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A node scheduling scheme for energy conservation in large wireless sensor networks

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Summary

In wireless sensor networks that consist of a large number of low-power, short-lived, unreliable sensors, one of the main design challenges is to obtain long system lifetime without sacrificing system original performances (sensing coverage and sensing reliability). In this paper, we propose a node-scheduling scheme, which can reduce system overall energy consumption, therefore increasing system lifetime, by identifying redundant nodes in respect of sensing coverage and then assigning them an off-duty operation mode that has lower energy consumption than the normal on-duty one. Our scheme aims to completely preserve original sensing coverage theoretically. Practically, sensing coverage degradation caused by location error, packet loss and node failure is very limited, not more than 1% as shown by our experimental results. In addition, the experimental results illustrate that certain redundancy is still guaranteed after node-scheduling, which we believe can provide enough sensing reliability in many applications. We implement the proposed scheme in NS-2 as an extension of the LEACH protocol and compare its energy consumption with the original LEACH. Simulation results exhibit noticeably longer system lifetime after introducing our scheme than before. Copyright © 2003 John Wiley & Sons, Ltd.

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1. Introduction

Recently, the idea of wireless sensor networks has attracted a great deal of research attention because of wide-ranged potential applications that will be enabled by wireless sensor networks, such as battlefield surveillance, machine failure diagnosis, biological detection, home security, smart spaces, inventory tracking, and so on [1–4]. A wireless sensor network consists of tiny sensing devices, deployed in a region of interest. Each device has processing and wireless communication capabilities, which enable it to gather information from the environment and then to generate and deliver report messages to the remote base station (remote user). The base station aggregates and analyzes the report messages received and decides whether there is an unusual or concerned event occurrence in the deployed area.

Considering the limited capabilities and vulnerable nature of an individual sensor, a wireless sensor network has a large number of sensors deployed in high density (high up to 20 nodes/m^3 [5]). Thus, redundancy must be exploited to increase data accuracy and sensing reliability.

In wireless sensor networks, energy source provided for sensors is usually battery power, which has not yet reached the stage for sensors to operate for a long time without recharging. Moreover, since sensors are often intended to work in remote or hostile environments, such as a battlefield or desert, it is undesirable or impossible to recharge or replace the battery power of all the sensors. However, long system lifetime is expected by many monitoring applications. The system lifetime, which is measured by the time until all nodes have been drained out of their battery power or the network no longer provides an acceptable event detection ratio, directly affects network usefulness. Therefore, energy efficient design for extending system lifetime without sacrificing system original performances is an important challenge to the design of a large wireless sensor network.

In wireless sensor networks, all nodes share common sensing tasks, which implies that not all sensors are required to perform the sensing tasks during the whole system lifetime. Making some nodes sleep does not affect the overall system function as long as there are enough working nodes to assure it. Therefore, if we initially deploy a large number of sensors and schedule them to work alternatively, system lifetime can be prolonged correspondingly, that is, redundancy is exploited to increase system lifetime. In this work, we present a novel node-scheduling scheme, which is used to configure node work status and schedule the sensor on-duty time in large sensor networks. Our design was driven by the following requirements. First, since it is inconvenient or impossible to manually configure sensors after they have been deployed in hostile or remote working environment, self-configuration is mandated. Second, the design has to be fully distributed and localized, because a centralized algorithm needs significant overhead for global synchronization and is not scalable to large populated networks. Third, the algorithm should allow as many nodes as possible to be off-duty most of the time. At the same time, it should preserve the initial sensing coverage with minimal 'sensing hole' or 'blind points'. It is ideal if the working nodes can cover the same monitored area as the original one. Fourth, the scheduling scheme should be able to maintain certain sensing reliability, that is, certain redundancy is still needed.

In the proposed approach, each node in the network autonomously and periodically determines its work status (on-duty or off-duty) only using its own and its local neighbor information. To preserve sensing coverage, a node decides to be off-duty when it discovers that its neighbors can help it to monitor its whole working area. To avoid blind points, which may appear when two neighboring nodes expect each other's helping, a back-off scheme is introduced to let each node delay its decision with a random period of time. In this work, we evaluate the performance of our node-scheduling rule in terms of maintaining sensing coverage and sensing reliability. We investigate how unfavorable issues in practice affect these performances. Experimental results show that sensing coverage degradation caused by location error, packet loss and node failure is very limited, not more than 1%. We also implement the proposed scheme as an extension of the existing data gathering protocol, LEACH [6]. We compare its energy consumption with the original Low-Energy Adaptive Clustering Hierarchy (LEACH) and analyze the effectiveness of our algorithm in terms of energy saving. Our simulation results show a noticeable increase in the system lifetime after introducing our node-scheduling scheme.

The rest of this paper is organized as follows. Section 2 presents a review of the related work in the literature. In Section 3, we introduce the proposed scheme, which is divided into two parts: coverage-based off-duty eligibility rule and back-off based node-scheduling algorithm. In Section 4, we present experimental and simulation results as the performance evaluation of our scheme. Section 5 concludes the paper.

2. Related Work

Minimizing energy consumption and maximizing the system lifetime has been a major design goal for wireless sensor networks. In the last few years, researchers actively explored advanced power conservation approaches for wireless sensor networks. On the one hand, device manufacturers have been striving for low power consumption in their products. In [7,8], low-power transceiver architectures and low-power signal processing systems are discussed separately. In [9], an energy-scavenging technique, which enables self-powered nodes using energy extracted from the environment, is presented. In [10], a low-power data converter, signal processing, RF communication circuits are integrated into one chip. On the other hand, protocol designers are seeking energy efficient communication architectures, which involve all levels from the physical layer to the application layer [4]. For instance, in wireless sensor networks, network layer protocols take care of routing data from source nodes to the base station in an energy efficient way. Directed diffusion [11] and LEACH [10] are two of them. In directed diffusion, routes (called gradients) that link source nodes to sink nodes are formed when interest is disseminated throughout the network. When a source node has data of interest, it sends the data along the gradient paths back to the sink nodes. Energy is saved by in-routing data aggregation, caching and reinforcement-based adaptation to the empirically best path. In LEACH, clusters are formed by local coordination. Data from a non-clusterhead node must be sent to its local clusterhead node first, then to the base stations. The positions of clusterhead are rotated among all the nodes to evenly distribute the energy load in the network. LEACH conserves energy by in-routing data fusion as well. The Time Division Media Access (TDMA) scheme used in its data transmission phase enables non-clusterhead nodes to turn off radio outside their allocated transmission time, to further reduce energy dissipation. According to the categories in [4], our work can be classified into the energy management branch of application layer protocols. It is dedicated to scheduling nodes by using application knowledge and located above the network layer. It can be integrated with the existing energy efficient data communication protocols to save more energy.

In [12], a probing-based density control algorithm is proposed to schedule node in wireless sensor networks as well. In this protocol, a subset of nodes are selected out initially and are maintained in working mode until they run out of their energy or are destroyed. Other redundant nodes are allowed to fall asleep and are required to wake up occasionally to probe their local neighborhood. Sleeping nodes start working only if there is no working node within its probing range. In this algorithm, geometry knowledge is used to calculate the value of probing range as a function of redundancy. Thus, desired redundancy can be obtained by choosing the corresponding probing range. Compared with ours, this algorithm schedules nodes from the sensing coverage perspective as well. However, the guidelines under algorithm design are different. Our main purpose is to guarantee sensing coverage to the maximal extent, while theirs is to control redundancy as desired. Therefore, their algorithm does not intend to preserve the original sensing coverage as ours. Furthermore, the derivation of the relationship between probing range and redundancy is based on the implicit assumption that all the nodes have exactly the same sensing range. It is hard to get the equation, if nodes have different sensing ranges. In contrast, our algorithm has no such restriction.

Recently, the dominating-set-based routing problem has been intensively studied in the context of *ad hoc* networks. A dominating set is defined as a subset of the vertices of a graph if every vertex not in the subset is adjacent to at least one vertex in the subset [13]. The main advantage of connected dominating-set-based routing is to restrict routing and searching to a subgraph induced from the dominating set, therefore reducing the overall energy consumption. Wu and Li [13] proposed a simple and efficient distributed algorithm for the formation of connected dominating set, which marks a dominating node by determining if two of its neighbors are not directly connected. They also introduce two rules to optimize the size of dominating set based on node ID. In References [14,15], Wu *et al*. presents other rules for further decreasing the size of the dominating set based on node degree or balancing energy load based on energy level. In [16,17], the other two algorithms for dominating set formation are discussed, although the authors did not explicitly mention the concept of dominating set. In Reference [16], Chen *et al*. presented *Span*, a distributed, randomized algorithm in which nodes make local decisions on whether to sleep or stay awake as a coordinator and participate in the forwarding backbone topology. To preserve capacity, a node decides to serve as a coordinator if it discovers that two of its neighbors cannot communicate with each other directly or through an existing coordinator. In [17], an algorithm, called Geographical Adaptive Fidelity (GAF), was proposed, which uses geographic location information to divide the area into fixed square grids. Any nodes within a square can directly communicate with any nodes in the adjacent square. Therefore, within each grid, it needs only one node staying awake to forward packets. Although these algorithms are proposed for *ad hoc* networks, they are desirable and applicable in the domain of wireless sensor networks, because wireless sensor networks have communication redundancy as well. However, besides communication redundancy, wireless sensor networks have another kind of redundancy: sensing redundancy, which is not discussed in any of these algorithms. For sensors with independent communication unit and sensing unit, although removing any type of redundancies enables a lot of energy saving, combining them is expected to save more energy. For instance, one of possible combination approaches is that some redundant nodes in sensing interfaces are picked out first and then the redundancy in communication interfaces is removed from the remainders.

