot be monitored by any sensor. Fortunately, most applications may not require completed coverage of the monitored area [5].Several researchers have proposed node scheduling schemes without location information. Kui Wu et al. proposed a lightweight deployment-aware scheduling (*LDAS*) scheme to turn off some redundant sensors [5]. But LDAS only considers one-hop neighbours of sensors which may lead to larger redundant coverage. Younis proposed two distributed protocols (*LUC-I and LUC-P*) relying on distance and two-hop neighbours' information [6].Li-Hsing Yen proposed a range-based approach that attempts to approach an optimal sensor selection pattern [7].Each foreman node needs cooperation of six co-workers without knowing their exact locations. But the methods above are all achieved under the ideal model that nodes are distributed uniformly.

While networks with uniform nodes distribution, both single-hop and multi-hop transmission will lead to unbalanced energy consumption. Simulation experiments [8] show that as much as 90% of the total energy will be wasted in uniform nodes distribution. For large-scale wireless sensor networks, multi-hop communication is often adopted. Sensors closer to the Sink node tend to

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exhaust their energy faster than other sensors because of transmitting more data, as known as “energy hole” around the Sink. When energy hole appears, no data can be delivered to the Sink and the network premature dies, while a large number of nodes are still alive. Ideally, energy of each node deployed in the region should give out at the same time and the residual energy of the entire network is almost zero when the network dies.

To solve this problem, researchers proposed different solutions. A non-uniform energy distribution model is proposed in [9].Sensors closer to the Sink are equipped with more initial energy. But this method is difficult to implement in practice. A non-uniform node distribution strategy is proposed in [10]. The authors prove that suboptimal energy efficiency of the networks is possible if the number of nodes in the network is increasing in a geometric progression from the outer to the inner ring. But this strategy requires very precise distribution technology and this distribution strategy is possible only when sensor nodes can be mass production with a low cost. A distributed energy-balanced unequal clustering routing protocol (*DEBUC*)is proposed in [12]. DEBUC partitions all nodes into clusters of unequal sizes, in which clusters closer to the Sink have smaller sizes to balance energy consumption. But the optimal cluster size is not discussed.

Aiming at the problem that energy holes are easy to form around the Sink in multi-hop communication networks, this paper proposes a simple non-uniform distribution strategy and an energy-balanced non-uniform distribution node scheduling algorithm called EBNDNS is also discussed. This algorithm needs sensor-to-sensor distance but no location information. Simulation results show that EBNDNS performs nearly as well as location-based scheme can do in terms of the quality of coverage and the number of active sensors. In the meantime, it can also make the network energy consumption more balanced, and prolong the lifetime of the network.

The rest of this paper is organized as follows. Section 2 introduces preliminary definitions and the system model. Section 3 details the non-uniform distribution strategy and EBNDNS. Simulation results are presented in section 4. Finally, section 5 gives a conclusion.

2 Preliminaries

2.1 System model

In this paper, we focus on large-scale, dense networks with several hundreds to thousands of sensors. Our analysis is based on the following assumptions:

(1) Nodes are randomly and redundantly deployed. Sensors and the Sink are all stationary after deployment.

(2) All sensors are homogeneous and have the same capabilities and initial energy. The energy of the Sink is not limited.

(3) Each node is assigned with a unique identifier (ID) and the sensors’ sensing range is a circle area.

(4) Sensors do not possess GPS but can compute approximate distance from another node according to strength of received signal.

(5) R $\geq$ 2r, we consider R is the radius of the transmission rage and r is the radius of the sensing range. Under this condition, coverage implies connectivity [3].

Definition 1 (Neighbor nodes). The neighbor set of sensor i is defined as $\mathrm{N}(i)=\{j \in \aleph \mid \mathrm{d}(i,j) \leqslant 2\mathrm{r},\ i \in \aleph,\ j \neq i\}$. Where $\aleph$ represents the sensor set in the deployment region. $\mathrm{d}(i,j)$ denotes the distance between the sensor i and j.

Definition 2(1-hop neighbors [5]). $\mathrm{N}_1(i)=\{j \in \mathrm{N}(i) \mid \mathrm{d}(i,j) \leq \mathrm{r},\ i \in \aleph\}$.

