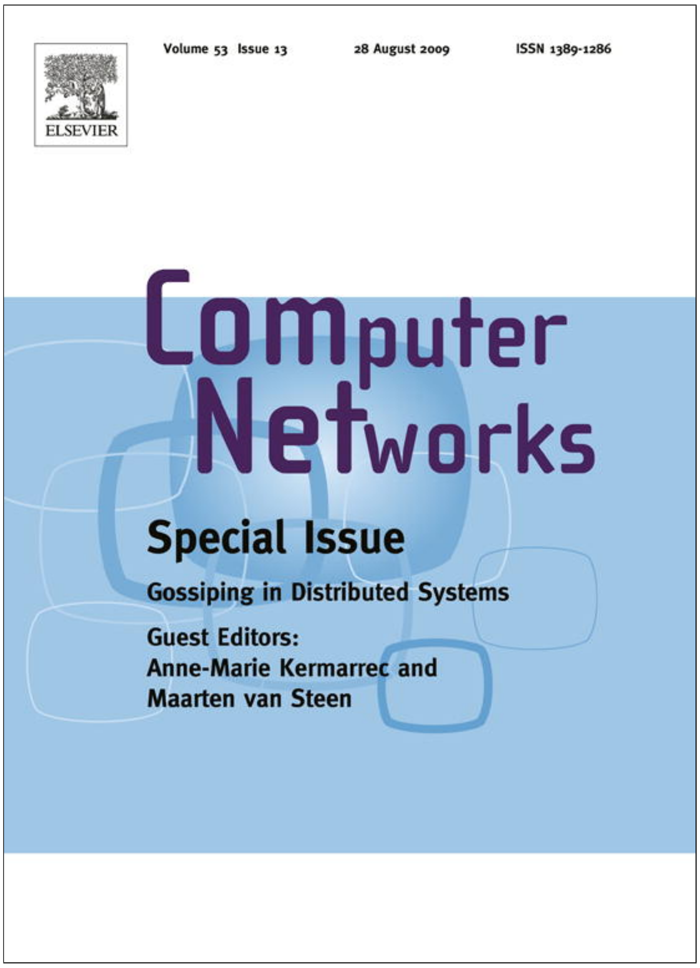
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A novel gossip-based sensing coverage algorithm for dense wireless sensor networks

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ABSTRACT

Wireless sensor networks (WSNs) have been widely studied and usefully employed in many applications such as monitoring environments and embedded systems. WSNs consist of many nodes spread randomly over a wide area; therefore, the sensing regions of different nodes may overlap partially. This is called the "sensing coverage problem". In this paper, we define a maximum sensing coverage region (MSCR) problem and present a novel gossip-based sensing-coverage-aware algorithm to solve the problem. In the algorithm, sensor nodes gossip with their neighbors about their sensing coverage region. In this way, nodes decide locally to forward packets (as an active node) or to disregard packets (as a sleeping or redundant node). Being sensing-coverage-aware, the redundant node can cut back on its activities whenever its sensing region is *k*-covered by enough neighbors. With the distributed and low-overhead traffic benefits of gossip, we spread energy consumption to different sensor nodes, achieve maximum sensing coverage with minimal energy consumption in each individual sensor node, and prolong the whole network lifetime. We apply our algorithm to improve LEACH, a clustering routing protocol for WSNs, and develop a simulation to evaluate the performance of the algorithm.

1. Introduction

Wireless sensor networks are usually self-organized ad hoc networks consisting of a large number of wireless sensor nodes with small size, low battery capacity, low processing power, limited buffer capacity, and a low-power radio. Sensor nodes collaborate using wireless communications with an asymmetric many-to-one data transfer model. Typically, they send their sensed events or data, by a specific communication protocol, to a specific node called the sink node or base station, which collects the requested information. WSNs are primarily designed for monitoring environments that humans cannot easily reach (e.g., motion, target tracking, fire detection, chemicals, temperature); they are used as embedded systems (e.g., biomedical sensor engineering, smart homes) or mobile applications (e.g., when attached to robots, soldiers, or vehicles). In wireless sensor networks, sensor nodes are usually battery-powered, but it is not practical to recharge or replace the batteries of all the sensors, because either the number of sensor nodes is too large, or the nodes are in remote, battlefield, desert or hostile areas. Energy loss could destroy important information, isolate sensor nodes, or even partition and disconnect the entire network. Once deployed, however, most applications of sensor networks expect a long system lifetime. The energy expenditure of sensors has to be wisely managed by their architectures and protocols to prolong the overall network lifetime. Therefore, energy efficiency is the essential requirement in WSNs.