In Reference [18], Xu *et al*. proposed a scheme in which energy is conserved by letting nodes turn off their radio when they are not involved in data communication. Also, in this paper, node density is leveraged to increase the time of powering off radio. Unlike the algorithms mentioned in the preceding paragraph, nodes schedule themselves by using only their own application-level information or simple neighbor size, without considering global connectivity. Similarly, sensing redundancy was not addressed either.

Besides reducing the number of active nodes, there are other network topology control techniques, which also intend to increase power efficiency and extend network lifetime. References [19,20] discuss how such techniques produce a minimum-energy communication subnetwork by adjusting transmission power. The subnetwork is computed in a distributed manner at each node using local neighbor location information [11,19] or directional information [20]. Instead of controlling the transmission power level, the node-scheduling schemes power-off or power-down some redundant nodes in the network and therefore can achieve further energy conservation. Also, these algorithms provide energy saving solutions only from the communication perspective.

3. Node Self-Scheduling Scheme

We now describe our node self-scheduling scheme. We divide the scheme into two problems and describe them in Sections 3.1 and 3.2 separately. The first problem is the rule that each node should follow to determine its work status. The second is the time when nodes should make such a decision.

Before we describe the algorithm in detail, we state the assumptions of this work as follows:

1. Each node knows its own location, which can be obtained at a low cost from Global Positioning System (GPS) or some localization system [22,23], and presumably is already available because of the needs of wireless sensor network applications. Also, each node knows who its neighbors are and where they are located; this is obtained through a simple neighbor information exchange process, as described in Section 3.2.1.
2. Each node knows the size of its sensing area. In Section 3.1, we assume that all nodes are deployed on a 2-D plane and a node's sensing area is a circle centered at this node with known radius. The rule

described there is also applicable to a 3-D space. The sensing range of each node can be identical or different. The model based on identical sensing range is described in Section 3.1.1 and that for different sensing range is presented in Section 3.1.2.

3. All the nodes in the network are time-synchronized. The approaches for maintaining synchronized time energy efficiently have been discussed in [3]. We assume that this is already available.
4. After node-scheduling, some nodes are assigned off-duty state. Off-duty is a power-saving sleep mode, compared to normal on-duty mode. It may be implemented by powering off the sensing unit and communication unit, powering off the sensing unit, or just ignoring detected events without powering off any unit. Among the three methods, the first one consumes the least energy and the last one the most. Therefore, the first one is the most desirable from the energy saving perspective. However, which method is used in practice depends on the intelligence owned by sensors and the cost for sleeping and waking up the sensing unit and communication unit.

3.1. Coverage-based Off-duty Eligibility Rule

3.1.1. Sponsored coverage calculation–basic model

As discussed above, the main objective of this algorithm is to minimize the number of working nodes, as well as maintain the original sensing coverage. To achieve this goal, we calculate each node's sensing area and then compare it with that of its neighbors. If the sensing area of one node is fully embraced by the union set of its neighbors', that is, neighbors can cover the current node's sensing area, this node falls asleep without reducing the system overall sensing coverage. In this section, we will describe how a node determines that its neighbors can cover its sensing area given its own and their neighbors' location information.

We denote node i's sensing area as *S(i)* and the sensing range of each node is r. To facilitate the calculation, we only consider the neighbors whose distance from the current node is equal to or less than the sensing range r as shown in definition 1.

Definition 1: Neighbor. *The neighbor set of node i is defined as*

$$N(i) = \{n \in \aleph | d(i, j) \leq r, n \neq i\}$$

where $\aleph$ *is the node set in the deployed region, d(i, j) denotes the distance between node i and node j.*

Thus, for node i, the off-duty eligibility rule can be expressed as $\bigcup_{j \in N(i)} S(j) \supseteq S(i)$, that is, the union of its neighbors' sensing areas is a superset of node i's sensing area. The expression is equivalent to $\bigcup_{j \in N(i)} (S(j) \bigcap S(i)) \supseteq S(i)$. By observation, we know that the crescent-shaped intersection $S(j) \bigcap S(i)$ in Figure 1(a) includes a sector as illustrated in Figure 1(b). Although the area of the sector is smaller than that of the crescent, it is much easier to calculate the area of the sector rather than that of the crescent, because the area of a sector can be represented by its central angle accurately and uniting two sectors is equivalent to merging two central angles, as illustrated in Figure 1(d). Therefore, although node j can cover a crescent-shaped region within node i's sensing area (the shadow region of Figure 1(a)), node i will only 'admit' that node j can help it monitor a sector-shaped region (the shadow region of Figure 1(b)) if node i is sleeping.

To help the further description, we define this sector as a sponsored sector.

Definition 2: Sponsored sector. Suppose nodes i and j are neighbors, and both sensing areas *S(i)* and *S(j)* touch at point P_1 and P_2. As illustrated in Figure 1(b), the sector, bounded by radius N_iP_1, radius N_iP_2 and inner arc P_1P_2, is defined as the sponsored sector by node j to node i, and is denoted as $S_{j \to i}$. The central angle of the sector is denoted as $\theta_{j \to i}$ in Figure 1(b). The direction of node j

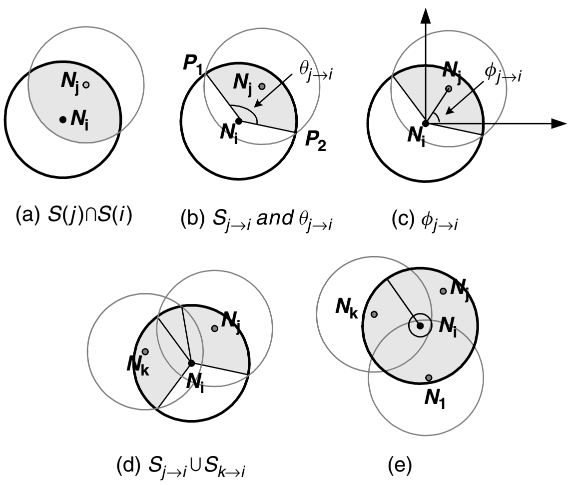


Fig. 1. Sponsored coverage calculation-basic model.

referred to node i is denoted as $\phi_{j\to i}$, as illustrated in Figure 1(c).

Lemma 1 If $\bigcup_{j\in N(i)} S_{j\to i} \supseteq S(i)$, then $\bigcup_{j\in N(i)} (S(i)\bigcap S(j)) \supseteq S(i)$.

Proof: $\because (S(i)\bigcap S(j)) \supseteq S_{j\to i} \therefore \bigcup_{j\in N(i)} (S(i)\bigcap S(j)) \supseteq \bigcup_{j\in N(i)} S_{j\to i} \therefore \bigcup_{j\in N(i)} (S(i)\bigcap S(j)) \supseteq S(i)$. □

Lemma 1 ensures that investigating whether the neighbors can cover the current node's sensing area is equivalent to checking whether the union of sponsored sectors (called sponsored coverage) contains the current node's sensing area, which in turn, is equivalent to calculating whether the union of central angles can cover the whole 360° as illustrated in Figure 1(e).

If the condition $\bigcup_{j\in N(i)} S_{j\to i} \supseteq S(i)$ is satisfied, the neighbors of node i are its off-duty sponsors.

From geometry calculation, the directional angle is given as $\phi_{j\to i} = arctg(y_j - y_i)/(x_j - x_i)$ and the central angle is given as $\theta_{j\to i} = 2\cdot \arccos(d(i,j)/(2\cdot r))$. Since $0 < d(i,j) \le r$, it is easy to know that the range of the central angle is $120^\circ \le \theta_{j\to i} < 180^\circ$. Obviously, a node must have at least three neighbors to cover its whole sensing area.

If an off-duty node takes the form of powering-off both its sensing unit and its communication unit, the network connectivity has to be considered as well during selecting off-duty nodes. When the transmission range is large compared with the sensing range, network connectivity can still be ensured, even after turning off many nodes simultaneously. However, when the transmission range is relatively small, the connectivity of the original network may be destroyed after node scheduling. To prevent it, each node can examine connectivity of its neighbors by using their position information. If two neighbors of a node cannot reach each other directly, the node should keep on-duty even if it satisfies the eligibility rule described above.