Definition 3 Quality of service (*QoS*): the percentage of the region that can be covered with regard to the total monitored area. The objective of sleep scheduling scheme is to turn as many as possible redundant sensors into sleep for energy-saving without degrading *QoS*.

2.2 Energy consumption model

In our simulation, we use the same energy parameters and radio model as discussed in [13]. The energy spent for a *l-bit* packet to transmit over distance *d* is:

$$E_T = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2 & d < d_0 \\ lE_{elec} + l\varepsilon_{amp}d^4 & d \geq d_0 \end{cases} \tag{1}$$

The reception energy consumption is:

$$E_R = lE_{elec} \tag{2}$$

Where E_{elec} is the energy consumed for the radio electronics, ε_{fs} and ε_{amp} for a power amplifier. d_0 is the threshold distance to determine the free space (d^2 power loss) or the multi-path fading (d^4 power loss) channel models to be used. Since there is a huge difference between data of different clusters, we only consider the energy consumption of fusing data within cluster members regardless of data fusing between different clusters. We assume that each member node transmits k bits data to its cluster head, and the cluster head can always aggregate the data gathered from its members into k bits packet. The energy consumed for performing data aggregation (ED) is 5nJ/bit.

3 Node sleep scheduling design

3.1 Non-uniform distribution strategy

In multi-hop communications, each cluster head spends its energy on both intra-cluster and inter-cluster processing. The reason why energy hole forms mainly

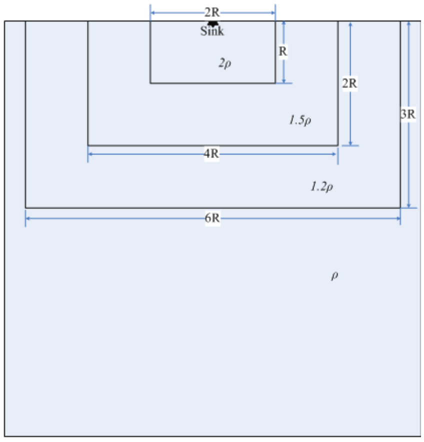


Fig. 1: Non-uniform distribution of nodes

around the Sink is that heads closer to the Sink act as routers of the heads farther away from the Sink in delivering data to the Sink. The heads closer to the Sink consume much more energy because they have a higher load of relay traffic. They will die much earlier than other heads, forming an energy hole. If more nodes are deployed around the Sink, there will be more nodes to relay data from father. So the problem of energy hole in wireless sensor networks will be mitigated. But if nodes are deployed densely, scalability, redundancy, and radio channel contention will occur. It will not only fail to solve the problem of energy hole effectively but also waste more energy. Therefore, the non-uniform nodes distribution strategy must be combined with an effective sleep scheduling scheme to improve energy efficiency and prolong the lifetime of the network.

As shown in Fig. 1, a non-uniform distribution strategy is proposed. We assume that the monitored region is a square area, and the Sink is placed at the center of one boundary. ρ is the density of nodes. Different region has different densities of nodes. R is the radius of transmission rage.

3.2 Coverage redundancy determine

Suppose there are n sensors deployed in a monitored region. S_i is the circle sensing areas covered by node i, i=1,2,3,...n. Node j is the neighbour sensor of node i, $j \in N(i)$, and $N(i) = \{j \in \{1,2,\cdots m\}, m < n\}$. d_{ij} is the distance between node i and node j. Referring to [2], it is not difficult to calculate the sensing area that covered by sensor i and sensor j, defined as $S_{i\cap j}$.

