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Energy-Efficient Distributed Lifetime Optimizing Scheme for Wireless Sensor Networks*

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Abstract: In this paper, a sensing model for the coverage analysis of wireless sensor networks is provided. Using this model and Monte Carlo method, the ratio of private range to sensing range required to obtain the desired coverage can be derived considering the scale of deployment area and the number of sensor nodes. Base on the coverage analysis, an energy-efficient distributed node scheduling scheme is proposed to prolong the network lifetime while maintaining the desired sensing coverage, which does not need the geographic or neighbor information of nodes. The proposed scheme can also handle uneven distribution, and it is robust against node failures. Theoretical and simulation results demonstrate its efficiency and usefulness.

Keywords: wireless sensor networks; lifetime optimization; coverage; reliability; Monte Carlo method

The limited energy of nodes seriously constrains the lifetime of wireless sensor networks (WSNs) and their large-scale application. To improve the energy efficiency and increase the network lifetime, a broadly used method is to deploy the sensor nodes with density up to 20 nodes/m^3[1,2], where redundancy can be exploited[3].

In order to ensure the complete coverage of the monitored area, geographic information acquired from Global Positioning System (GPS) is usually needed. However, it is still difficult to estimate the sensors' locations, since GPS and other devices consume too much energy and the cost is too high for tiny sensors[4]. Fortunately, most applications may not need the complete coverage of monitored region. Without geographic information, most schemes require the knowledge about the coordinates of sensors. However, in a high density network with frequent unpredictable node failures, maintaining each node's geographic or neighbor information consumes too much energy and control overhead.

A new node sensing model is presented to obtain the coverage in the large-scale networks. Our analysis is based on random deployment of sensors because of its low cost[5]. According to theoretical analysis, the ratio of private range to sensing range needed to obtain the desired coverage can be derived. Then, a new distributed robust node scheduling scheme without requiring the knowledge of location or neighbor information is proposed. Simulation results indicate that the proposed method is efficient.

1 Related works

Many scholars proposed methods to select exclusive sets of sensor nodes mutually, where the members of each of these sets completely cover the monitored area together, and only one of these sets is active at any time. This problem was proved to be NP-complete[6,7]. Cardei and Du[6] proposed a heuristic method to compute the maximum disjoint set cover (DSC). In Ref. [8], the authors presented two greedy algorithms for optimizing the number of cover sets, and a node selection strategy was proposed based on a cost function that evaluates the available nodes according to their coverage status and remaining energy. In Ref. [9], Mohamadi *et al* presented a learning automata (LA) based scheduling scheme. Bulut and Korpeoglu[10] proposed an energy efficient sleep scheduling scheme. However, all these schemes require the geographic information of sensor nodes.

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The algorithm proposed in Ref. [1] does not re-quire knowledge of the location of nodes, but each sensor needs to know the distances between adjacent nodes in its transmission range and its sensing range. In Ref. [4], Wu *et al* proposed a lightweight deployment-aware scheduling (LDAS) algorithm, which turns off redundant sensors without using accurate location information. In Ref. [11], an energy balanced non-uniform distribution node scheduling algorithm (EBNDNS) was proposed, which needs sensor-to-sensor distance rather than geographic information.

2 Preliminary

2.1 Sensing model

In this model, each sensor has three parameters: sensing range R_s, communication range R_c and private range R_p (Fig. 1). A sensor can only sense the environment and detect events within its sensing range. A point is covered if and only if it lies within the sensing range of at least one sensor. So the deployment area is partitioned into two regions: covered region and vacant region. Communication range is the radio transmission range of a sensor. In Ref. [12], it was shown that if the transmission radius of each sensor is at least twice of its sensing radius, then the coverage implies connectivity of the sensor network. We make the same assumption without explicitly considering connectivity. Private range is a node's own range, and there is no other node in this area and $R_p < R_s$.

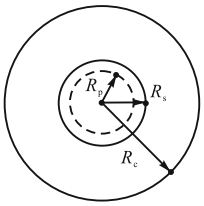


Fig. 1 Sensing model

2.2 Assumptions

(1) A set of sensor nodes, N, are randomly deployed in a two-dimensional rectangular area with size of $L \times L$. The sensors and the sink are all stationary after deployment.