3.1.2. Sponsored coverage calculation–extended model

In the initial discussion, we assume that each node has the same sensing range r. In this part, we will extend the basic model and provide solution for the case that nodes have different sensing ranges.

Two reasons may cause different sensing ranges. First, nodes have different initial sensing ranges. Second, a node's sensing range changes during its lifetime. For instance, the power level may have an impact on the sensing range. We denote node i's and its neighbor node j's current sensing range as r_i and r_j respectively. There are many different cases of how a node's sensing area and its neighbors' are laid out. For instance, Figure 2 presents four of them.

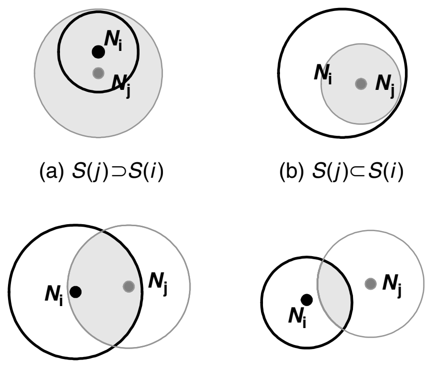
In order to still be able to use central angles to calculate sponsored coverage, we only consider the following two cases conservatively, as shown in Figure 3(a) and (b).

Case 1: node j's sensing area completely contains node i's sensing area, which happens whenever $r_i + d(i,j) \le r_j$ holds. In this case, node i can fall asleep without further calculation.

Case 2: The sensing areas of both nodes touch at two points, and the intersection area includes a sector centralized at node i. This case happens whenever both $d(i,j) \le r_j$ and $r_i - r_j \le d(i,j)$ are true. In this case, the central angle is $\theta_{j\to i} = 2\cdot\theta = 2\cdot \arccos((d(i,j)^2 + r_i^2 - r_j^2)/(2\cdot r_i\cdot d(i,j)))$.

In summary, when nodes have different sensing ranges, a node's neighbor set definition is modified as

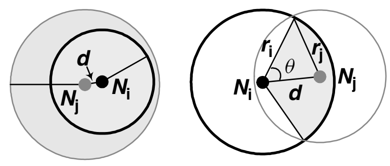
$$N(i) = \{n \in \aleph \mid (d(i,j) \le r_j \wedge r_i - r_j \le d(i,j)) \vee (r_i + d(i,j) \le r_j), n \ne i\}$$



(a) $S(j)\supset S(i)$ (b) $S(j)\subset S(i)$

(c) $(S(j)\cap S(i))\supseteq S_{j\to i}$ (d) $S_{j\to i}\not\subset(S(j)\cap S(i))$

Fig. 2. Layout of neighboring nodes with different sensing ranges.



(a) $S(j)\supset S(i)$ (b) $(S(j)\cap S(i))\supseteq S_{j\to i}$

Fig. 3. Considered cases in extended model.

Obviously, the basic model described previously is a special case of this extension when $r_i = r_j = r$.

3.2. Node-scheduling algorithm based on eligibility rule

In this section, we describe the node-scheduling algorithm based on the eligibility rule presented in Section 3.1. In our algorithm, the operation is divided into duty cycles. Each duty cycle begins with a self-scheduling phase, followed by a working phase. In the self-scheduling phase, nodes investigate the eligibility rule described in the previous section and determine their operation mode (off-duty and on-duty). Eligible nodes do not work in the duty cycle and may turn off its sensing unit, sometimes even the communication unit to save energy. Non-eligible nodes perform sensing tasks during the working phase and are responsible for collecting and delivering data to the sink node. To minimize the energy consumed in the self-scheduling phase, the working phase should be long compared to the self-scheduling phase. How on-duty nodes collect and deliver data to the sink node is the issue of the data gathering protocols and is out of the scope of this paper.

Each self-scheduling phase consists of two steps. First, each node advertises its position and listens to advertisement messages from other nodes to obtain neighboring nodes' position information. Second, each node decides whether it is off-duty or not by calculating the sponsored coverage by its neighbors and comparing it with its own sensing area. The details of these two steps are introduced as follows.

3.2.1. Neighbor information obtaining step

To obtain neighbor node information, a straightforward, simple approach is that each node broadcasts a Position Advertisement Message (PAM), which contains its ID and its current location, at the beginning of each duty cycle. Each neighboring node adds an entry into its neighbor list after receiving a PAM. If nodes have different sensing ranges, PAM should also include the current sensing range of the sender as well. To reduce the energy consumption in this step, some technologies can be used if they are available. For instance, because only neighbors within a node's sensing range are considered in the basic model of the eligibility rule, each node transmits a PAM with the minimum power as long as it reaches its sensing range. Thus only nodes within the sender's sensing range can receive its PAM.

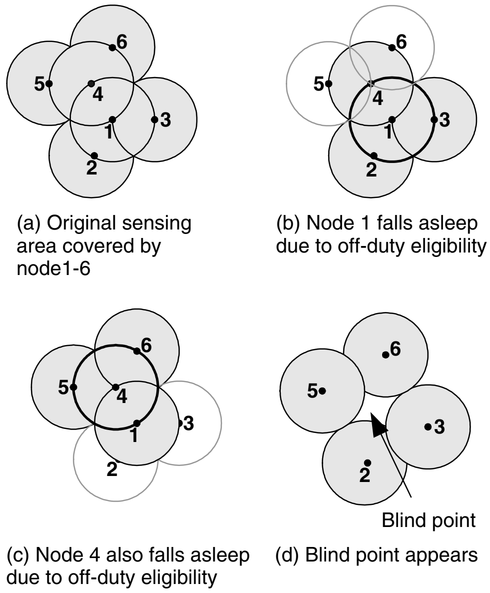


Fig. 4. Blind point due to simultaneous removal.

3.2.2. Back-off based self-scheduling step

After finishing the collection of neighbor information, each node evaluates its eligibility for off-duty by calculating the sponsored coverage, as described in the previous section. However, if all nodes make decisions simultaneously, blind points may appear, as illustrated in Figure 4. Node 1 finds its sensing areas can be covered by nodes 2, 3 and 4. According to the off-duty eligibility rule, node 1 falls asleep. While at the same time, node 4 finds its sensing area can be covered by nodes 1, 5 and 6. Believing node 1 is still awake, node 4 sleeps as well. In the result, a blind point appears after both node 1 and node 4 become off-duty, as shown in Figure 4(d). We resolve this problem by introducing a back-off scheme. We let each node delay its determination for a random back-off time T_d. If a node is eligible for off-duty, it broadcasts a *Status Advertisement Message* (SAM) to notify its neighbors the result. Initially, all the nodes sending PAM messages are supposed to have a default on-duty status. If a node receives a SAM message, it will mark the sender as an off-duty node in its neighbor list. The nodes, which have a longer back-off delay, will not consider those neighboring nodes that have been marked as off-duty before. Thus, as long as node 1 and node 4 select different random numbers, the blind point shown in Figure 4(d) can be avoided. Assuming W is the size of random back-off time choices, the probability of node 1 and node 4 selecting the same random number is *1/W*. Although a large W can reduce the probability to a sufficient small value, there is still a chance that node 1 and node 4 may select the same random number. To avoid a blind point further, we let each off-duty eligible node wait for a short period time T_w after sending the SAM out, instead of changing its status immediately. This ready-to-off period should be enough for this node to receive a SAM sent from its neighbor, or vice versa. If a SAM is received by a node during its ready-to-off period, the node will reinvestigate its off-duty eligibility. If the eligibility doesn't hold any more, the node returns its status from ready-to-off to on-duty immediately. Otherwise, the node sets its work status as off-duty after time T_w. The nodes, which have decided to serve as on-duty ones, do not reevaluate their off-duty eligibility once the decision has been made. For instance, in Figure 4, node 1 and node 4 select the same back-off time. Node 1 finds it is eligible for off-duty status, so it broadcasts a SAM to its neighbors. The same thing is done by node 4. Thus both nodes 1 and 4 are ready to be off-duty and wait for the expiration of T_w. During this time, the SAM message sent by node 1 is received by node 4. Node 4 finds that it cannot fall asleep with node 1's help. So node 4 sets its status as on-duty. The same decision is made by node 1 during its ready-to-off period. Eventually, both of them have on-duty status. From the minimal off-duty node number perspective, this result is not perfect, since either node 1 or node 4 (not both of them) falling asleep will not degrade the sensing area illustrated in Figure 4(a). However, to avoid the 'process loop' and to reduce the traffic, we do not let a node send a SAM to notify its neighbors when its status changes from ready-to-off to on-duty. The status transition graph of this step is presented in Figure 5. The flowchart of the whole self-scheduling phase is illustrated in Figure 6.

Besides the random back-off delay described above, network topology or energy factor can be considered in the derivation of the back-off delay. In nonuniform network topologies, nodes have different neighbor numbers. Let $D(i)$ be the neighbor number of node i. The nodes with higher $D(i)$ have higher probability to become off-duty. However, if they make their off-duty determination early, their neighbors, which evaluate their eligibilities later, may have less chance to be off-duty. Therefore, we can let nodes with higher $D(i)$ have a longer delay, thus there may be more off-duty nodes in total. Our experimental results show that setting delay in the ascending order of $D(i)$ can obtain more off-duty nodes than using random delay.