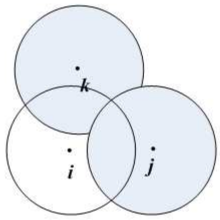


Fig. 2: Nodes intersection

$$S_{i\cap j} = \begin{cases} 2r^2 \arccos\frac{d_{ij}}{2r} - d_{ij} r \sqrt{1 - \frac{{d_{ij}}^2}{4r^2}} & d_{ij} \le 2r \\ 0 & otherwise \end{cases} \quad (3)$$

The redundant coverage ratio θ of node i covered by m neighbours can be expressed as:

$$\theta = \frac{\bigcup\limits_{j\in N(i)} S_{i\cap j}}{S_i} \quad (4)$$

Supposed $S_{uncoveredm}$ is the area of S_i that not covered by m neighbours, then

$$\theta = 1 - \frac{S_{uncoveredm}}{S_i} \quad (5)$$

If node j is the neighbour of node i, then according to the probability distribution function, the probability of the two nodes to be intersected can be calculated as:

$$P = \frac{S_{i\cap j}}{\pi r^2} \quad (6)$$

As shown in Fig. 2, if node i has one neighbour node j, then we can get $S_{uncovered1} = S_i$-$S_{i\cap j}$. If there is another node k, $k \in N(i)$, and $k \neq j$, then the mathematical expectation of the intersection area of node k and node i that falls just in $S_{uncovered1}$ is

$$\begin{aligned} E[S] &= \iint\limits_{S_{uncovered1}} P dS = \iint\limits_{S_{uncovered1}} \frac{S_{i\cap k}}{\pi r^2} dxdy \\ &= \frac{S_{i\cap k} \times S_{uncovered1}}{S_i} \end{aligned} \quad (7)$$

The redundant coverage area of node i caused by node j and node k is

$$S_{i\cap j} \cup S_{i\cap k} = S_{i\cap j} + \frac{S_{i\cap k} \times S_{uncovered1}}{S_i} \quad (8)$$

The area that is not covered by the two neighbour nodes of S_i can be expressed as:

$$\begin{aligned} S_{uncovered2} &= S_i - S_{i\cap j} \cup S_{i\cap k} \\ &= (1 - \frac{S_{i\cap k}}{S_i}) S_{uncoverd1} \end{aligned} \quad (9)$$

So we can deduce from formula(7) and (9), get the area of S_i that is not covered by m neighbours is as follows:

$$S_{uncoveredm} = (1 - \frac{S_{i \cap m}}{S_i}) S_{uncoverd(m-1)} \quad (10)$$

According to formula(5), the θ of node i that is covered by all the neighbours can be calculated. When θ meets the given QoS, node i can be turned off.

3.3 EBNDNS

Initially, we assume that all nodes are active. The detailed steps are below:

Step 1:Network initialization. Firstly, the Sink broadcasts the ADV message including the QoS value and other information through flooding. Each sensor exchanges *Hello*-message with its neighbours to estimate the distance between itself and each of its neighbours.

Step 2:Node scheduling. Each node has three states: active, ready-to-off, and sleep. Each round begins with a competition phase, in which every node determines whether it is active or sleep according to the given QoS value and its θ value. Before a node falls asleep, it will enter a ready-to-off state within a short time T_W to avoid blind points when several neighbour sensors turn off at the same time. Within T_W, if the node at the ready-to-off state receives another sensor's *sleep*-message, the node returns to the active state. Otherwise, it will broadcast *sleep*-message after waiting for T_W time and then goes to sleep, falling asleep for a period of time T_s. In order to balance the energy consumption, the value of T_W is related to the residual energy of the node to ensure that the node which has less energy sleeps first.

$$T_{Wi} = k \times WT \times \frac{RE_i}{IE} \quad (11)$$

Where k is a random number uniformly distributed at the interval (0.9, 1) for reducing the probability of several sensors broadcasting messages at the same time. WT represents a predefined time to wait. RE_i is the residual energy of sensor i. IE is the initial energy.

Step 3: Clustering. Active nodes randomly select nodes as cluster heads based on LEACH algorithm. Then the cluster heads broadcast *Hello*-messages and other active nodes select the closet head to join in.