(2) All sensors are homogeneous and have the same capabilities.

(3) Each node is assigned with a unique identifier and the sensors' sensing range is a circular area.

3 Proposed scheme

The purpose of the scheme is to prolong network lifetime by exploiting the high redundancy without geographic or neighbor information. The basic method is to keep a number of sensor nodes in the active state in WSN. However, this scheme raises the following problems:

Problem 1 Since nodes are not aware of their locations or neighbor nodes, whether the node should turn itself off or not, and how to keep the desired coverage?

Problem 2 When should nodes make such a decision?

3.1 Solution to Problem 1

3.1.1 State change mechanism

Definition 1 Let $S(i)$ and $P(i)$ denote node i 's sensing area and private area, respectively.

Definition 2 A sensor node has four states: active, ready, sleeping and dead. The state of node i is denoted by $W(i)$.

Definition 3 The private neighbor set of node $i \in N$ is defined as $N_p(i) = \{j \in N \mid d(i,j) < 2R_p, j \neq i\}$, where $d(i,j)$ denotes the distance between node i and node j. Define

$$A = \{i \in N \mid W(i) = \text{active}\}$$

$$D = \{i \in N \mid W(i) = \text{dead}\}$$

$$O = \{i \in N \mid W(i) = \text{ready or sleeping}\}$$

Obviously, $N = A \cup O \cup D, A \cap O = A \cap D = O \cap D = \varnothing$. The initial value of set $A = \varnothing, B = N, D = \varnothing$. The purpose of the mechanism can be expressed as follows:

For every node $i \in A, \forall j \in N_p(i), j \in O$;

For every node $i \in O, \exists\, j \in N_p(i), j \in A$, and j is unique.

For $i \in N$,

Rule 1 If $W(i) = \text{active}$. After working time, node i goes to sleep state.

Rule 2 If $W(i) = \text{ready}$.

Rule 2.1 If $\exists\, j \in N_p(i), \text{s.t.}\ j \in A$, then $W(i) = \text{sleeping}$.

Rule 2.2 If $\forall j \in N_p(i), j \in O$, then $W(i) = \text{active}$.

Rule 3 If $W(i) = \text{sleeping}$. After sleeping time and random back-off time, node i goes into ready state.

Theorem 1 The state change mechanism is self-stabilizing.

Proof According to the state change rules, it is

straightforward to prove the following lemmas and this theorem follows from these lemmas.

(1) For $i \in N$, there is at least one node $j \in N_p(i)$, s.t. $W(j) = \text{active}$.

(2) When a node is not sleeping, it can make at most 2 moves.

(3) When a node is not ready or active, it can make only 1 move.

A node changes its state according to the state change mechanism until the node runs out of its energy. We will illustrate when the nodes should make such a decision in Section 3.2.

3.1.2 Desired coverage

Definition 4 The coverage of sensor networks is defined as the percentage of a given deployment area that can be monitored.

$$\text{Coverage} = \frac{\bigcup_{i \in A} S(i) \cap (L \times L)}{L \times L} \tag{1}$$

While a node's state is changed to sleeping, it is hard to obtain the desired coverage especially without accurate geographic or neighbor information. Therefore, it is critical to provide a method based on which changing the node's state would not degrade coverage.

According to the sensing model proposed in Section 2.1 and the state change rules proposed in Section 3.1.1, we can get $d(i,j) > 2R_p$, for $\forall i, j \in A$. In an area of $L \times L$, for given values of R_s and R_c, we can change R_p to get different coverage rates. Intuitively, the coverage rate decreases with the increase of R_p. We will describe this problem mathematically.