In order to achieve better system performance and provide monitoring capabilities, in many applications, thousands of sensor nodes are generally densely deployed—mostly at random—to ensure that the area of interest is

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completely or sufficiently covered and to increase sensing reliability. Some of them are very close to or inside a phenomenon to be observed. Therefore, in a dense network, the sensing areas of different nodes may be similar and overlap with those of neighboring nodes. It is important to place or select them so that the monitored area is covered as much as possible without diminishing the overall system coverage. This is known as the "sensing coverage problem" and leads to the main goal of achieving maximum sensing coverage with minimal energy consumption in the design and implementation of routing protocols for WSNs.

The sensing coverage problem also appears in practice as we implement the ARPEES [1,2], and LEACH [3] protocols. The average amount of residual energy decreases quickly with both the LEACH and ARPEES protocols at network initiation. The available energy reduces slowly and smoothly later. This is because, at the beginning of the application, nodes in the sensor network are dense: the sensing area covered by neighboring nodes may be similar and overlapped. In this scenario, thus, the total energy dissipates at the beginning more rapidly than at the end of the network's lifetime when some nodes have died or the density of the network has decreased. As mentioned in many papers [4,5], an efficient approach to prolong the lifetime of a dense sensor network while solving the sensing coverage problem is to determine a localized and distributed protocol for selecting a sufficient subset of active sensor nodes as working nodes (on-duty), designating other nodes as off-duty. Furthermore, the network must be able to configure itself to any feasible degree of coverage and connectivity in order to support different applications and environments in accordance with the quality-of-service (QoS) requirement. If we can identify and schedule a subset of active sensor nodes according to local information while satisfying the global coverage requirement and indicating which subset of the sensors can currently be active, we can significantly prolong the network lifetime.

Energy conservation is the major problem in sensor network communications. Flooding is a traditional robust algorithm that delivers data packets from a source to a destination by broadcasting. However, the natural property of flooding causes broadcast storms that not only waste energy due to their extreme redundant packet receptions caused by retransmission [6], but also increase the number of collisions, together depriving sensors of valuable battery power. Therefore, the original flooding algorithm may not be suitable in the context of dense networks like wireless sensor networks. A straightforward solution to the broadcast storm problem is to minimize redundant communication. Several approaches in the literature have been proposed to reduce retransmission.

Gossiping, an algorithm based on the repeated probabilistic exchange of information between two members [7], addresses some critical problems of flooding overhead. The goal of gossip is to reduce the number of retransmissions by making some of the nodes discard the message instead of forwarding it. In the gossiping scheme, nodes in the network are required to forward packets with a prespecified probability p. When a node receives a message, rather than immediately retransmitting it as in flooding, it relies on the probability p to determine whether or not to retransmit. The probability p that a node forwards a message is called the gossip probability p_{gossip}. The main benefit is that when p_{gossip} is correctly chosen, the entire network receives the broadcast message with very high probability, even though only a non-deterministic subset of nodes has forwarded the message [8]. Probabilistic choice is a key element of gossiping, and in general refers to the choice of member nodes that communicate [7]. However, choosing the correct value of p_{gossip} or which attributes to use for gossiping is a very difficult problem.

Several modified gossip-based approaches that are most relevant to our method minimize redundant communication by identifying a suitable subset of nodes and assigning them the responsibility of forwarding messages [8–12]. These approaches use meta-data negotiation [9], sleep schedules [10], geometry (directional) information [11], or local connectivity [12] as a parameter to gossip. The objective is to increase the overall network lifetime by allowing redundant nodes in the network to sleep for a given period of time. The distinction between our method and these approaches mentioned above is the criterion applied to gossip and behavior of nodes after getting the gossip results.

In WSNs, as mentioned above, the sensing coverage problem is directly related to node redundancy. However, to the best of our knowledge, no work has been done with a gossiping mechanism that is aware of sensing coverage. In our paper, we use sensing coverage information as a probabilistic choice or a criterion for gossiping among sensor nodes. The result of gossip is to determine the behavior of nodes: forwarding nodes serve as active nodes, and disregarding nodes serve as sleep nodes. Using the sensing coverage criterion for gossiping can overcome the problem of initial gossiping of a source node that has very few neighbors, where there is a fair chance that none of them will gossip and that the gossip will never spread [13].

Our contributions in this paper are as follows: First, we define the maximum sensing coverage region (MSCR) problem and propose a novel gossip-based sensing-coverage-aware algorithm to solve it. In our algorithm, sensor nodes gossip their sensing coverage region with their neighbor nodes to decide in a localized manner to forward packets (as an active node) or to disregard packets (as a sleep/redundant node). Being sensing-coverage-aware, the redundant node can cut back on its activities whenever its sensing region is k-covered by enough neighbors. We schedule nodes alternating between active and sleep modes while guaranteeing the k-coverage requirement over the whole working area, where k is predetermined and can be changed by users. Second, we apply this algorithm to improve the performance of the LEACH protocol, a well-known hierarchical routing protocol for WSNs. By integrating the MSCR algorithm with the LEACH routing protocol, we propose a new architecture for routing in large distributed WSNs. This efficient architecture includes eligibility for removing redundant sensor nodes, permits configurable QoS coverage parameters, and provides sufficient sensing coverage with balanced sensor energy and low communication overhead, each being individually adapted to maximize the network lifetime in its own right.

