

Optimal Sleep Scheduling Scheme for Wireless Sensor Networks Based on Balanced Energy Consumption

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Abstract—Node scheduling scheme of sensor nodes is one of the most important method to solve the energy-constrained wireless sensor networks. Because there are the defects that high computational complexity of exact location information and the energy consumption unbalance of location-unaware in traditional schemes. Aiming at these problems, an optimal sleep scheduling scheme based on balanced energy consumption (ECBS) was proposed in this paper. Accounting the residual energy, the precision for node redundancy evaluating was improved by using the distance information between the sensor and its neighbors. The numerical experiments results illustrate that our scheduling scheme may improve the energy efficiency and extends the network lifetime while ensure the coverage requirement.

Index Terms—wireless sensor networks; node scheduling algorithm; energy balance; Location-Unaware

I. INTRODUCTION

Rapid advances in micro-electro-mechanical systems and wireless communication have led to the deployment of large scale wireless sensor networks (WSNs). The potential applications of sensor networks are highly varied, such as environmental monitoring like temperature, humidity, seismic events, vibrations, and so on. But the energy source of WSNs often consists of a battery with a limited energy budget; and it is difficult or impossible to replace the power supplies for sensor nodes after deployed. So lifetime is the key performance measure for WSNs [1]. Sensors are usually deployed densely to prolong the network lifetime. But a high-density network will waste a lot of energy and cause severe problems such as redundancy, radio channel contention. A broadly-used method is to place nodes in sleep mode by scheduling sensor nodes to work alternatively. But selecting the optimal sensing ranges for all the sensors is a well-known NP-hard problem [2]. Random putting nodes to sleep mode for fixed time interval [3 and 4] would cause the network to synchronize and may generate some blind points that cannot be monitored by any sensors^[5,6]. Based on the location of sensor nodes, some schedule schemes are

known as GAF [7], PEAS [8], SSC [9], etc. Using the geography (location, direction, or distance) with global position system (GPS) or the directional antenna technology may ensure the coverage and connectivity effectively. But the costs of GPS or other complicated hardware devices are too high for tiny sensors. Due to the limited processing and memory capabilities, it is not realistic to take the sensor nodes equipped with specialized hardware components such as GPS into mass production [10]. Furthermore, most applications may not suit equip with GPS, such as underground, etc. Nodes scheduling schemes without location information are more valuable in practical.

Without accurate geography information, however, it is very hard to check whether a sensor's sensing area can be completely covered by other sensors. Fortunately, most applications may not require complete coverage of the monitored area. Fewer researchers have proposed the node scheduling schemes without the accurate location information. Gao et al [11] propose a mathematical model to describe the redundancy in randomly deployed sensor networks. The results indicate that: a sensor requires about 11 neighbors to get a 90% probability of being a complete redundant sensor. If we only require a sensor's 90% sensing area to be covered by its neighbors, 5 neighbors are necessary. Based on this theoretical analysis, a Lightweight Deployment-Aware Scheduling (LDAS) scheme to turn off redundant sensors has been proposed [12]. LDAS uses a weighted random voting method to decide who will be eligible to fall asleep. But LDAS only consider a sensor's 1-hop neighbors which can cause larger redundancy coverage. Younis proposed two distributed protocols (LUC-I and LUC-P) rely on distance between one-hop neighbors along with advertised tow-hop neighborhood information [13]. In [14], Li-Hsing et al presented range-based sleep scheduling (RBSS) protocol, an optimal sensor selection patter to ensure the coverage quality. These methods can effectively reduce network energy consumption without any location or directional information. But none of them take the balance of energy consumption into account. The

unbalanced energy consumption means that the nodes inequality sleeps. It leads to the number of nodes premature death, and then speed up those nodes died in this region, called as “funneling effect”. Thus the “energy hole” are formed and the network lifetime is reduced [15-18]. Ideally, all of the nodes deployed in the region should be consumed their energy at the same time as possible. The residual energy of the entire network is almost zero when the network is death.

In this paper, we propose an optimal sleep scheduling scheme (ECBS) which relies on approximate neighbor distances and two-hop neighbors’ information but no location information. Simulation results indicate that our scheme not only prolongs the network lifetime, but also improves energy efficiency. The reset of the paper is organized as follows. Section II introduces the system model and problem statement. Section III presents and analyzes the algorithm. In section IV, we present our experimental results for performance evaluation. Finally, section V gives a summary and conclusion.