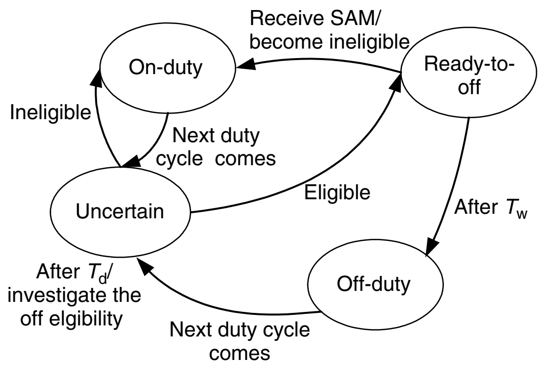


Fig. 5. FSM for node self-scheduling step.

Another consideration is that of unequal energy left at each node. The on-duty nodes consume more energy than off-duty ones. To balance energy load, the nodes with less energy left should be more reluctant for working and therefore should have a shorter delay (nodes with a longer delay have less opportunity to be eligible for off-duty). Let $E(i)$ denote the amount of energy already consumed at a node i and $E_m(i)$ be the initial energy at this node, a simple linear delay function, which reflects this factor is

$$\text{delay} = \left(1 - \frac{E(i)}{E_m(i)}\right) \times W \qquad (1)$$

Both network topology and energy factor can be combined to achieve more off-duty nodes and energy balance.

$$\text{delay} = \left(\alpha \times \left(\frac{\min(D(i), \overline{D})}{\overline{D}}\right) + \beta \times \left(1 - \frac{E(i)}{E_m(i)}\right) + R(i)\right) \times W \qquad (2)$$

where, $\overline{D}$ is the rough estimation of average node degree. Given a deployment area $\mathcal{R}$, the number of deployed nodes as $|\aleph|$ and sensing range r, $\overline{D}$ can be pre-calculated as $\frac{|\aleph| \cdot \pi \cdot r^2}{\mathcal{R}}$ $\cdot$ W is the size of the back-off window. $R(i)$ is a random factor within the interval $[0, 1 - \alpha - \beta]$, α and β are tunable weights.

A similar back-off mechanism is used in *Span* [16]. A distinct difference between theirs and ours is that they signal the nodes that are on-duty (coordinators), other than the nodes that will fall asleep as in ours. We compared these two signaling approaches in the context of our node-scheduling scheme and found that signaling off-duty nodes is more efficient in terms of off-duty node number than the opposite approach, as shown in Table I.

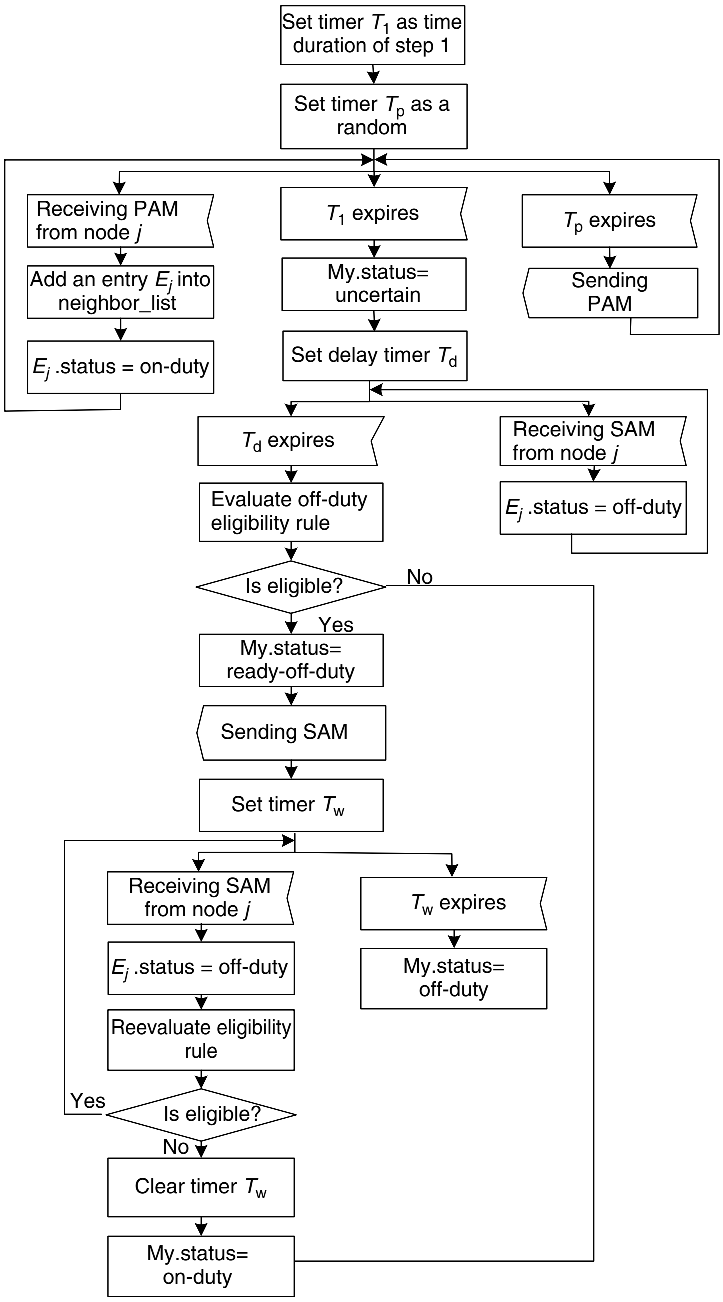


Fig. 6. Flowchart for self-scheduling phase.

Table I. Comparison of two signaling approaches ($\mathcal{R} = 50$ m $\times$ 50 m, $r = 10$ m).

Deployed node number	100	150	200	250	300	350	400
	Off-duty node number						
Signaling on-duty nodes	29	62	101	140	184	226	296
Signaling off-duty nodes	50	96	143	190	237	285	334

4. Performance Evaluation and Simulation

In this section, we present some experimental and simulation results as performance evaluation of our scheme. We divide the evaluation into two parts. The first is to evaluate the coverage-based off-duty eligibility rule in terms of maintaining system original performances. The second is to study its efficiency in terms of energy savings.

4.1. Performance evaluation of the eligibility rule

This subsection is to evaluate the performance of our coverage-based off-duty eligibility rule in its capabilities of controlling on-duty node number, remaining sensing reliability and preserving sensing coverage. We first evaluate these performance metrics in an idealized environment, that is, without location error, packet loss and node failure. And then, we investigate the influence of these practical issues respectively.

We deploy 100 nodes in a square space (50m by 50m). Nodes' x- and y-coordinates are set randomly. Each node has a sensing range of 10 m and knows who are its neighbors and where the neighbors are located. We let each node decide its work status in a random sequence. The decision of each node is visible to all the other nodes. The nodes, which make decisions later, cannot 'see' the nodes that have been off-duty before. After all nodes have made decisions, the number of off-duty nodes is counted and the current sensing coverage by on-duty nodes is compared with the original one when all nodes are active. To calculate sensing coverage, we divide the space into 1 m $\times$ 1 m unit cells. We assume an event occurs in each cell, with the event source located at the center of the cell. We investigate how many original nodes and how many on-duty nodes can detect every event. If an event cannot be detected by any on-duty node, but is within the range of the original sensing coverage, we call the event source cell a 'blind point'. The occurrence of blind points means that the corresponding off-duty eligibility rule cannot preserve the original sensing coverage. We also compute the sensing degree before and after node-scheduling. Sensing degree is defined as the average number of nodes simultaneously detecting and reporting a single event. The value of sensing degree is the indicator of sensing reliability. We investigate the change of on-duty node number, sensing coverage and sensing degree as a function of node density. For each node density, we generate 100 random network topologies and take the average values as the final results.

4.1.1. On-duty node number versus node density

We change node density by varying the sensing range from 6 to 13 and the deployed node number from 100 to 300 in the same 50 m $\times$ 50 m deployed area. Figure 7 shows a 3-D surface plot of the off-duty node number in different sensing range and deployed node number. From it, we can see that increasing the number of the original deployed nodes and increasing the sensing range will result in more nodes being off-duty, which is consistent with our expectation.