With the distributed and low-overhead traffic benefits of gossip, we spread energy consumption over different sensor nodes, and achieve maximum sensing coverage with minimal energy consumption in the design and implementation of routing protocols for WSNs to prolong the whole network lifetime. Finally, we develop a computer simulation for performance evaluation and confirm that our method can achieve better performance than the conventional methods to prolong network lifetime.

The remainder of the paper is organized as follows: Section 2 presents some previous work on the sensing coverage problem and gossip-based approaches in WSNs. Section 3 presents definitions and the MSCR problem formulation. In Section 4, we present an algorithm to solve the MSCR problem. We apply our algorithm to the LEACH protocol in Section 5 (the improved version of the original LEACH protocol, called MSCR-LEACH). We use simulation to evaluate our method and compare the MSCR-LEACH with the original LEACH protocol in Section 6. The last section is the conclusion of the paper.

2. Related work

2.1. Sensing coverage in WSNs

Sensing coverage, reflecting the quality of monitoring provided by a sensor network, has been the focus of intense study recently. There are two types of coverage problems: area coverage [14,15], in which the main goal is to cover (monitor) a desired area; and point or target coverage [4,5,16–18], in which the object is to cover a set of interesting points or targets. In this paper, we address the first problem.

For the sensor network application to succeed, the active nodes must maintain both sensing coverage and network connectivity [4,19] so that nodes can communicate for data fusion and report to the base stations. A straightforward solution is to use a communication range (R_c) that is at least twice the sensing range (R_s), so that area coverage implies connectivity of active sensors [19]. Xinh et al. [4] studied the relationship between coverage and connectivity, and proposed a coverage configuration protocol (CCP). In a CCP, each sensor consults an eligible rule, finds all intersection points between the borders of its neighbors' sensing radii, and considers its own eligibility for deactivation if each of those intersection points is covered with the desired sensing degree. Xinh generalized this conclusion [4]: when $R_c = 2R_s$, a sensor network that achieves k-coverage is k-connected.

To increase network lifetime, most techniques have divided the sensor nodes into a number of sets, such that each set completely covers all the targets. These sensor sets are activated successively, such that at any instant only one set is active. The sensors from the active set are in the active state (e.g., transmit, receive or idle) and all other sensors are in the sleep state. Cardei et al. [16] proposed an efficient scheme to address the target coverage problem, with the objective of maximizing the network lifetime of a power constrained wireless sensor network deployed for monitoring (coverage) of a set of targets with known locations in a randomly and densely deployed sensor network. They model the target coverage problem as a maximal set-cover problem, and propose and evaluate two heuristics for it. The DAPR protocol [17] is based on an application cost that considers coverage and available energy. It lets sensors be active according to the network coverage quality demand and to sleep whenever possible during the rest of the time. Tsai proposed coverage-preserving routing protocols [20], which are modified from the LEACH protocol and virtual grid routing protocols in which different nodes should be assigned different probabilities of being a cluster head. This probability depends on the normalized effective sensing area of a node, which is defined as the ratio of the effective sensing area to the maximum sensing area of a node. Tian and Georganas [15] proposed a distributed selection algorithm for coverage preservation in sensor networks, in which a sensor measures its neighborhood redundancy as the union of the sectors or central angles covered by neighboring sensors within the sensor's sensing range.

Various different scheduling schemes have been proposed in the literature [5,18]. In these papers, the authors consider the arc or angle created by the overlapped sensing area of two neighboring nodes as a critical parameter in their algorithms. Distributed as well as centralized algorithms can allow the selection of the set of sensors that are on the boundary of the coverage holes in the region [5]. They consider hole boundary detection as a crucial problem for optimizing sensor placement and identifying regions of interest for end users. However, the authors of the above papers do not consider the worst case of the algorithms. Zhang and Hou address the issue of density control: an area is completely covered if there are at least two disks that intersect and all crossings are covered [21]. Based on this idea, the authors proposed a distributed algorithm called optimal geographical density control (OGDC). In OGDC, a node can be in one of three states: UNDECIDED, ON, or OFF. The algorithm repeatedly runs using the back-off mechanism to determine the status of each node.

2.2. A gossip-based approach to WSNs

Several modified gossip-based approaches that are most relevant to our method minimize redundant communications by identifying a suitable subset of nodes and assigning them the responsibility of forwarding messages [9–11,13].

Heinzelman et al. [9] applied gossiping and negotiation to for data dissemination in WSNs. They proposed the SPIN protocol, in which nodes avoid transmitting redundant data throughout the network, using meta-data negotiation and resource adaptation.