II. SYSTEM MODEL AND PROBLEM STATEMENT

A. System Model

We consider sensor nodes for which r_t is the transmission range and r_s is the sensing range. And our analysis is based on the following assumes: (1) sensors are stationary and are deployed randomly within an area; (2) A sensor’s sensing range is a circle area; (3) all sensors are supposed to have the same sensing range and no two sensors can be deployed exactly at a same location; (4) no geography information is available; (5) a node can estimate the approximately distance between itself and a neighbor based on the received signal strength[19],and fusion, conflict and retransmission are not taken into account when data transmitting; (6) $r_t \geq 2r_s$, under this condition, coverage implies connectivity[20].

Definition 1 (Neighbor nodes): the neighbor set of sensor i is defined as

$$N(i) = \{j \in \mathcal{N} \mid d(i, j) \leq 2r_s, i \in \mathcal{N}, j \neq i\} .$$

Where \mathcal{N} represents the sensor set in the deployment region. $d(i,j)$ denotes the distance between sensor i and j .

Definition 2 1-hop neighbor of sensor i :

$$N_1(i) = \{j \in N(i) \mid d(i, j) \leq r_s, i \in \mathcal{N}\} .$$

Definition 3 Half-hop neighbor of sensor i :

$$ND(i) = \{j \in N(i) \mid d(i, j) \leq 0.5r_s, i \in \mathcal{N}\} .$$

Definition 4 Network lifetime: the running time of the network meeting the required coverage.

B. Energy Dissipation

In our simulations, we use the same energy parameters and radio model as discussed in [21] which are used widely. In the model, the mainly energy consumption of

the wireless communication module to send the data is on the transmitting circuit and the power amplifying circuit. And the mainly energy consumption to receive the data focus on the receiving circuit. Under the reasonable SNR condition, the transmission energy consumption to send k bit data is:

$$E_T(k, d) = \begin{cases} E_{elec} \times k + \epsilon_{fs} \times k \times d^2 & d < d_{crossover} \\ E_{elec} \times k + \epsilon_{mp} \times k \times d^4 & d \geq d_{crossover} \end{cases}$$

and the reception energy consumption is

$$E_R = E_{elec} \times k .$$

Among the formulas, E_{elec} is the energy consumption coefficient for the radio electronics, ϵ_{fs} and ϵ_{mp} are the energy consumption coefficients for a power amplifier under different condition. Radio parameters are set as table I . We only consider the data aggregation, while ignore other processing energy consumption. The energy for performing data aggregation is 5nJ/bit/signal.

TABLE I.

RADIO PARAMETERS

Parameter	Value
Threshold distance(dcrossover)(m)	87
E_{elec} (nJ/bit)	50
ϵ_{fs} (pJ/bit/m ²)	10
ϵ_{mp} (pJ/bit/m ⁴)	0.0013
Initial energy(J)	0.05
Data packet size(bits)	4000

C. Problem Statement

Assume that N nodes are distributed in a field, and the number of the active nodes is N_A . Then the sleep ratio of the network is defined as:

$$Q = \frac{N - N_A}{N} \tag{1}$$

The sleep ratio is one of the standards for measuring the efficiency of energy consumption. When the total number of nodes in the network is fixed, the higher the sleep ratio, the better the energy can be saved. If θ is the desired coverage rate of the network, the objective of sleep scheduling scheme is to maximize the lifetime and the sleep ratio of the network while ensue the coverage rate of active nodes meet the θ requirement.