Given an area of $L \times L$, which is filled with circles $C_1, C_2, C_3, \cdots$ with radius R_p in random (the center of the circles must be inside the area) and $S_i \cap S_j = \varnothing (i \neq j)$, with S_i being the area of C_i, we will calculate the coverage rate in the following by using Monte Carlo method (MCM)[13]. In statistics theory, $\bar{X} \pm z_{1-\alpha/2}\sqrt{\frac{S^2}{n}}$ is a confidence-interval for population mean μ, where $\bar{X}$ is sample mean, S^2 is sample variance, $z_{1-\alpha/2}$ is the $(1-\alpha/2)$ quantile of the standard normal distribution.

In order to control the confidence-interval half-length (or the error of $\bar{X}$), we need to choose a proper n. Define $\delta(n,a) = z_{1-\alpha/2}\sqrt{\frac{S^2}{n}}$, and simulation accuracy $\gamma = \frac{\delta(n,a)}{|\bar{X}(n)|}$. Then,

$$1-\alpha \approx P\left(\frac{|\bar{X}(n)-\mu|}{|\bar{X}(n)|} \leqslant \frac{\delta(n,a)}{|\bar{X}(n)|}\right) =$$
$$P\left(|\bar{X}(n)-\mu| \leqslant \gamma |\bar{X}(n)|\right) \leqslant$$
$$P\left(|\bar{X}(n)-\mu| \leqslant \gamma\left(|\bar{X}(n)-\mu|+|\mu|\right)\right) =$$
$$P\left(\frac{|\bar{X}(n)-\mu|}{|\mu|} \leqslant \gamma/(1-\gamma)\right) \tag{2}$$

Thus, μ has a relative error of $\gamma/(1-\gamma)$ with an approximate probability of $1-\alpha$. Given the relative error of μ and confidence level, the least number of MCM is

$$N_{\min}(\gamma) = \min\left\{n : \frac{z_{1-\alpha/2}\sqrt{\frac{S^2}{n}}}{|\bar{X}(n)|} \leqslant \gamma\right\} \tag{3}$$

Based on the analysis above, the flowchart of coverage analysis is shown in Fig. 2. Fig. 3 shows the numerical results of an example. The area is set as 200 m×200 m and the confidence level is set as 99%. The simulation accuracy $\gamma = 0.006\ 7$, and the sensing range $R_s = 10$ m. Fig. 3 demonstrates the relationship between the ratio of private range to sensing range and the desired coverage.