Hou et al. [10] present an energy conservation scheme for wireless ad hoc and sensor networks using a gossip-based sleep protocol (GSP) to put nodes into an energy-saving sleep state. The GSP is based on the observation that in a well-connected network, there are usually many paths between a source and a destination, so a percentage of nodes can be in an energy conserving sleep mode without losing network connectivity. With GSP, each node randomly goes to sleep with gossip sleep probability p. The network connectivity is determined by the probability p. The authors claim that certain values of p will make almost all the waking nodes in the network connected, affecting the performance of the network only slightly.

Li et al. [11] propose a regional gossip approach, which uses the geometry information of the source node and the destination node as a criterion for gossiping. Only the nodes within some regions forward a message with some probabilities.

Haas et al. [13] present a simple gossip-based routing protocol for ad hoc networks by choosing some sets of nodes to gossip with a probability p. A source sends the route request with the probability p. When a node first receives a route request, with the probability p it broadcasts the request to its neighbors, and with the probability $1-p$ it discards the request; if the node receives the same route request again, it is discarded. This simple protocol is called GOSSIP1(p). The authors claim that, given a sufficiently large network and a gossip probability p greater than a certain threshold, almost all the nodes in the network can receive the message [13]. They did simulations to investigate the gossiping probability and concluded that a gossiping probability between 0.65 and 0.85 is sufficient to ensure that almost every node gets the message in almost every routing. In a random ad hoc network, a node may have very few neighbors. In this case, GOSSIP1(p) has a slight problem with initial gossip. There is a fair chance that none of the nodes will gossip and that the gossip will die.

In the paper, we propose a novel gossip-based sensing-coverage-aware algorithm that overcomes this problem by using sensing coverage, which directly relates to the number of neighbors, as a criterion for gossiping. The purpose of gossip is to determine the behavior of nodes: forwarding nodes will serve as active nodes; disregarding nodes play a role as sleep nodes.

3. Definitions and MSCR problem formulation

One fundamental problem in current WSNs is efficient deployment of the required coverage. Specifically, given a monitoring region, how can we guarantee that every point in the region is covered by the required number of sensors? In other words, we need to recognize which areas are covered by enough sensors. This problem is challenging due to the limitations of wireless sensors, as well as the ad-hoc deployment properties of wireless sensor networks. In this section, we define sensing coverage and formulate the maximum sensing coverage region problem.

Consider a WSN consisting of n homogeneous sensor nodes $s_1, s_2, \ldots, s_n$, in a two-dimensional network area. Each sensor node $s_i, i = 1 \cdots n$ is located on coordinate (x_i, y_i) inside the network area, where they have the same sensing range R_s and communication range R_c. We assume that sensor nodes are static and that each sensor node knows its own location, all its neighbors, and the base station location. The positions of neighbors can be obtained by exchanging "Hello" messages. Sensor nodes have synchronous timers and know their own residual energy level.

Definition 1. The neighbor set of a sensor node s_i, denoted by $N(s_i)$, is defined as the set of nodes within the communication range of the node s_i:

$$N(s_i) = \{s_j | d(s_i, s_j) \leqslant R_c, j \neq i\}. \tag{1}$$

The overlapped neighbor set of a sensor node s_i, denoted by $O(s_i)$, is defined as the set of nodes within the sensing range of the node s_i:

$$O(s_i) = \{s_j | d(s_i, s_j) \leqslant 2R_s, j \neq i\}, \tag{2}$$

where $d(s_i, s_j)$ is the Euclidean distance between two sensors s_i and s_j.

Definition 2. The sensing region of a sensor s_i located at (x_i, y_i), denoted by S^i_{region}, is a set of all points within s_i's sensing range. A point p is said to be k-covered if it is within at least k sensors' sensing regions.

For a sensor node s_i located at given point i, we use a circle (i, R_s) that is centered at the point i and has a radius R_s to represent the sensing region of the sensor node s_i. Assuming that a sensor node can cover any point inside its sensing region, we define a point p to be covered (monitored) by a sensor node s_i if it is located in the sensing region of the sensor node s_i or if the Euclidean distance from p to the sensor node s_i is less than the sensing range of the sensor node s_i.

Given a set of sensor nodes deployed in a monitoring area, we want to determine whether the area is sufficiently k-covered. The parameter k is called the "coverage level" or "coverage degree", meaning that each point in the interesting area is within the sensing range of at least k active sensors. Different applications require different coverage levels. For example, the applications require $k = 1$ if sensors are deployed in a building to monitor temperature, sound or moisture, where the environment is friendly and fault tolerance may not be important. Meanwhile, $k > 1$ may be required in situations where a stronger monitoring environment is necessary: for example, when sensor nodes operate in hostile regions such as battlefields or chemically polluted areas. In applications such as triangulation-based positioning and target tracking, multiple sensors are required to detect a moving target at any moment; thus, the coverage level is required to be at least $k = 3$ for fault-tolerance purposes. With k-coverage, the network still operates properly even when any $k - 1$ sensors fail at the same time [22].