III. OPTIMAL SLEEP SCHEDULING SCHEME

A. Coverage Redundancy Determines

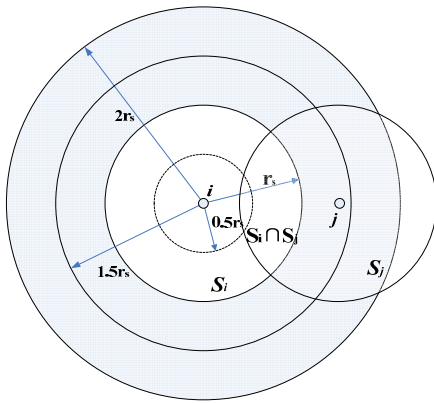


Figure 1. $S_i \cap S_j$

Supposed that sensor i has a neighbor sensor j . S_i and S_j denote the circle sensing area covered by node i and j respectively. d_{ij} is the distance between node i and j . And $S_{i \cap j}$ denotes the sensing area that is covered by node i and j , as shown in Figure 1. Refer to [22], we can get that:

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

So from formula (2), we can get that when the distance between node i and j is less than or equal to $0.5r_s$, the redundant coverage area $S_{i \cap j}$ is more than about 68.5% of S_i . When the distance of node i and node j is more than $1.75r_s$, the area $S_{i \cap j}$ is very small, about 0.052 S_i . These results can be used in our nodes scheduling. If $d_{ij} \geq 1.75r_s$, the effects that node i to node j will be ignored in this paper.

If θ is the percentage of the redundant area covered by all the neighbors of node i . Refer to paper [22, 23], θ can be expressed as

$$\theta = \frac{\bigcup_{j \in N(i)} S_j \cap S_i}{S_i} = \frac{S_i - \overline{S_{N(i)}}}{S_i} = 1 - \prod_{j=1}^m \left(1 - \frac{S_{i \cap j}}{S_i}\right) \quad (3)$$

$\overline{S_{N(i)}}$ is the area that covered by sensor i but not covered by its neighbors. Then, if node i has a neighbor node k and $d_{ik} \leq 0.5r_s$. Based on formula (2) and (3), the θ of node i can be expressed as

$$\theta \geq 1 - 0.32 \cdot \prod_{\substack{j=1 \\ j \neq k}}^m \left(1 - \frac{S_{i \cap j}}{S_i}\right) \quad (4)$$

Suppose node j is a neighbor node of node i . Based on the above definition, the distance between node i and j satisfy the condition: $0 < d_{ij} < 2r_s$. By mathematical statistics knowledge we can get the probability

distribution function of node j is $f(j) = \frac{1}{\pi \cdot (2r)^2}$. Then

the probability that node j is an 1-hop neighbor of node i is:

$$p = \int_{S_i} f(j) dj = \frac{S_i}{4\pi r^2} = \frac{1}{4}$$

Using the same method, we can calculate the probability that node j deployed in different area around node i . In this paper, the region around sensor is divided into three parts: $0 < d_{ij} \leq 0.5r_s$, $0.5r_s < d_{ij} \leq r_s$, $r_s < d_{ij} \leq 1.75r_s$. According to probability distribution function, the number of sensors that deployed in different parts can be calculated. Combined with formula (3) and (4), we can get table II. Where K , M , L is the neighbor numbers in different regions. When the redundancy coverage area of a sensor meets the requirement θ , this sensor can be off-duty.

TABLE II.
REDUNDANCY WITH DIFFERENT NEIGHBORS

K ($d_{ij} \leq 0.5r_s$)	M ($0.5r_s < d_{ij} \leq r_s$)	L ($r_s < d_{ij} \leq 1.75r_s$)	The redundancy coverage rate $\theta(\geq)$
0	2	4	80.12%
0	2	5	82.98%
0	2	6	85.44%
0	3	6	91.13%
0	4	8	96.05%
1	1	3	87.79%
1	1	4	89.55%
1	2	6	95.34%

B. Optimal Sleep Scheduling Scheme

In this paper sensors include three states: active, sleep, and pre-sleep. Pre-sleep state is set to avoid a blind hole

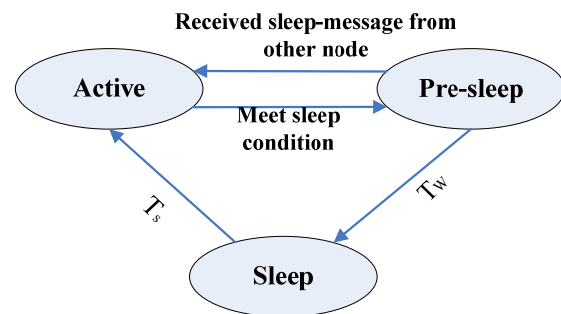


Figure 2. Three states exchange machine.

when several neighbor nodes to sleep simultaneously [12, 24]. As shown in Figure 2, when an active sensor meets

the condition to sleep, it enters the pre-sleep state with a random short time T_w . If the node received other sensor's *sleep*-message at the pre-sleep state, it will return the active state. Otherwise, it broadcasts itself *sleep*-message after waiting T_w time and then goes to sleep state; fall asleep for a period of time T_s .