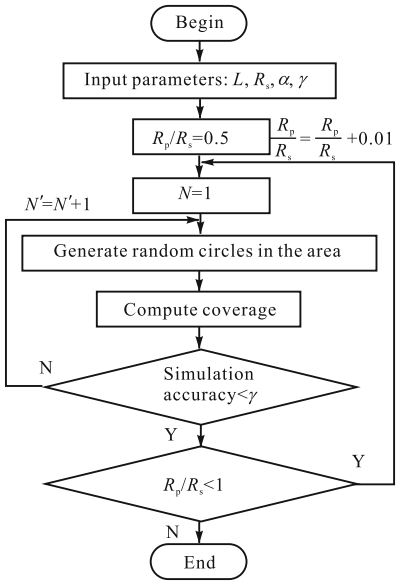


Fig. 2 Flowchart of coverage analysis

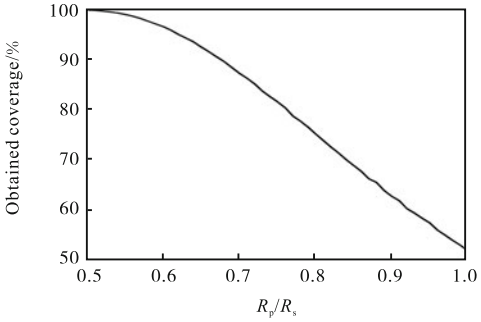


Fig. 3 Numerical results

3.2 Solution to Problem 2

3.2.1 Overview

Initially, all sensor nodes are set as sleeping. After a random time period T_s, node i goes into ready state. The node broadcasts a HELLO message to acquire when its active neighbor nodes are going to sleep. It is possible that several sleeping nodes may wake up at the same time and contend with the HELLO message. To avoid this problem, we present a back-off mechanism. We let each node start to broadcast a HELLO message after a back-off time period T_b. If there is no reply for the HELLO message after a predetermined time T_p, node i believes that no active nodes exist within its private neighbors. Then node i turns into active state and starts working for its active time T_a. Each node has a timer variable, i. e., the remaining active time T_r, which is used to indicate the length of the remaining time when this active node starts sleeping. When a node goes to active state, this variable is initialized as T_a, which decreases with time. After T_r, node i will go to sleeping state. If there are active nodes within node i's private neighbor nodes, it receives the reply messages from its active neighbor nodes. Each reply message contains the remaining active time T_r of the active node. The node may collect one or more REPLY messages, and then chooses the shortest T_r as its sleeping time.

Using this method, we ensure that when an active node starts sleeping, the other sleeping nodes in the neighborhood will go to ready state.

3.2.2 Selection of system parameters

The system parameters include back-off time T_b, active time T_a and sleeping time T_s. When a node turns into ready state, the node selects back-off time T_b, which is inversely proportional to its remaining energy for balancing energy consumption. A node whose remaining energy is higher than others should wait for a shorter time. Thus, we can derive the back-off time of node i as follows:

$$T_b(i)=\left(1-\frac{E_r(i)}{E_{ini}(i)}\right)\times T_{s,max} \tag{4}$$

where $T_{s,max}$ is the predetermined maximum sleeping time; $E_r(i)$ and $E_{ini}(i)$ are the remaining energy and initial energy of node i, respectively.

In active state, node i is responsible for sensing tasks. When a node changes its state to active, the node should determine its active time T_a. For balancing energy consumption, a node whose remaining energy is higher than other nodes should work for a longer time. Thus we can derive the active time of node i from an exponential distribution by

$$T_w(i)=T_{a,max}\left[\alpha\left(1-\sqrt{\frac{e-e^{\left(\frac{E_r(i)}{E_{ini}(i)}\right)}}{e-1}}\right)+\beta\right] \tag{5}$$

where $T_{a,max}$ is the predetermined maximum active time; α and β are tunable system parameters, $\alpha+\beta=1$. After $T_w(i)$ expires, node i goes to sleeping state and the sleeping time T_s is set as $\beta\times T_{a,max}$ [14].

There are another two cases about the sleeping time. One is the random time. For large-scale sensor networks, it may be desired to start up faster at the beginning of the network operation, and we can use a smaller T_s to ensure that. The other is the shortest remaining active time T_r, which is obtained from the REPLY messages.

3.3 Performance

3.3.1 Control overhead

The control overhead are merely the HELLO and REPLY messages exchanged during the network operation. The energy consumed by control overhead is in proportional to the time of state changing from sleeping to ready. Each time a node goes to ready state, the energy will be consumed by broadcasting HELLOs and REPLYs and waiting for REPLYs.

3.3.2 Handling uneven distribution

It is an ideal assumption that nodes are uniformly distributed in WSN. In reality, it is possible that some sensors may have much fewer private neighbors than others. Our node scheduling scheme can evenly keep a set of active nodes in the deployment area, which is independent of particular node distribution. We will simulate this in Section 4.6. The node distribution has an influence on the network performance. An uneven node distribution may decrease the network lifetime, because the areas with fewer nodes will die out earlier. When many sparse areas take place, the network cannot maintain the desired coverage for a long time. Therefore, the nodes deployed evenly perform better than those deployed unevenly.

3.3.3 Robustness against node failures

Node failures are more likely to occur in large-scale networks, especially in the harsh or hostile environment. An active node failing unexpectedly will cause large gaps, i.e., there are no other nodes available to replace this dead node (Fig. 4). When an active node fails, one of its private neighbors will become active after remaining active time T_r. Thus, the duration of gaps is shorter than the

active time T_a. Although the gaps may exist because of the node failures, these gaps have upper bound. The gaps reflect how long a dead node is replaced. According to the formula of T_w, we can choose a proper $T_{a,max}$ to make the gaps tolerable by applications. As shown by our simulation results in Section 4.7, the node scheduling scheme can withstand up to 26% of the node failures.