However, on-duty node number does not remain constant over different deployed node number when the sensing range and the deployed area are fixed. Instead, it increases as the deployed node number increases as illustrated in Figure 8. This is due to

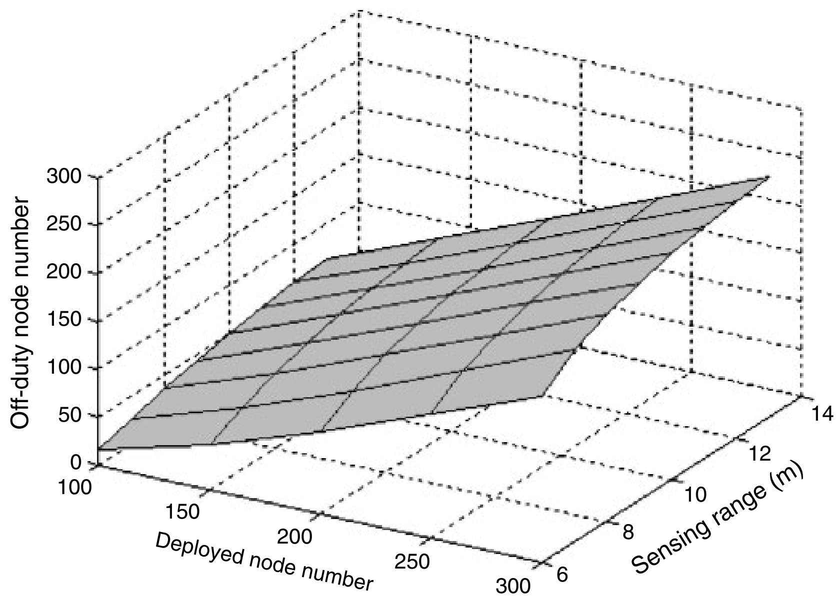


Fig. 7. Off-duty node number versus node density.

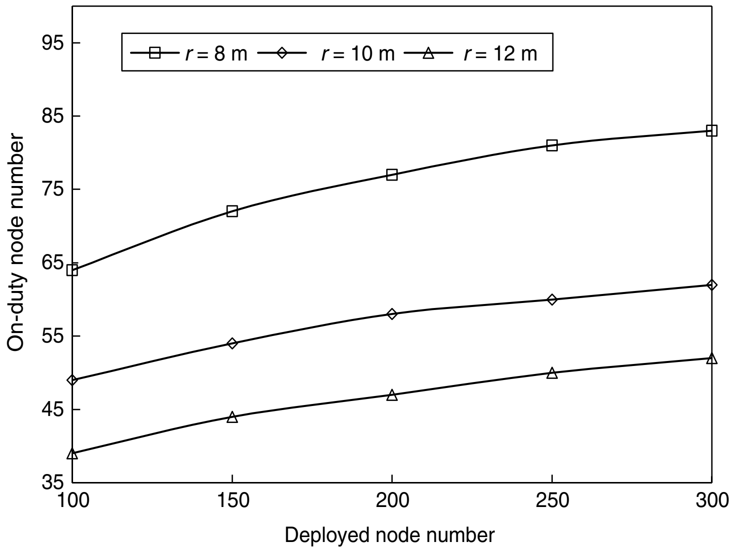


Fig. 8. On-duty node number versus deployed node number ($\mathcal{R} = 50$ m $\times$ 50 m).

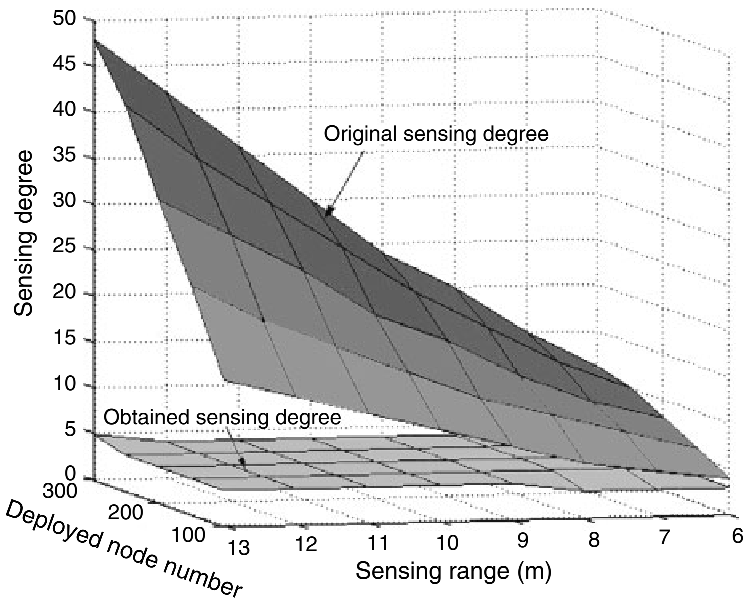


Fig. 9. Sensing degree reduction versus node density.

the increase in edge nodes (located at the boundary of the deployed area). According to the off-duty eligibility rule, edge nodes have no chance to be off-duty because all the other nodes are located on one side of them. Intuitively, increasing edge nodes will cause the increase in the on-duty node number. However, experimental result shows that our coverage-based off-duty eligibility rule still effectively limits the on-duty node number. When the deployed node number is changed from 100 to 300, the number of on-duty nodes just increases about 30%.

4.1.2. Sensing degree versus node density

We also investigate the change of obtained sensing degree over node density. As shown in Figure 9, although the range of the initial sensing degree is varied from 3 to 48, the obtained sensing degree is stable at 3 or 4 in almost all the test cases. Therefore,

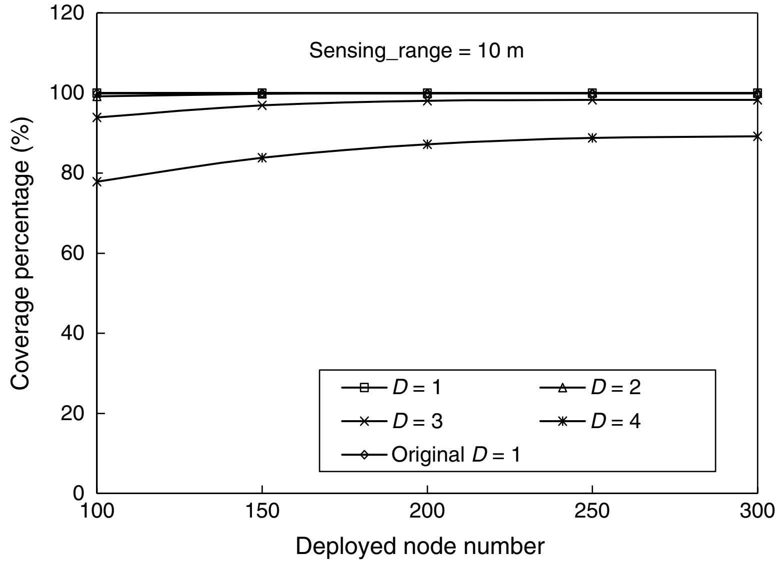


Fig. 10. Coverage versus deployed node number ($\mathcal{R} = 50$ m $\times$ 50 m, $r = 10$ m).

the coverage-based off-duty eligibility rule effectively controls the network redundancy, and meanwhile remains some sensing reliability.

4.1.3. Sensing coverage versus node density

Figure 10 presents the same effectiveness as in Figure 9 but from the different view: the percentage of the deployed area that can be monitored by at least D on-duty nodes. In addition, it implies the capability of the rule in preserving the original sensing coverage. We still divide the space into 1 m $\times$ 1 m unit cells as mentioned in Section 4.1.1. An event occurs in each cell, with the event source located at the center of the cell. We investigate the ratio of the cell number reached by at least D on-duty nodes to the total number of cells when sensing range is 10 m. As illustrated in this figure, most of the area, above 93%, can be covered by at least three on-duty nodes. Almost 100% cells can be reached by at least one on-duty node; and about 99% cells can be monitored by at least two on-duty nodes.

Furthermore, from the figure, we can see that increasing the deployed node number leads to more coverage ($D = 1$). This is because less sensing holes exist in the original network. Furthermore, the two curves ($D = 1$, original $D = 1$) are exactly the same in the figure, which implies that the coverage-based off-duty eligibility rule completely preserves the original sensing coverage in the idealized environment. We vary the value of sensing range and observe the same behavior.

4.1.4. Sensitivity to location error

The results presented in Section 4.1.3 are relatively ideal, because in the real application, location errors can be caused by either imprecise measurement from GPS or localization system.

To investigate the sensitivity of our scheme to location error, we artificially introduce location errors at each node. We modeled the error by randomly recoding the location of each node in the range $[x - e, x + e]$ and $[y - e, y + e]$. Simulation results show that our scheme is not sensitive to location errors. For example, Figure 11 plots the sensing coverage changes (original $D = 1$ and $D = 1$) when e is set as 5 m or 10 m. When e is 5 m, the maximal sensing coverage reduction is less than 0.051% in this figure. If we introduce a randomized error $[-10\,\text{m}, +10\,\text{m}]$ in each node's x- and y- coordinates, the simulation results show only 0.16% sensing coverage reduction. The reason for such insensitivity is that there is still enough redundancy after performing the node scheduling. Although inaccurate position information 'shifts' a single node' sensing area in the calculation, the overall sensing coverage will not be affected too much in that the 'empty area', which had expected to be covered by this node, can be filled up by 'shifting' of other on-duty nodes. Another observation in Figure 11 is that the reduction of the sensing coverage decreases as the number of deployed nodes increases. This is because there are more on-duty nodes when more nodes are deployed initially.