Based on the classic LEACH cluster protocol, time is divided into fixed-length time periods called rounds. Each round begins with a competition phase, in which every node determines whether it can be active or sleep. Then those active sensors enter into clustering and sensing. We detail the steps as follows.

Step1: Networks initialization. We assumed that all sensors are active initially. Each sensor broadcasts messages to estimate the distance between itself and its every neighbor and then record these information. According to the QoS demand (the coverage rate θ) of network, sink broadcasts the system message including the two parameters HT and AT. Where HT is the minimum number of active neighbors with one half-hop neighbor and AT is the minimum number of neighbor nodes that have no half-hop neighbor. For example, the network coverage (θ) is required to 85%. According to table II, we can set HT = 5 and AT = 8. While the coverage rate θ is more than 90%, we can set HT = 6 and AT = 9.

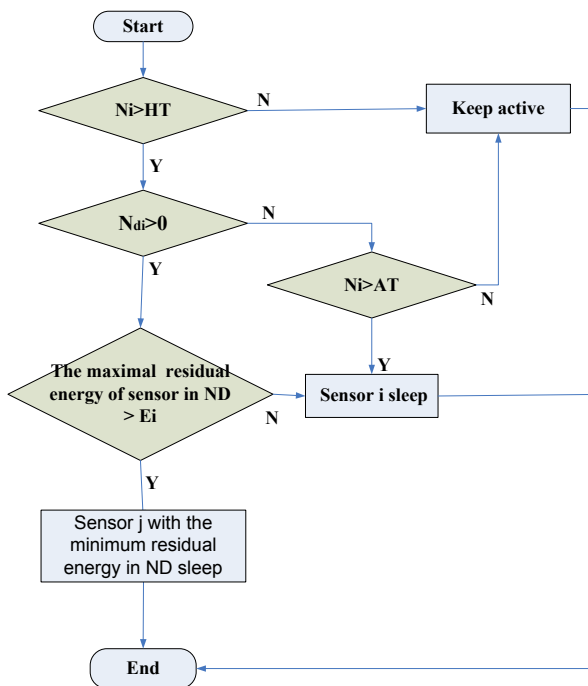


Figure 3 The scheduling process of an active sensor i

Step 2: Nodes-scheduling. At the beginning of each round, each active node determines whether it is a redundancy sensor or not. The scheduling scheme is detailed in **Figure 3**. Where N_i is the number of sensor i's active neighbors, and N_{di} is the number of sensor i's half-hop neighbors, ND is the set of sensor i's half-hop neighbors, E_i is the residual energy of sensor i.

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 closest head to join.

Step 4: Sensing.

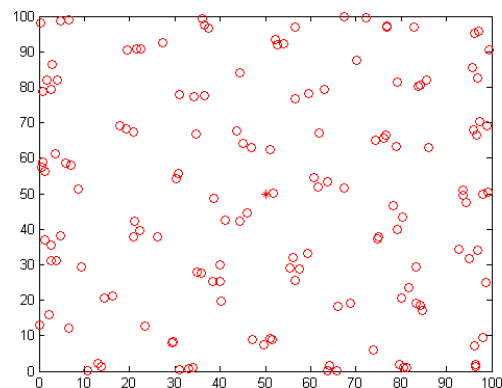
Step 5: The current round end and return step 2.

IV. SIMULATION RESULTS

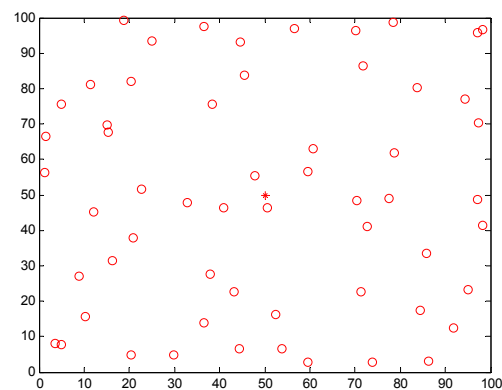
We focus on the construction of one cover and assume that 1000 nodes are deployed randomly in a 100 meter×100 meter square. Each sensor has a sensing range of 15 meters. The transmitting, receiving (idling), and sleeping power consumption ratio is 20:4:0.01[21]. We conducted simulations with matlab simulator for comparing among two sleep scheduling methods: LDAS and our proposed scheme (ECBS).