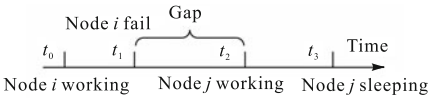


Fig. 4 Gaps when nodes fail

4 Simulation results

4.1 Simulation model

All sensors are randomly deployed in an area with size 200 m × 200 m. The sensing range and communication range of a node are 10 m and 20 m, respectively. The simulation accuracy γ = 0.006 7, and the confidence level is set as 99%. The energy model is similar to the hardware in Ref. [15], where the transmitting (active state), idling (ready state), and sleeping (sleeping state) power consumptions are 60 mW, 12 mW, and 0.03 mW, respectively. The initial energy of a node is uniformly distributed between 7 000 mJ and 7 200 mJ. The node density is expressed as $\rho = N_s R_p^2 / L^2$, where N_s is the number of sensors. In the simulation, when multiple nodes begin to send messages simultaneously, a packet collision may occur. Because of the low frequency of transmitting messages, the packet collision is not serious.

4.2 Effectiveness

To see how the scheme keeps the desired coverage, we set the desired coverage as 97%, 95%, 90%, 85%, 80% and 75%, and simulate for a long enough time until the first node dies.On the basis of the MCM in Section 3.1, we set the values of R_p as listed in Tab. 1.

Tab. 1 Private range with different desired coverages

Coverage/%	R_p/m
97	5.91
95	6.20
90	6.75
85	7.20
80	7.60
75	8.00

Fig. 5 demonstrates that because the gaps exist when nodes change their states and the scheme has significance in a statistical sense, the scheme cannot provide perfect matching between obtained coverage and desired coverage. We also see that the obtained coverage gets close to the desired coverage as the node density increases. This result indicates that the proposed scheme has a better performance in high density network.

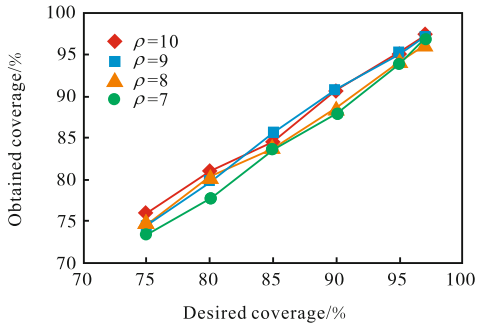


Fig. 5 Desired coverage and obtained coverage

4.3 Relationship between active nodes and desired coverage

We change the desired coverage from 85% to 95%, and change the initial node density from 6 to 10. Fig. 6 shows the information for the number of active nodes in different desired coverages and node densities. We can see that the number of active nodes only depends on the desired coverage, which is independent of the initial density of nodes. Fig. 6 also demonstrates that a higher desired coverage needs to keep more active nodes and thus consumes more network energy.

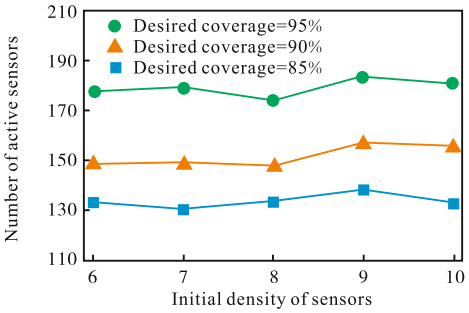


Fig. 6 Active nodes and desired coverage

4.4 Network lifetime

Fig. 7 shows the corresponding changes of the obtained coverage with different desired coverages in a network of 8 000 nodes. As can be seen from Fig. 7, the network lifetime is obviously improved by the proposed scheme. Without the node scheduling scheme, all nodes keep active and provide maximal coverage. As time goes

by, the nodes deplete energy quickly and the coverage decreases sharply from 100% to 0 in 120 s. Using the proposed scheme, the nodes are scheduled to work alternatively and prolong the network lifetime. The network can obtain a desired coverage for a period of time, then decreases slowly to 0 due to the death of nodes. We also observe that the higher the desired coverage, the faster the decrease of obtained coverage to 0. The reason is that a higher desired coverage needs to keep more active nodes, which is shown in Fig. 7, causing quicker energy consumption. Obviously, there is a clear tradeoff between the desired coverage and the network lifetime. To eliminate the effect of the chance factor, a number of simulations are carried out to obtain the statistical average. The result is listed in Tab. 2.