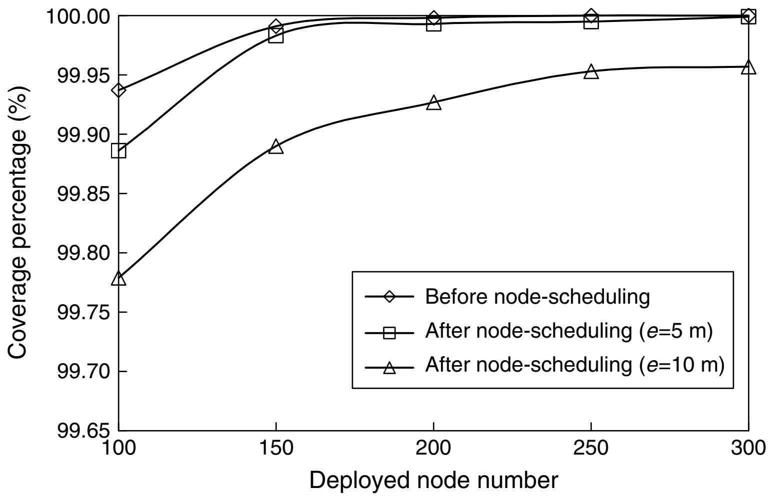


Fig. 11. Result sensitivity to location error ($\mathcal{R} = 50$ m $\times$ 50 m, $r = 10$ m).

4.1.5. Sensitivity to packet loss

In wireless transmission, packets can be lost because of collision, interference, rain or other reasons. To investigate the sensitivity of our scheme to packet loss, we introduce a packet loss rate in each message transmission. Table II lists the performance change corresponding to different packet loss rates. From the table, we can see that the sensing coverage does not decrease dramatically as the packet loss rate increases. When the packet loss rate is 30%, the sensing coverage reduction is 0.31%. Furthermore, the packet loss does not affect the off-duty node number and obtained sensing degree too much. Such insensitivity to packet loss is the combination effect of two counterforces. On one hand, loss of PAM messages may make some nodes invisible to their neighbors. With incomplete neighbor list, some nodes originally eligible for off-duty may make on-duty decisions. On the other hand, loss of SAM messages isolates some off-duty nodes from their neighbors and causes them to make wrong off-duty decisions.

Table II. Result sensitivity to packet loss rate ($|\aleph| = 200$ nodes, $\mathcal{R} = 50$ m $\times$ 50 m, $r = 10$ m).

Packet loss rate(%)	Original coverage percentage (original $D = 1$)	Coverage percentage ($D = 1$)	Off-duty node rate(%)	Obtained sensing degree
0	100	100.00	71.5	4
5	100	100.00	71.5	4
10	100	99.99	71.5	4
15	100	99.97	71.5	4
20	100	99.86	71.0	4
25	100	99.74	70.5	4
30	100	99.69	69.0	4

4.1.6. Sensitivity to node failures

In wireless sensor networks, since sensors are often intended to work in remote or hostile environment, sensor nodes failures are inevitable. Our node-scheduling scheme has a certain inherent immunity to node failures, because at the beginning of each duty cycle, nodes need to exchange and update their position information. Dead nodes will not send PAM messages to their neighbors any more and therefore will be eventually removed from the neighbor lists of their neighbors. Sensing coverage reduction caused by node failures in the working phase of one duty cycle will be stopped in the next duty cycle. Therefore the shorter the duty cycle is, the shorter the impact of node failures to the sensing coverage lasts and the more robust the scheme is against node failures. In our experiments, we investigate how node failures, which occur in the working phase of a duty cycle, affect the sensing coverage in the current cycle. To do this, we set all the nodes as alive before node scheduling is executed. After off-duty nodes have been selected, we randomly selected some nodes from all the deployed nodes and marked them as 'dead'. The ratio of node failure is changed from 0% to 30% with an increment of 1%. Then, we calculated the sensing coverage covered by all the alive nodes and by all the alive on-duty nodes respectively and compared their difference. We found that although the degradation increases as the node failure rate increases, it is still within an acceptable limit. For

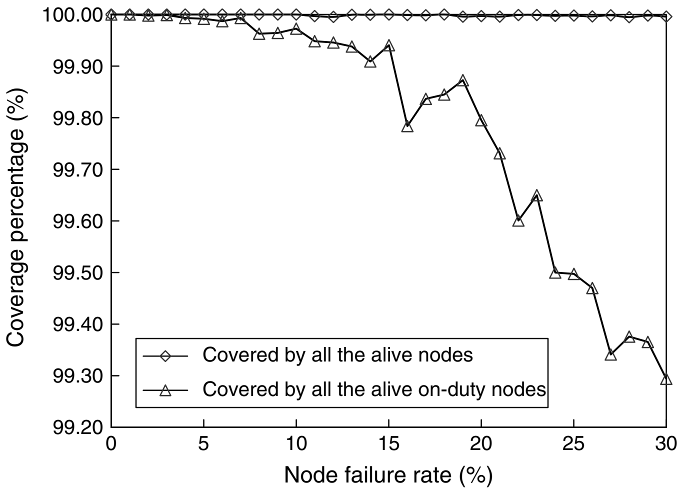


Fig. 12. Result sensitivity to node failure ($|\aleph| = 200$ nodes, $\mathcal{R} = 50$ m $\times$ 50 m, $r = 10$ m).

instance, in the networks with 200 deployed nodes and 10 m sensing range, when the node failure rate is 30%, the average degradation is only 0.7% as shown in Figure 12 and the sensing degree drops a little, from 4 (when node failure rate is 0%) to 3.

4.2. Simulation Results

In this section, we describe the implementation of our proposed node-scheduling scheme as an extension of LEACH [6]. Our main purpose is to analyze the energy efficiency of our proposed scheme by comparing the energy consumption with and without the extension.

4.2.1. Simulation environment

We implement the proposed scheme as an extension of an existing data gathering protocol, LEACH [6]. Although the proposed scheme can be combined with any other data gathering protocols, we select LEACH because it has a similar timeline as our proposed scheme.

LEACH (Low-Energy Adaptive Clustering Hierarchy) is a clustering-based communication protocol proposed by the MIT LEACH project. In LEACH, nodes are organized into local clusters, with one node acting as the local base station or clusterhead. All the other nodes must transmit their data to the clusterheads, while the clusterhead nodes must receive data from all the cluster members, perform signal processing functions on the data (e.g. data aggregation) and then, transmit data to the remote base station. Being a clusterhead is much more energy-intensive than being a non-clusterhead node. In order to evenly distribute the energy load associated with a clusterhead and to avoid draining the battery of a single sensor, clusterhead position is rotated randomly among all the nodes. The medium access protocol in LEACH is also chosen to reduce energy dissipation in non-clusterhead nodes. Since a clusterhead node knows all the cluster members, it can act as a local control center and create a TDMA schedule that allocates timeslots for each cluster member. This allows the nodes to remain in the sleep state as long as possible. In addition, using a TDMA schedule for data transfer prevents intracluster collisions.

In LEACH, the operation is also divided into rounds, which are composed of a cluster set-up phase in which the clusters are formed, and a steady-state phase in which sensors collect data from the environment and transfer data to the clusterheads and then to the base station.

To extend LEACH with our node-scheduling scheme, a straightforward way is to insert the self-scheduling phase of our scheme before the LEACH cluster set-up phase. At the beginning of each round, all the nodes self-determine whether to serve as on-duty nodes or not. Off-duty nodes will not participate in the cluster set-up and steady-state phase that follows. The advantage of such a timeline is that our node-scheduling scheme can be embedded into the LEACH seamlessly without any modification of its original workflow. The timeline of the implementation is illustrated in Figure 13.

The simulation is carried out in a network with 100 nodes, each with a sensing range of 10 m. Nodes are placed randomly in a rectangular region, the area of

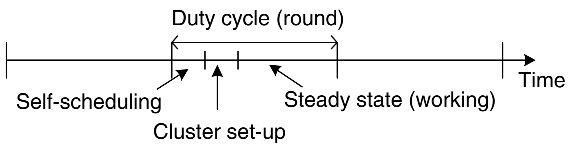


Fig. 13. Timeline of LEACH with extension.

which is 50 m × 50 m. The remote base station (or sink node) is located at the low left corner, that is, origin point (0,0). The initial energy of all nodes is 2J. Each sensor sends a 2000-bit report message to the base station with a 0.5 s time interval. The time duration of each duty cycle is 10 s.