A. Coverage Effectiveness

Set $\theta \geq 90\%$. Run LDAS and ECBS at the same condition to compare. We sampled on the No.100 round respectively as shown in Figure 4 (only active sensors are marked to see clearly). Only 58 nodes are active in our algorithm, but 150 nodes are on-duty by LDAS algorithm. And Figure 5 shows the coverage condition with the active nodes on No.100 round by different algorithm. It can be easy to see that the fewer numbers of active nodes are needed in our algorithm to meet the same coverage required and the sensors distribute more uniform in Figure 4(b). However, there is more redundancy coverage in Figure 5(a).



(a) LDAS



(b) ECBS

Figure 4 The distribution of active nodes on No.100 round

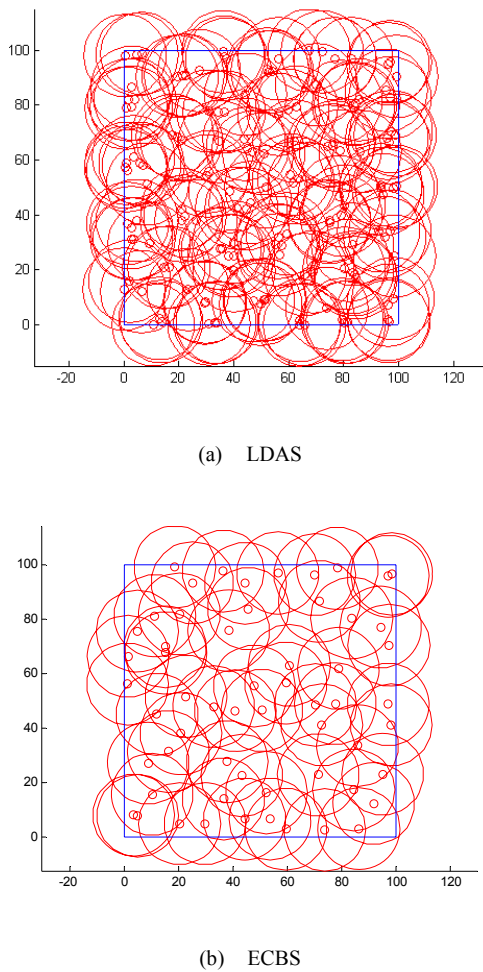


Figure 5 The coverage condition on No.100 round

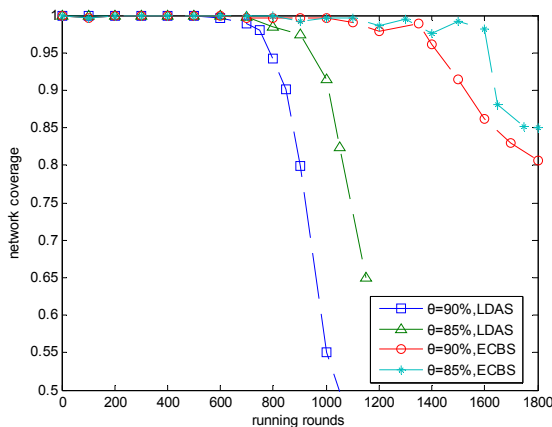


Figure 6 Comparisons of network coverage ratio

The network coverage (η) is the ratio of the area covered by those active nodes to the whole monitoring area during the nodes scheduling scheme running process.

$$\eta(t) = \frac{A_{active} \cap A}{A} \quad (5)$$

A is the whole monitoring area, and A_{active} is the area

covered by those active nodes at some time.

As shown in Figure 6, the network coverage is reducing with the network running using both the two algorithms. The higher the network coverage required, the shorter survival time of the network. During the initial operation, the two algorithms have maintained a higher coverage rate. But with the operation of network, more and more nodes exhausted their energy, the network coverage also decreased. Furthermore, the coverage rate of ECBS is always higher than LDAS at the same round during the whole running time.