For successful operation of the sensor network, the active nodes must maintain both sensing coverage and network connectivity, since network connectivity is necessary for any routing algorithm to find a routing path. We further assume that the communication range of a sensor R_c is at least twice its sensing range $R_s, (R_c = 2R_s)$. In this model, any two sensor nodes s_i and s_j, can directly communicate with each other if $d(s_i, s_j) \leqslant R_c$. Here, $d(s_i, s_j)$ is the Euclidean distance between s_i and s_j. Thus, the k-coverage can guarantee k-connectivity [14,19].

Definition 3. Boundary arc: The arc created by two overlapped sensor nodes s_i and s_j is the arc created by two intersection points between two sensing region boundaries.

By Definition 1, the sensing region of a node is described by an area enclosed by a circle (disk). Consider two sensors s_i at (x_i, y_i) and s_j at (x_j, y_j), the *intersection* (overlapped area) of two sensing regions S^i_{region} and S^j_{region} produces a lens-shaped area (the area A marked in Fig. 1). Without loss of generality, let s_j reside to the west of s_i (i.e., $y_i = y_j$ and $x_i > x_j$) as illustrated in Fig. 1.

Regarding $d(s_i, s_j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$ as the distance between s_i and s_j, if $d(s_i, s_j) < 2R_s$, the overlapped area A is the intersection of two sensing regions:

$$A = S^i_{region} \bigcap S^j_{region} \tag{3}$$

or it can be obtained by the geometric calculation below:

$$\begin{aligned} A &= 4 \times A_1 \\ &= 4 \times \left[\frac{\alpha}{2\pi} \times \pi R_s^2 - \frac{1}{2} \times \frac{d(s_i, s_j)}{2} \sqrt{R_s^2 - \left(\frac{d(s_i, s_j)}{2}\right)^2}\right] \\ &= 2R_s^2 \times \left[\alpha - \frac{d(s_i, s_j)}{2R_s} \sqrt{1 - \left(\frac{d(s_i, s_j)}{2R_s}\right)^2}\right] \end{aligned} \tag{4}$$

with the angle $\alpha = \arccos(\frac{d(s_i, s_j)}{2R_s})$. Clearly, based on the Definition 1, every point p located in area A can be covered by both sensor nodes s_i and s_j. The boundary arc arc_j created by two overlapped sensor nodes s_i and s_j can be regarded as the start and end angles of the node s_i that is covered by its neighbor s_j determined by node s_i's central angle 2α. In other words, the boundary arc created by two overlapped sensor nodes s_i and s_j is the arc starting from the intersection point I_1 to I_2 going counterclockwise $\widehat{I_1 m I_2}$. To use the boundary arc in the following algorithm, we transform it to the angle $[\pi - \alpha, \pi + \alpha]$, as illustrated in Fig. 1.

Definition 4 (*Maximum sensing coverage region (MSCR)*). Given a set of m sensors $S = s_1, s_2, \ldots, s_m$ deployed in a desired area and a natural number k, the MSCR problem is the problem of finding a subset $S' \subseteq S$ that (1) S' guarantees that the whole area is k-covered and (2) achieves a maximum sensing region.

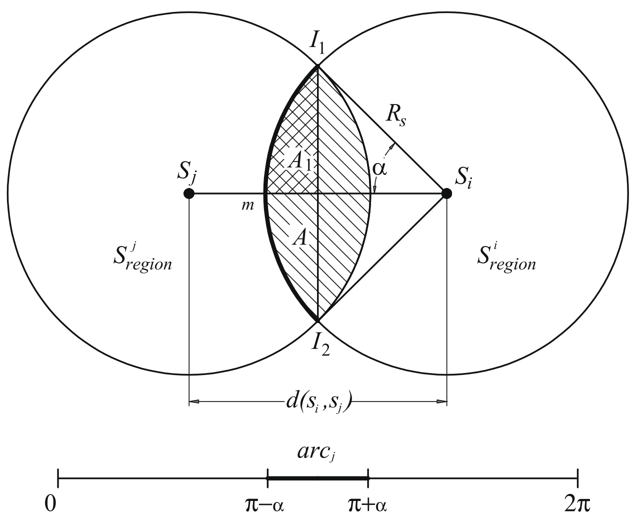

Fig. 1. The boundary arc created by two overlapped sensor nodes and its transformation to the angle of $[0, 2\pi]$.