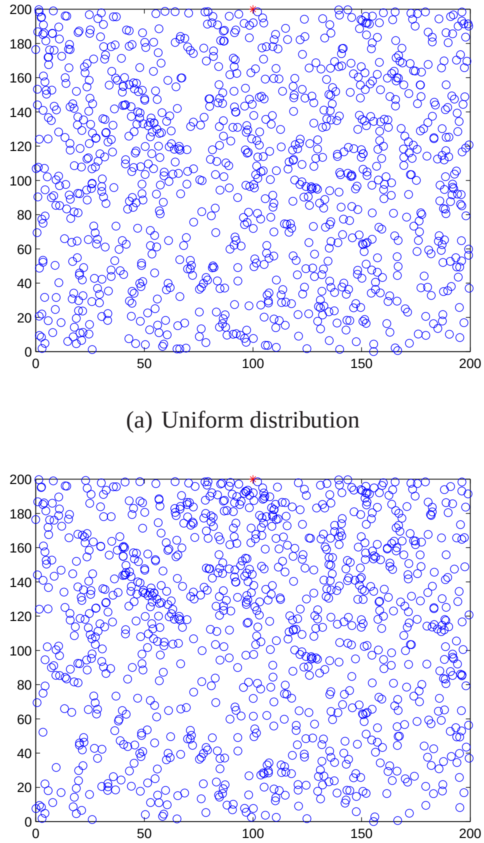
Step 4: Routing. The cluster heads establish multi-hop route using minimum spanning tree algorithm (Prime).

Step 5: Sensing.

Step 6: This current round ends. Return to Step 2.

4 Simulation results and analysis

We conduct simulations with Matlab simulator to compare the two sleep scheduling: LDAS and EBNDNS.



(a) Uniform distribution

(b) Non-uniform distribution

Fig. 3: nodes distribution

The simulation parameters are given in Table I. For comparison, we adopt two strategies to deploy nodes. In Fig. 3(a), 1000 nodes are deployed uniformly in a 200m×200m square randomly, and Fig. 3(b) shows that 1000 nodes are deployed non-uniformly using the method described in 3.1. All the simulation results in our paper are based on the two cases. The sensing radius is 15m. The Sink node is located on (100,200). We assume that the Sink node has the same transmission radius with other nodes.

TableI Simulation Parameters

Parameter	Value
Initial energy	0.5J
Threshold distanc(do)	87m
E_{elec}	50(nJ/bit)
ε_{fs}	10pJ/bit/m^2
ε_{amp}	0.0013pJ/bit/m^2
Data packet size	4000bits
Control packet size	100bits

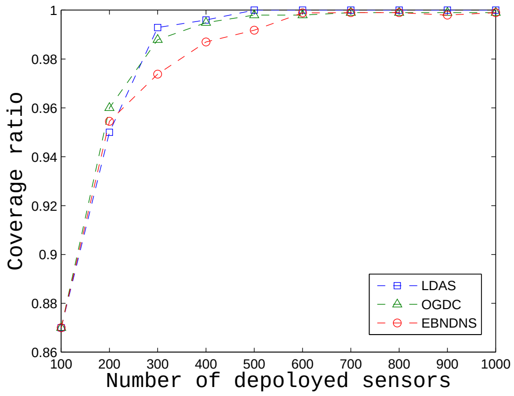


Fig. 4: Coverage ratios in 200×200m^2 networks

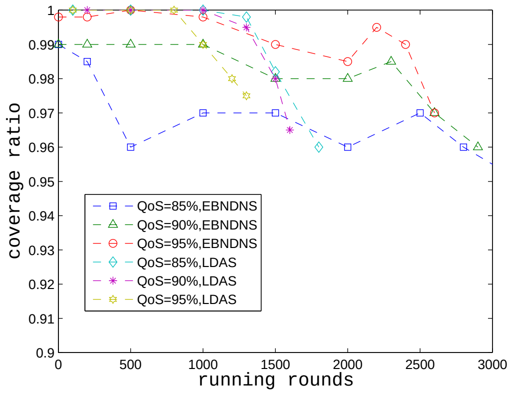


Fig. 6: Comparison of coverage ratio under Fig.3(a)