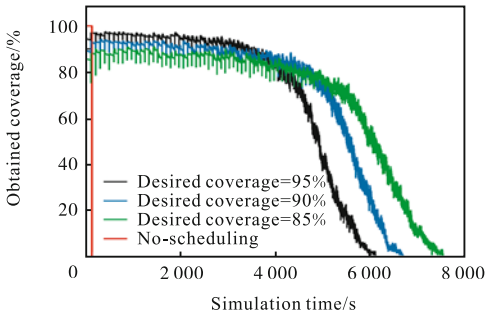


Fig. 7 Coverage and lifetime

Tab. 2 Statistical average of lifetime

Desired coverage/%	Lifetime/s
85	7 521
90	6 692
95	6 104

4.5 Energy consumption

Fig. 8 shows the curve of the ratio of remaining energy to the total energy of the sensors with different desired coverages in a network of 8 000 nodes. The smaller slope of the curve indicates slower energy consumption and longer lifetime of the network. In Fig. 8, the curve' slope of the proposed scheme is minimal. The total energy consumption of the network is lower than the no-scheduling case, so the energy consumption of the network is reduced successfully by using the proposed node scheduling scheme. We also observe that the higher the desired coverage, the larger the slope of curve. This phenomenon demonstrates that the higher desired coverage results in faster energy consumption and shorter network lifetime.

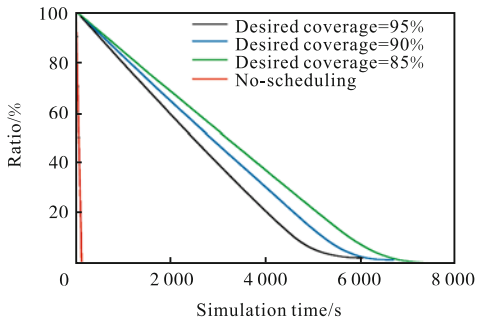


Fig. 8 Ratio of remaining energy to the total energy

4.6 Uneven distribution

Tab. 3 shows the number of active nodes and the obtained coverage with 90% desired coverage in different distribution networks of 8 000 nodes after 300 s simulation. From Tab. 3, we can see that although the node distribution is different, the number of active nodes and the obtained coverage are almost equal. Simulation results demonstrate that our node scheduling scheme can evenly keep a set of active nodes in the deployment area, which is independent of particular node distribution.

Tab. 3 Active nodes and obtained coverage with different distribution networks

Node distribution	Number of active nodes	Obtained coverage/%
Uniform	156	90.70
Poisson	154	90.59
Gaussian (σ = 5.5)	150	89.49

4.7 Node failure

Similarly, we use the historical obtained coverage change and network lifetime to estimate the robustness of the proposed scheme against node failures. Fig. 9 shows the corresponding changes of the obtained coverage with 90% desired coverage and different failure rates in a network of 8 000 nodes. We increase the failure rate from 0 to 0.3 failures per second. The failure percentage is described as the ratio of failed nodes to the total number of nodes. The related parameters are shown in Tab. 4. As can be seen from Fig. 9, the node scheduling scheme can maintain the desired coverage for a period of time, which is independent of different node failures. We also observe that the higher the failure rate, the faster the decrease of obtained coverage to 0 . As the failure rate increases, the network lifetime tends to decrease. However, for each failure rate, the percentage of network lifetime reduction is lower than the failure percentage. The simulation results show that the proposed scheme is ro-bust enough to keep sufficient active nodes and maintain the desired coverage in the presence of node failures.