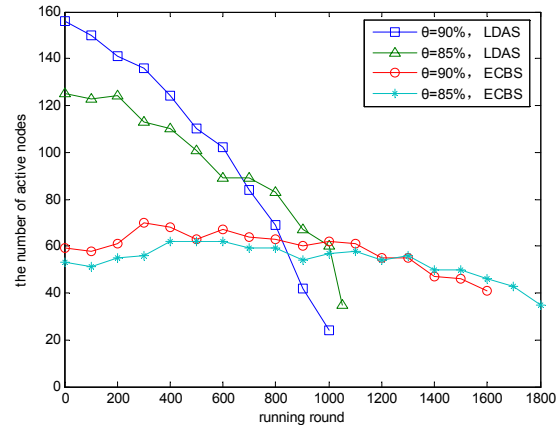


Figure 7 Comparisons of active nodes

Figure 7 shows the number of active nodes during the network running. As can be seen from Figure 7 and Figure 6, the number of active nodes by ECBS is always less than the number that used by LDAS when the coverage ratio meeting the requirement. Because there are more active nodes in the early operation by LDAS, too much energy were consumed. The active nodes decreased with more and more nodes run out of their energy. And the coverage percentage dropped from 98% to 50% quickly. But the number of active nodes used by ECBS algorithm is kept stability in the whole running process. Using the less active nodes to meet a high coverage, thus the energy has been saved and the lifetime has been prolonged.

B. Network Lifetime

According to the definition 4 in this paper, network lifetime is the running time of the network meeting the required coverage. As illustrated in Figure 8, the network lifetime is only 70 rounds with no scheduling scheme. Set $\theta \geq 90\%$, using LDAS scheduling scheme the lifetime is 850 rounds and the first dead node occurred on No.104 round. But by ECBS scheduling scheme, the lifetime extends to 1520 rounds and the first dead node occurred on No.382 round. Set $\theta \geq 85\%$, the lifetime is 1020 rounds and the first dead node occurred on No.117 round by LDAS. But by ECBS algorithm, the lifetime extends to 1750 rounds and the first dead node occurred on No.402 round. ECBS algorithm can prolong the network lifetime efficiently. And the lower required coverage, the longer the network lifetime.

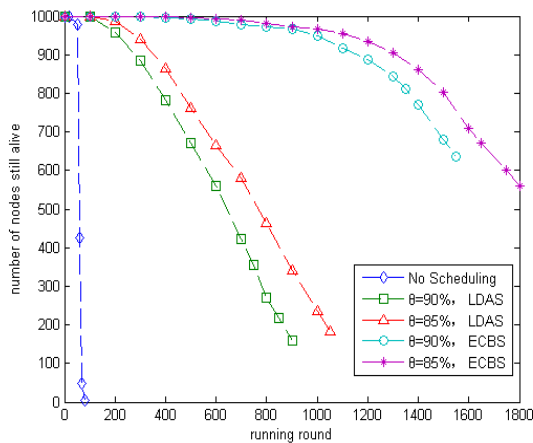


Figure 8 Comparison of network lifetime

C. Energy Efficiency

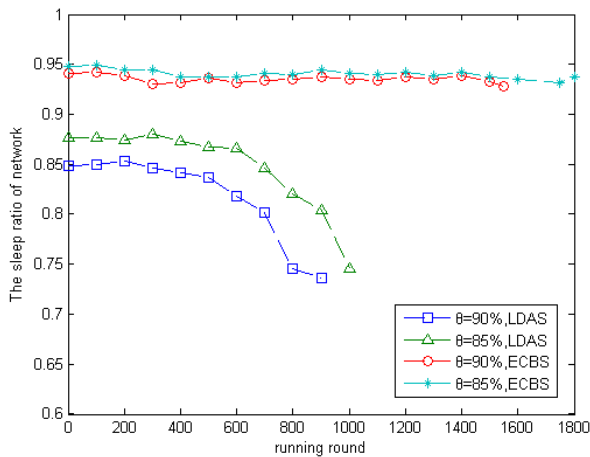


Figure 9 Comparison of sleep ratio

As mentioned above, the sleep ratio is an important parameter to describe the situation of saving energy during the operation. When meeting the coverage requirement, the higher the sleep ratio, the better the energy can be saved. Figure 9 shows that the sleep ratios of ECBS are always higher than that of LDAS algorithm and maintain stability in the whole running time. Moreover with different coverage requirement, the sleep ratios of LDAS are also much different. The higher the network coverage requires the lower sleep ratio. But the sleep ratios of our algorithm have a little change. Figure10 shows the average residual energy of network during operation. It confirms that the residual energy of ECBS is always higher than that of LDAS on the same round.