We use the same energy parameters and radio model as discussed in [24] and used in [25], which indicates that the transmission energy consumption is

$$E_{Tx}(k,d) = \begin{cases} E_{\text{elec}} \times k + \varepsilon_{\text{friss-amp}} \times k \times d^2 & : d < d_{\text{crossover}} \\ E_{\text{elec}} \times k + \varepsilon_{\text{two-ray-amp}} \times k \times d^4 & : d \geq d_{\text{crossover}} \end{cases}$$

and the reception energy consumption is $E_{Rx} = E_{\text{elec}} \times k$, where E_{elec} is the energy consumed for the radio electronics, $\varepsilon_{\text{friss-amp}}$ and $\varepsilon_{\text{two-ray-amp}}$ for a power amplifier. Radio parameters are set as $E_{\text{elec}} =$ 50 nJ/bit, $\varepsilon_{\text{friss-amp}} = 10$ pJ/bit/m^2, $\varepsilon_{\text{two-ray-amp}} =$ 0.0013 pJ/bit/m^4, $d_{\text{crossover}} = 87$ m. We only consider the data aggregation, while ignoring other processing energy consumption. The energy for performing data aggregation is 5 nJ/bit/signal. Off-duty nodes do not generate, send and receive any message. The energy consumed by them is negligible.

4.2.2. Energy consumption

In terms of energy conservation, we cannot only evaluate the energy saving alone in the working phase, because node-scheduling itself also consumes energy in transmission of PAM and SAM messages as well as computation, which should not be ignored. If the cost of the self-scheduling phase dominates the overall energy consumption in each duty cycle, it is better not to turn off nodes. In the original LEACH protocol, energy is mainly consumed in two parts: data transmission for clustering forming (E_c) and data gathering (E_g). While in the extended LEACH, extra energy is needed in node-scheduling phase, which is denoted as E_s. Assuming the number of data gatherings in each round is N_g, then the energy dissipation of each round in the original LEACH is $E = E_c + N_g \times E_g$, while the energy dissipation per round in the extend LEACH is $E' = E_s' + E_c' + N_g \times E_g'$. As long as $E' < E$, energy savings can be achieved by node-scheduling. In fact, the energy coefficients in E and E' are affected by many factors: the size of sensing range, the length of report message, the number of data gatherings in each duty cycle, and the power consumption model, and so on. Therefore, the potential for energy saving is the combination effect of multiple factors.

Figure 14 illustrates the energy dissipation curve per node in the original LEACH and the extended LEACH in random network topology when $N_g = 20$. The energy dissipation in the extended LEACH is slower than the original one.

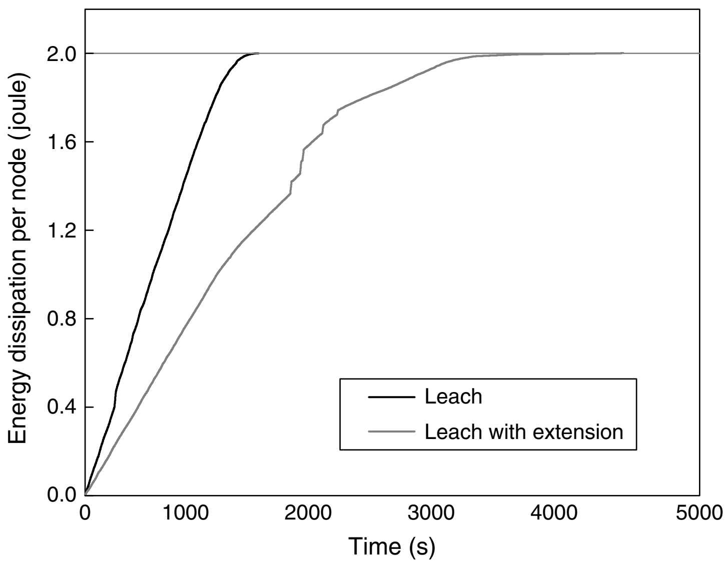


Fig. 14. Energy dissipation curve per node ($|\aleph| = 100$, $\mathcal{R} = 50$ m × 50 m, $r = 10$ m, $N_g = 20$).

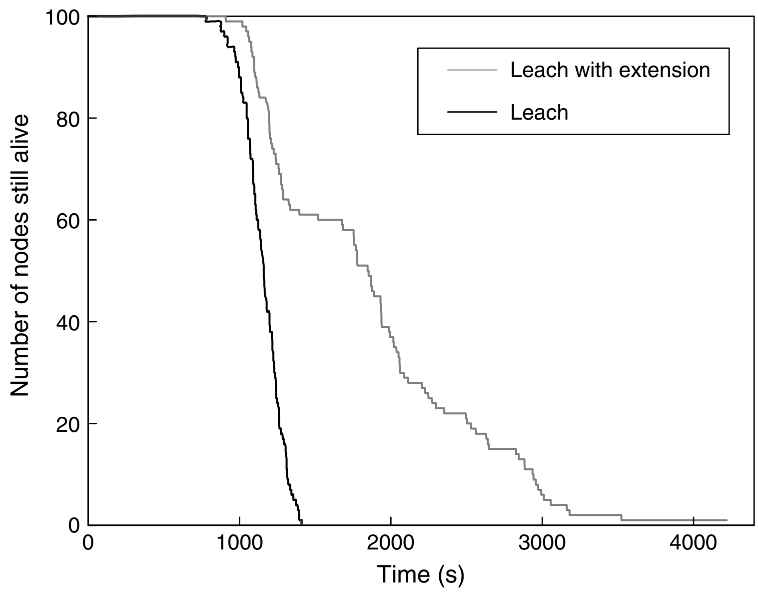


Fig. 15. Number of nodes alive over time ($|\aleph| = 100$, $\mathcal{R} = 50$ m $\times$ 50 m, $r = 10$ m, $N_g = 20$).

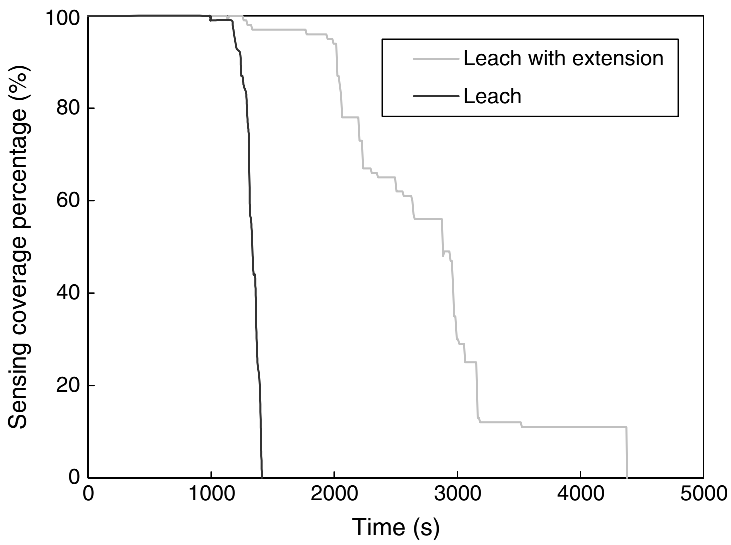


Fig. 16. Sensing coverage over time ($|\aleph| = 100$, $\mathcal{R} = 50$ m $\times$ 50 m, $r = 10$ m, $N_g = 20$).

Figures 15 and 16 show an increase of the system lifetime in the same simulation setting. Here, we use two metrics to evaluate the system lifetime: the total number of nodes alive over time and the system sensing coverage over time (the ratio of the area monitored by on-duty nodes to the deployed region). As illustrated in Figures 15 and 16, although the extended LEACH does not outperform the original one in terms of first node dead time, the number of nodes alive and the system sensing coverage drop more quickly in the original LEACH than in the extended one. In the result, it takes approximately 4378 s for the last node to die in the extended LEACH, while 1412 s in the original LEACH. And it takes approximately 2055 s for the sensing coverage to drop 20% (reach 80%) in the extended LEACH, while 1285 s in the original one.

Furthermore, we also change the number of data gatherings in each duty cycle from 4 to 20 with the increment of 4, and compare the system lifetime

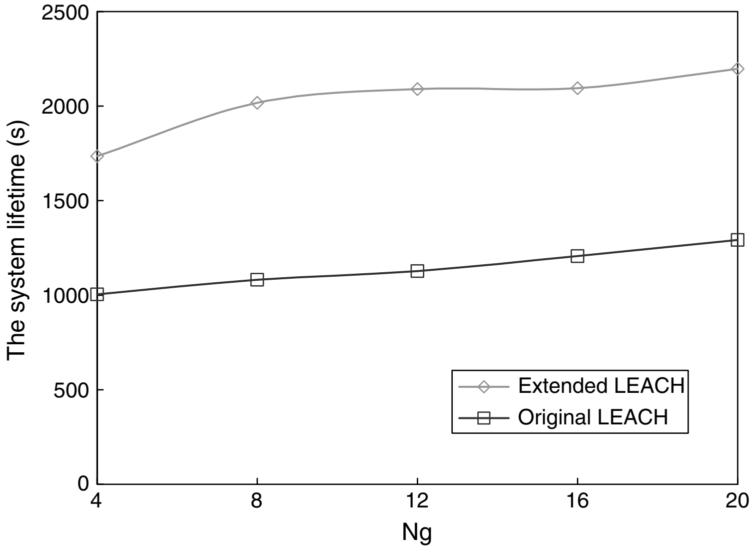


Fig. 17. System lifetime increase versus $N_g(|\aleph| = 100, \mathcal{R} = 50\ \text{m} \times 50\ \text{m}, r = 10\ \text{m})$.