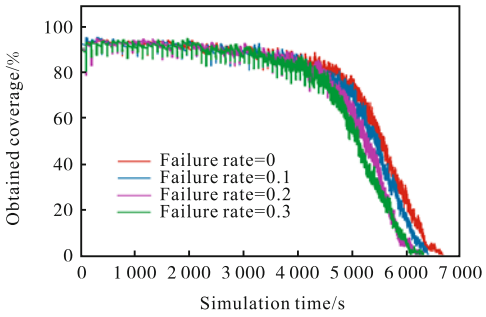


Fig. 9 Coverage and lifetime with different node failures

Tab. 4 Number of failure nodes and failure percentage

Failure rate	Number of failure nodes	Failure percentage/%
0	0	0
0.1	659	8.24
0.2	1 310	16.38
0.3	2 078	25.97

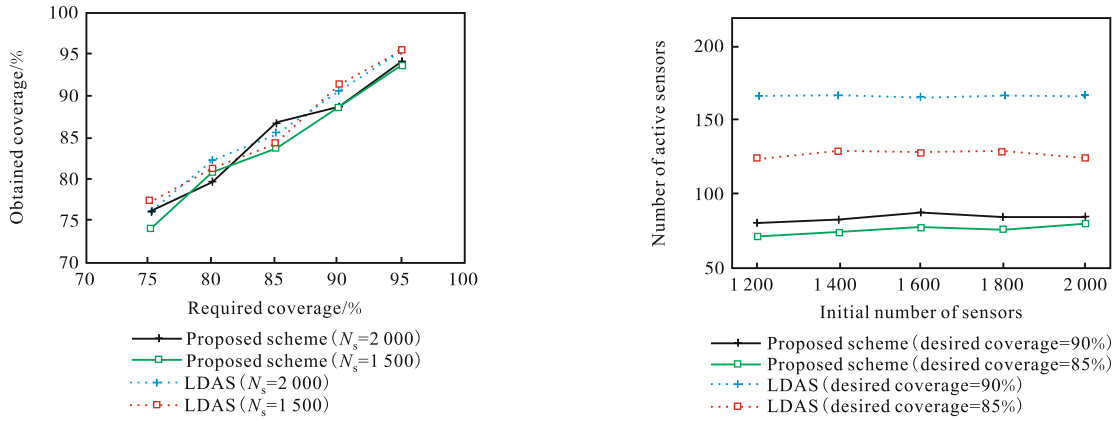
4.8 Comparison

In Fig. 10, we compare our node scheduling scheme with the existing node scheduling scheme LDAS in terms of coverage and the number of active nodes. Unlike our scheme, LDAS assumes that nodes need to acquire how many sensors are within their sensing range. Tab. 5 presents the simulation parameters.

Tab. 5 Simulation parameters

Parameter	Value
Two-dimensional area/(m×m)	150 × 150
Sensing range/m	10
Energy mode (active: ready: sleeping)	20: 4: 0.01
Lifetime of an individual sensor/s	500—600

Fig. 10 (a) demonstrates that both schemes can obtain reasonable matching between the desired coverage and obtained coverage. The proposed scheme, which does not require the knowledge about the coordinates of sensors, performs similarly to LDAS. Fig. 10 (b) provides the information of the number of active nodes after scheduled by different schemes in different desired coverages and numbers of nodes. The simulation result demonstrates that the number of active nodes using the proposed scheme is smaller than that using LDAS. The smaller the number of active nodes, the less network energy is consumed, and thus the lifetime of the network can be extended efficiently.



(a) Comparison of obtained coverage (b) Comparison of number of active sensors

Fig. 10 Comparison between LDAS and the proposed scheme

5 Conclusions

On the basis of the coverage analysis, we proposed a distributed node scheduling scheme to prolong the network lifetime while maintaining the desired sensing coverage, which does not require the knowledge about the coordinates of any sensor. Theoretical and simulation results demonstrate that our scheme can effectively extend the network lifetime and maintain the desired coverage without any geographic or neighbor information, and thus can reduce the cost of hardware and control overheads. Besides, the node scheduling scheme can handle uneven distribution and is robust to node failures. Compared with the neighbor-information-based scheduling scheme LDAS, the proposed scheme can achieve similar performance in coverage, but consumes less energy.

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