Sleep ratio can only demonstrate the total condition of energy consumed, but not measure the balance of energy consumed. In this paper, the average residual energy and the energy variance function are used to measure that the energy consumed is balanced or not at some time [25].

Considering the two values, the larger the average residual energy and the smaller the energy variance, the better balance of the energy consumed in the network.

The average residual energy function is:

$$m_E(t) = \frac{\sum_{i=1}^N E_i(t)}{N} \tag{6}$$

The energy variance function is:

$$D_E(t) = \frac{\sum_{i=1}^N [E_i(t) - m_E(t)]^2}{N} \tag{7}$$

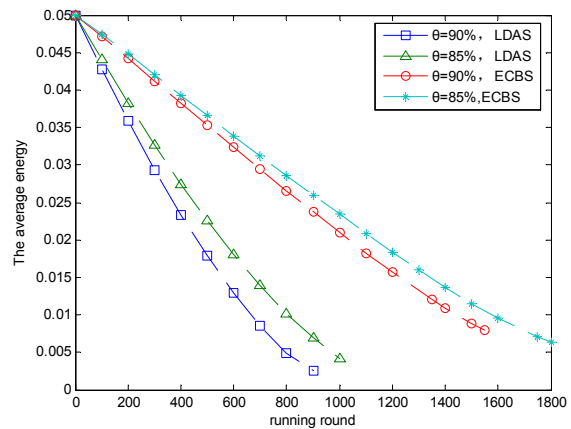


Figure 10 comparison of the average residual energy

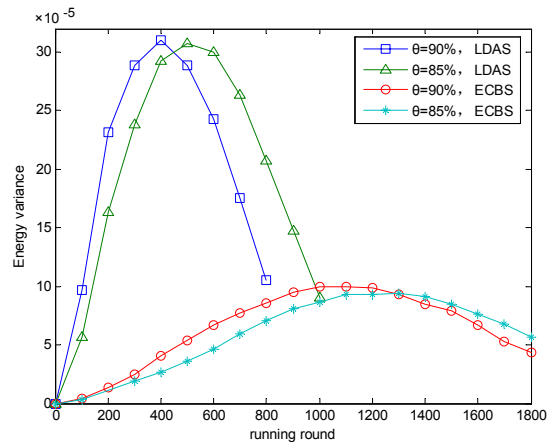


Figure 11 comparison of the energy Variance

From Figure 10 and Figure 11, it can be seen that the ECBS algorithm has a better balance of energy consumed. By LDAS algorithm, the $m_E(t)$ decreased more rapidly and the $D_E(t)$ were larger. The experiment data shows that using LDAS algorithm some nodes still remained more than 90% energy even when the network died. But using ECBS algorithm, the maximal ratio of the residual energy to the initial energy was about 40% when the network died. It also indicates that LDAS algorithm exits the problem that energy consumes uneven. Thus it will lead to some nodes run out their energy earlier. And then energy hole are formed so as to make the network dying prematurely. Ideally each node in a network running out its energy at the same time will obtain the optimal energy efficiency.

V. CONCLUSION

Energy saving in WSNs has attracted a lot of attention in the recent years. Extensive research has been conducted to address these limitations by developing schemes that can improve resource efficiency. In this paper, we have introduced an optimal energy-efficient sleep scheduling scheme for WSNs. Without accurate geography information, the two-hop neighbors are considered. Simulation results show that our scheduling scheme has improved the sleep ratio and extended the network lifetime. But in the simulation experiments, we discovered that there is approximately 17% residual energy when the network died. Considering the death spread from the border of the monitor region to the central, we believe that there is still space to improve. So, one of our future works is to find a solution to alleviate the inequality sleep of the boundary nodes.

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