In many wireless sensor applications, nodes are densely deployed at random over the entire desired area. Therefore, a particular region may have higher node density than it needs, and thus the sensing regions of different nodes may overlap partially, or an event or target in this location may be observed by multiple nodes. We aim to avoid this problem by dividing the sensor nodes into a number of subsets such that each subset completely meets the coverage requirements in the desired area, to make sure that all important events happening in that area can be accurately and timely detected. At any instant, only one subset is active to do sensing tasks. Other sensor nodes are in sleep mode to conserve their energy. The sensor nodes alternate between active and sleep modes. This increases the network and application lifetimes compared to the case where all sensor nodes are active continuously. We define the MSCR problem and address this problem in the following method: selecting a small number of delegated sensor nodes by identifying redundant nodes in high-density networks and assigning them to an off-duty operation mode while guaranteeing that the whole area is covered by at least k active sensor nodes. This method maintains the monitoring capability and quality of a sensor network to make sure that all important events occurring in that area can be accurately and timely detected by the delegated sensor nodes (achieves maximum sensing region).

4. Maximum sensing coverage region algorithm

Identifying redundant nodes in high-density networks and then assigning them an off-duty operation mode that has lower energy consumption than the normal on-duty mode without losing coverage is an efficient way to prolong the system lifetime. Furthermore, to maintain the quality of sensing, some applications require k-coverage of the monitored area. This means that a sensor should not be allowed to sleep unless its sensing area is considered sufficiently covered by its active neighbors. Therefore, the key point of a sensing coverage algorithm is to compute a sensor's redundancy property. Specifically, we aim to determine whether the sensing region of a sensor under consideration is sufficiently covered. By exchanging the location information with all of its one-hop neighbors, a correct decision can be made in a distributed and localized way. To be distributed and localized are important properties of a node decision mechanism, as they are adaptive to a scalable and dynamic network topology.

Definition 5 (*Redundant sensor node*). A sensor node s_i is a redundant node if its entire sensing region is covered by the sensing region of at least k active neighbor sensor nodes.

We design a mechanism that allows redundant nodes to decide whether and when they should enter sleep mode. To design such a mechanism, we must answer the following questions: (i) Which rule should each node follow to determine whether it is a redundant node? (ii) When should redundant nodes decide to enter sleep mode? (iii) How long should a redundant node remain in sleep mode?

Clearly, a sensor node is redundant if its sensing region is k-covered by its neighbors. Here we propose a redundancy rule, by which a sensor node can decide whether its sensing region is k-covered by its neighbors by checking two necessary and sufficient conditions.

Theorem 1 (Redundancy rule). *Considering a sensor node s_i and a set of its overlapped neighbors $O(s_i)$, given a natural number k, the sensor node s_i is a redundant node if two guarantee conditions are fulfilled.*

Condition 1 (*Necessary condition*).

The union of boundary arcs created by the set of the overlapped neighbor nodes $O(s_i)$ covers completely k times the entire boundary sensing region of node s_i:

$$\bigcup_j arc_j \geqslant 2k\pi \quad \forall j = 1 \cdots |O(s_i)|. \tag{5}$$

Condition 2 (*Sufficient condition*). The Euclidean distance from the node s_i to each node in the set $O(s_i)$ is less than or equal to the sensing range R_s:

$$d(s_i, s_j) \leqslant R_s \quad \forall s_j \in O(s_i). \tag{6}$$

Proof of Theorem 1. Given sensor node s_i and a set of m neighbors in $O(s_i)$, we first calculate the union of boundary arcs formed by the set of its neighbors $\{arc_1, arc_2, arc_3, \ldots, arc_m\}$ and then transform them to the angle in the range of $[0, 2\pi]$ respectively.

The necessary condition $\bigcup_{j=1}^{m} arc_j \geqslant 2k\pi$ means that the union fits k times in the angle $[0, 2\pi]$ or it covers k times 360 degrees of the central angle. Clearly in this case, the border of s_i's sensing region is fully covered by the m neighbors. The total overlapped area A in S^i_{region} can be calculated as:

$$A = \bigcup_{j=1}^{m} A_j = A_1 \cup A_2 \cup A_3 \cdots \cup A_m \tag{7}$$

with each A_j can be calculated base on the Eq. (3) as follows:

$$A_j = 2R_s^2 \times \left[arc_j - \frac{d(s_i, s_j)}{2R_s} \sqrt{1 - \left(\frac{d(s_i, s_j)}{2R_s}\right)^2} \right]. \tag{8}$$

If $d(s_i, s_j) \leqslant R_s$ then $\frac{2\pi}{3} \leqslant arc_j < \pi$ with $j = 1 \cdots m$, we can rewrite the Eq. (8) given:

$$2R_s^2 \times \left[\frac{\pi}{3} - \frac{\sqrt{3}}{4}\right] \leqslant A_j < 2\pi R_s^2. \tag{9}$$

Substituting A_j in Eq. (9) for Eq. (7), the satisfied necessary condition gives:

$$A = \bigcup_{j=1}^{m} A_j = A_1 \cup A_2 \cup A_3 \cdots \cup A_m = k2\pi R_s^2 \tag{10}$$

or

$$A = k \times S^i_{region}. \tag{11}$$

Now we can conclude that if the necessary condition is satisfied and the distances from node s_i to its neighbors $O(s_i)$ are less than or equal to the sensing range R_s, then the union of the overlapped region A is k times the entire sensing region S^i_{region} of node s_i. In other words, every point in the sensing region of node s_i is completely covered by k neighbors. As stated in the Definition 5, sensor node s_i is redundant with the k-coverage requirement. □