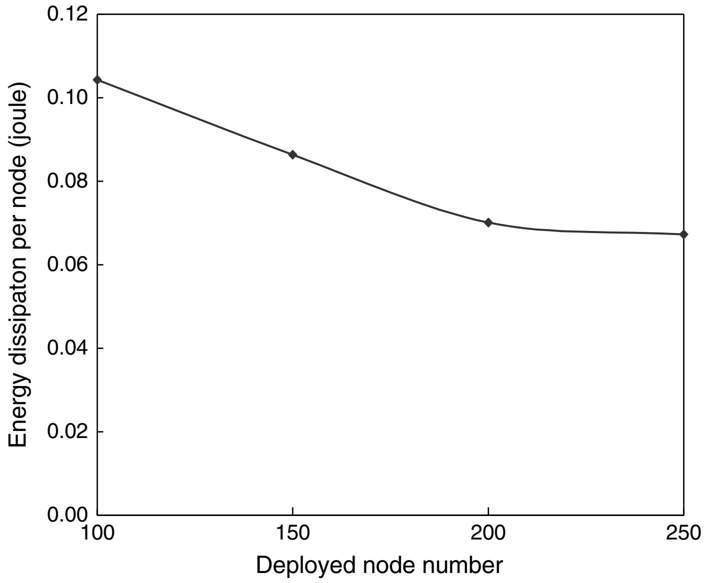


Fig. 18. Energy dissipation per node versus node density ($\mathcal{R} = 50\ \text{m} \times 50\ \text{m}, r = 10\ \text{m}$).

(only when system coverage drops below 80%) of the original and extended LEACH. Figure 17 shows that the system lifetime with extended LEACH is always longer than, and is about 1.7 times of, the original one.

4.2.3. Energy saving versus node density

In this section, we investigate the relation between node density and energy saving. Figure 18 shows how the average energy consumption per node during the first 100-s simulation time changes over different deployed node number. From it, we find that decreasing of energy consumption per node falls too slowly compared with the increasing of the deployed node number. This result may seem counterintuitive because although the on-duty node number changes as the deployed node number increases when sensing range and deployed region are fixed, it does not lead to a dramatic increase, as illustrated in Figure 8. To understand the reason, we make a simple mathematical analysis. We define the energy saving factor as

$$\alpha = \frac{\left(\frac{E_{\text{on}}}{N_{\text{on}}}\right) - \left(\frac{E_{\text{all}}'}{N_{\text{all}}}\right)}{\left(\frac{E_{\text{on}}}{N_{\text{on}}}\right)} \tag{3}$$

where, E_{all}' is denoted as the overall energy consumption per duty cycle if we have initially N_{all} nodes in the extended LEACH, E_{on} as the overall energy consumption per duty cycle if N_{on} nodes are deployed in the original LEACH. We define the redundancy factor η_r, as the ratio of the total number of initially deployed nodes (N_{all}) to the number of on-duty nodes (N_{on}) after performing node scheduling. Ideally, E_{all} equals to E_{on} if energy consumption in node scheduling is negligible. Thus, we have that $\alpha_{\text{ideal}} = 1 - \frac{1}{\eta_r}$. In fact, however, E_{all}' equals to $E_{\text{on}} + E'_s$, with E'_s denoted as the system energy consumption in node-scheduling. Therefore, the energy saving factor is expressed as

$$\alpha = 1 - \frac{1}{\eta_r} - \frac{E_s'}{\eta_r E_{\text{on}}} \tag{4}$$

which is smaller than α_{ideal} by $(E_s')/(\eta_r E_{\text{on}})$. When the ratio of energy consumption for node scheduling to that for clustering forming and data gathering decreases, the difference between α and α_{ideal} decreases. To verify this point, we increase the size of report message from 2000 bits to 8000 bits, that is, increasing E_{on} correspondingly and keeping the same E_s'. Figure 19 shows that increasing the size of the report message leads to decreasing of the difference between α and α_{ideal}.

In addition, we know that the main energy dissipation in E's is from transmission and reception of PAM, compared with other consumers. Each node transmits once a PAM message and receives approximately n PAM messages in each duty cycle, where n is the average neighbor number of each node. Therefore

$$\begin{aligned}\alpha &= 1 - \frac{1}{\eta_r} - \frac{N_{\text{on}} E_s}{N_{\text{all}} E_{\text{on}}} \approx 1 - \frac{1}{\eta_r} - \frac{N_{\text{on}}(E_{Tx} + nE_{Rx})}{E_{\text{on}}} \\ &= 1 - \frac{1}{\eta_r} - \frac{N_{\text{on}} E_{Tx}}{E_{\text{on}}} - \frac{nE_{Rx} N_{\text{on}}}{E_{\text{on}}}\end{aligned} \tag{5}$$

where, E_{Tx} is the energy consumed for transmitting a PAM message, E_{Rx} is the energy for receiving a PAM message. Equation (5) tells us that with fixed deployed area, sensing range and energy parameters, if we increase the deployed node number, n is the only coefficient in Equation (5), which is increased significantly. Therefore, the more nodes we have, the larger the distance between α and α_{ideal}. This explains why the reduction of energy consumption does not fall as quickly as the increase of the redundancy factor in Figure 18.

5. Conclusions

In this paper, we propose a coverage-preserving node-scheduling scheme, which can reduce energy consumption and therefore increase system lifetime, by

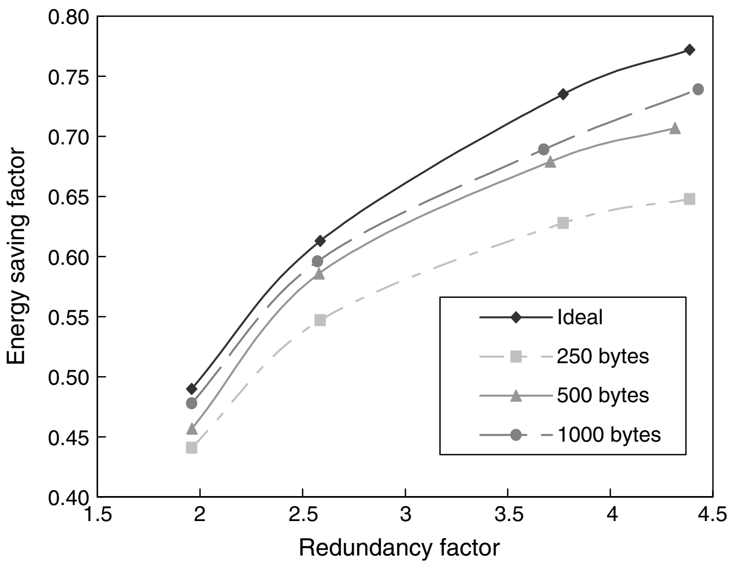


Fig. 19. Energy saving factor versus redundancy factor ($|\aleph| = 100$ to 250, $\mathcal{R} = 50$ m $\times$ 50 m, $r = 10$ m).

making some redundant nodes fall asleep. We present a basic model for coverage-based off-duty eligibility rule and then extend it to be applicable to the cases in which nodes have different sensing ranges. This kind of off-duty eligibility rule guarantees that the original sensing coverage can be completely preserved in idealized operation environment. And sensing coverage reduction is not more than 1% in location error, packet loss or node failure. Experimental results also show that certain redundancy still remains after node scheduling. To further preserve sensing coverage in a real-time environment, we introduce a back-off scheme in which nodes delay by a random time period, before investigating the eligibility rule, and wait for a short time, if they decide to turn off. Doing this is to avoid blind points due to simultaneous removing. We implemented this scheme as an extension to the LEACH protocol, which is an existing data communication protocol designed for wireless sensor networks. We compared the energy consumption in the original LEACH and the extended LEACH and analyzed the effectiveness of our scheme in terms of energy saving. Preliminary simulation results in the radio model and energy parameters proposed by the LEACH designer show noticeable energy saving and system lifetime increasing.

Although our algorithm achieves the goals of maintaining system original performance and function, and simultaneously reducing the active node number, it still has space for improvement. For instance, edge nodes have no chance to take a rest because all of their neighbors are located on one side of them. So relaxing the off-duty eligibility rules for edge nodes can increase the off-duty node number. Furthermore, our scheme is based on the assumption that the sensing area of each node is a symmetric circle. In practice, obstacles, weather or other factors may affect the sensing area and change its shape to irregular and asymmetric. Evaluating the sensitivity of our scheme to these factors in outdoor environment is necessary. In addition, the trade-off between the percentage of active nodes and the percentage of system sensing coverage is also part of our future work.

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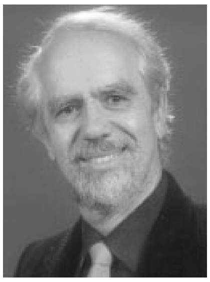
Authors' Biographies



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