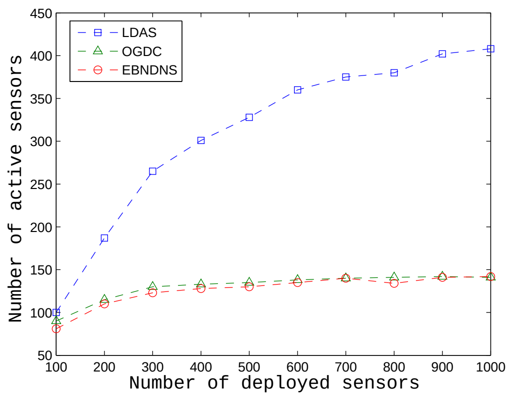


Fig. 5: Number of active sensors in 200×200m^2 networks

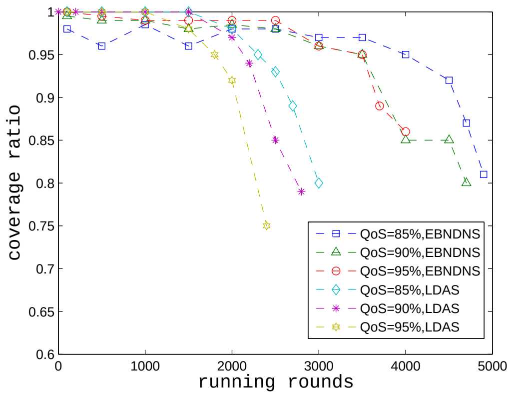


Fig. 7: Comparison of coverage ratio under Fig.3 (b)

4.1 Coverage effectiveness

We first measure the coverage ratio and the number of active nodes. We assume that all sensors are deployed uniformly and randomly in the monitored region. *QoS* is set at 90%. Fig. 4 and Fig. 5 show the compared results. All values are average numbers collected from over ten experiments.

As we can see from Fig. 4 and Fig. 5, LDAS needs more active nodes to ensure higher coverage ratio. Under the same conditions, OGDC [3], using exact location information of each node, tries to construct the optimal coverage set. It can get higher coverage ratio with fewer active nodes. When the density is not enough (the number of nodes $<$200) or too high (the number of nodes $>$600) in the monitored region, EBNDNS can get nearly the same coverage ratio as OGDS. When the number of nodes is between 200 and 600, EBNDNS has a lower coverage ratio than others. But even it is lower, the coverage ratio is still more than 95%, meeting the given *QoS* requirement. Fig. 5 shows that the number of active nodes using EBNDNS is even smaller than OGDC. The smaller number of active nodes, the less energy is consumed.

Fig. 6 shows the compared results of coverage ratio between LDAS and EBNDNS under Fig. 3(a) situation. Fig. 7 shows the compared results of coverage ratio between the two algorithms under Fig. 3(b). As can be seen in the two figures, LDAS algorithm can get higher coverage ratio than EBNDNS in early operation but it requires more active nodes to maintain the high coverage ratio. So as more nodes die, the coverage ratio of LDAS decreases quickly after 1000 rounds. However the coverage ratio of EBNDNS maintains stable and only after 3000 rounds, the coverage ratio decreases slowly.

4.2 Network lifetime

Network lifetime has different definitions based on the desired functionality [14]. Commonly, it is defined as the time the network can last till the first node dies (called as **LT-1** in this paper). In this paper network lifetime is

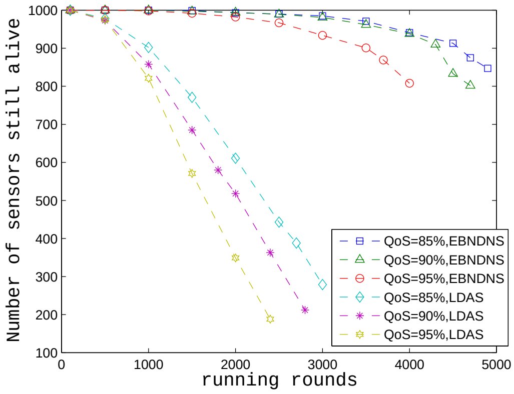


Fig. 8: comparison of the number of sensors still alive under Fig.3(b)

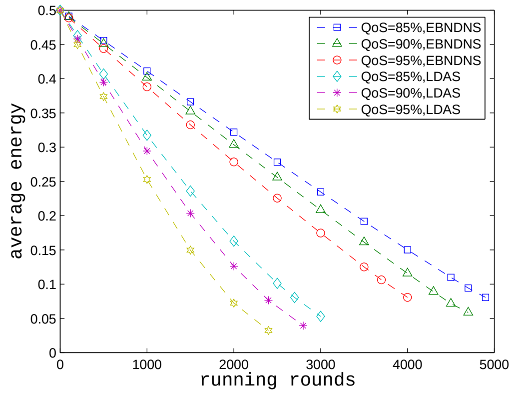


Fig. 9: comparison of average energy under Fig3(b)