Fig. 2 illustrates an example where sensor node s_i covered by three neighbor nodes s_1, s_2, s_3. The distance between s_i and s_1, s_2, s_3 is less than the sensing range R_s. The overlapped area $A = A_1 \cup A_2 \cup A_3 = S^i_{region}$ means every point in the sensing region of node s_i is covered by at least one sensor node. We can determine node s_i as a redundant node with $k = 1$. In Fig. 3, the set of overlapped neighbors completely covers the whole border of sensor node s_i, but with $d(s_i, s_j) > R_s$, the region near the center of s_i cannot be covered by any neighbor. The sensor node s_i in this case is not redundant. The percentage of overlapped sensing regions mainly depends on the distance between the node and each of its neighbors. Longer distances to the neighbors make overlapping areas smaller and representative of a lower percentage of covered area. That is why we need the sufficient condition: so that we can guarantee all the sensing area of node s_i covered by its neighbors in every case.

Based on the previous definitions and Theorem 1, we present a novel gossip-based sensing-coverage-aware algorithm to solve the MSCR problem, where the sensing coverage information is used as a probabilistic choice for gossiping among nodes. A standard approach to dissemination, a traditional gossip-based application, is to simply let peers (sensor nodes) forward messages to each other [7] with a pre-specified gossip probability p. The gossip probability p is a criterion to determine whether or not to forward messages.

In the modified gossip-based algorithm, we present another viewpoint on gossip. Here, the scope of gossip is only within a set of one-hop neighbor nodes. The criterion for gossiping is the arc transformation that is calculated from the sensing coverage region. The purpose of gossip is to determine the behavior of nodes: forwarding nodes will serve as active nodes; disregarding nodes play a role as sleep nodes. We apply gossiping in the distributed system framework introduced in [7] to model our method.

Algorithm 1. Maximum sensing coverage region

1. **for** each sensor node s_i **do**
2. Find $O(s_i)$ by Eq. (2)
3. Send *gossip_msg*. to $O(s_i)$
4. Wait t_{gossip} to receive the reply of *gossip_msg*.
5. Calculate the boundary arcs between s_i and $O(s_i)$
6. Transform the arcs into the angle $[0; 2\pi]$
7. **if** s_i | Eq. (5) and s_i | Eq. (6) **then**
8. $s_i \leftarrow$ *redundant_node*
9. Send *sleep_msg*. // sensor s_i is disregarding node
10. **else**
11. Send *active_msg*. // sensor s_i is forwarding node
12. **end if**
13. **end for**

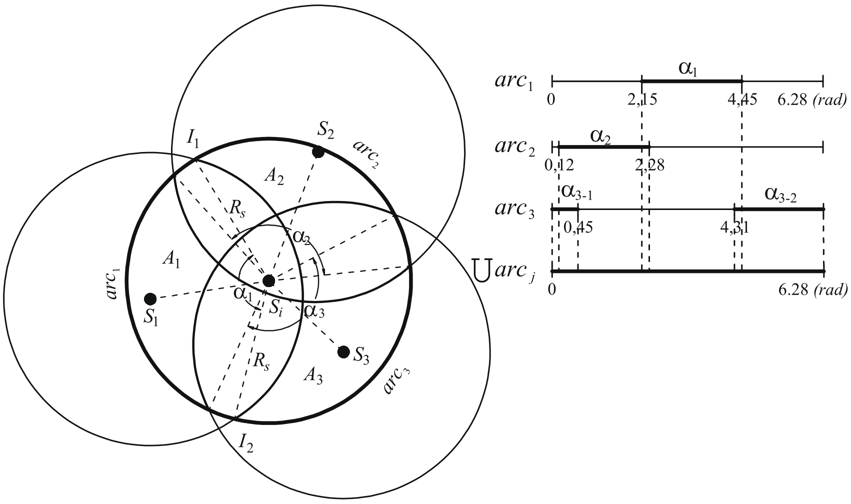

Fig. 2. An example of a redundant node with $k = 1$.