Table II Network lifetime comparison

Algorithm	LT-1(Fig3(a))	LT-2(Fig3(a))	LT-1(Fig3(b))	LT-2(Fig3(b))
LDAS	183	1600	171	2800
EBNDNS	992	2800	1243	4700

defined as the time-the period of time the network can work till the Sink cannot receive any data from sensors, namely till there are no cluster heads can transmit data to the Sink in its transmission range (called as **LT-2**).

Fig. 8 shows the number of sensors still alive with the running rounds using the two scheduling algorithms under Fig.3(b). It can be seen that EBNDNS can significantly improve the lifetime of the network including **LT-1** and **LT-2**.

Take *QoS*=90% for example, the comparison data are showed in TableII. It can be seen that EBNDNS can significantly improve the lifetime of the network both in uniform and non-uniform distributions. Obviously, it can better relieve the “hot spot” problem and prolong the lifetime of network combined with non-uniform distribution strategy. However LDAS is based on uniform distribution. The dense area and the spare area appearing in non-uniform distribution are not considered, so the **LT-1** of Fig.3(b) is less than the **LT-1** of Fig.3(a) using LDAS.

4.3 Energy consumption

In this paper, the average residual energy and the energy variance function are measured to see whether the energy consumed is balanced or not at a certain time [12]. The average residual energy function is defined as:

$$m_E(t) = \frac{\sum_{i=1}^{N} E_i(t)}{N} \quad (12)$$

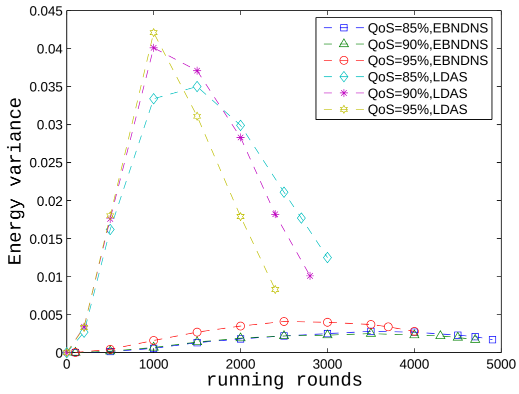


Fig. 10: the comparison of energy variance under Fig3(b)

The energy variance function is:

$$D_E(t) = \frac{\sum_{i=1}^{N} [E_i(t) - m_E(t)]^2}{N} \quad (13)$$

Combining the two values, the larger the average residual energy and the smaller the energy variance suggest better balance of energy consumption at a certain point. Fig. 9 shows the compared values of the average residual energy with the running rounds between LDAS and EBNDNS algorithm. Smaller slope indicates slower energy consumption and longer lifetime of the network. The curves of EBNDNS decline less obviously than the curves of LDAS. Furthermore, the values of average residual energy of the two algorithms are all less than 10% of the initial energy when the network dies. This indicates that EBNDNS can save energy more effectively. Fig. 10 compares the energy variance values of LDAS and EBNDNS with running rounds. The energy variance of EBNDNS is always small with few changes. It shows that EBNDNS can achieve balanced energy consumption better.

5 Conclusions

In this paper, the authors have proposed an energy-balanced node sleep scheduling scheme which needs sensor-to-sensor distance but no location information. Simulation results indicate that EBNDNS, which takes two-hop neighbours information into consideration, performs nearly the same as OGDC. Combined with the simple non-uniform distribution strategy that is proposed in this paper, simulation results show that EBNDNS can help to achieve balanced energy consumption under the premise of ensuring the coverage ratio. In this way, it can prevent the energy hole from being formed prematurely, and extend the network lifetime effectively. However, it is of no significance meaning just to extend the network lifetime without ensuring the reliability of data transmission. Wireless sensor networks have many uncertain factors, such as node failure, unexpected events, data congestion, etc. As a result, the next step in the future, we shall research a node scheduling algorithm for fault tolerance.

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