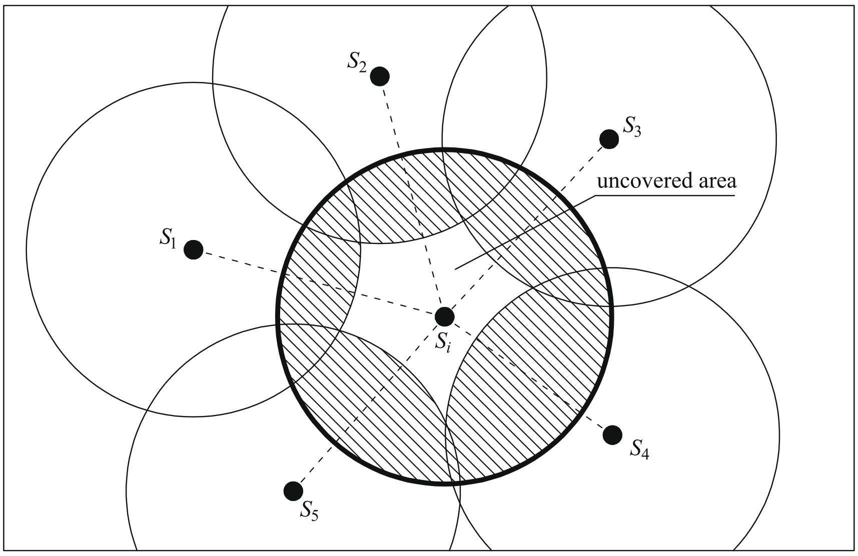

Fig. 3. An example of a non-redundant node.

- **Node selection:** The nodes in the set are ranked according to their number of neighbor nodes $O(s_i)$. The target of gossiping is to choose the nodes that fulfill the k-coverage requirement.
- **Data exchange:** The data exchange between nodes is the boundary arc and its transformation ranging from 0 to 2π.
- **Data processing:** Nodes store exchanged data for the next gossip iteration and send their status message (sleep/active message) to the source node.

5. Application of the MSCR algorithm

Our algorithm aims to find redundant nodes and schedules them alternately between sleep and active mode for conserving and balancing the energy of each individual sensor node. By doing so, the amount of sensed data is reduced before transmission to the base station. We evaluate the performance of our method by simply applying it to the LEACH routing protocol [3], a famous clustering routing protocol for WSNs. The purpose of this application is to achieve better LEACH performance while still guaranteeing coverage. We call our improved version of LEACH "MSCR-LEACH". In the LEACH protocol, sensing data from cluster members are aggregated by cluster head and then directly transmitted to the base station.

5.1. LEACH protocol

LEACH is a self-organizing and adaptive clustering protocol that uses randomization of the cluster heads in the corresponding clusters in order to achieve good performance in terms of system lifetime, latency, and application-perceived quality. In LEACH, the nodes organize themselves into local clusters with one node acting as the cluster head. All non-cluster-head nodes transmit their data to the corresponding cluster head. A cluster-head node receives data from all the cluster members, does signal processing functions on the data (e.g., data aggregation), and transmits data to the base station.

5.2. MSCR-LEACH protocol operation

The application scenarios are described as follows. The sensor network is deployed to observe any event that may occur at any location within the monitored battlefield (e.g., monitoring penetration of intruders, tracking moving vehicles) and to report the sensed events to the data collection center (also known as the base station). In this situation, sensing coverage, network connectivity, and energy efficiency are important requirements: A high sensing coverage level is necessary to meet the users' requirement that an event can be accurately and timely detected with high probability; network connectivity and routing strategy are to meet the users' requirement that the detected events can be delivered to the base station with a short delay; energy efficiency is to meet the users' requirement that the network should keep its operation as long as possible after the deployment. The MSCR algorithm can cover the two former requirements, while LEACH protocol is adopted to fulfill the last one.

Energy efficiency is a very important issue in WSNs. However, many current clustering algorithms suffer from the problem of imbalanced energy consumption, so that the cluster heads drain energy much faster than the cluster members, reducing the network lifetime. In order to balance the energy consumption among all wireless sensor nodes, an adaptive clustering algorithm need to be applied so that an adaptive node with residual energy available will take the role of cluster head for a certain amount of time.

The operation of the MSCR-LEACH protocol is organized into rounds. Each round begins with a setup phase when the clusters are organized, the sensing coverage issue is solved, and node scheduling are executed and followed by a steady phase. In the setup phase, nodes in each cluster gossip exchange their information about sensing coverage regions. The nodes that satisfied the criterion of boundary arc as presented in Section 4 are scheduled into sleep mode. They will not send or forward packets to the cluster head for the period of the steady phase. In the next round, clusters are reorganized; the criterion arc is re-evaluated to alternately schedule other nodes to sleep mode.

The setup phase of the MSCR-LEACH protocol is best explained by the flowchart in Fig. 4. In the steady phase, the cluster head collects sensing data from its active member nodes. And then, after doing appropriate data fusion or compression, the cluster head forwards the data to the base station. The duration of the steady phase is longer than that of the setup phase in order to minimize overhead.

5.2.1. Setup phase

The setup phase allows sensors to exchange necessary information such as node ID, location, and residual energy. During the phase each node calculates for itself whether to become a cluster head or not depending on the amount of energy left at the node. In this way, nodes with more energy remaining will become the cluster head. After the cluster heads are selected, they broadcast advertisement message to all sensor nodes in the network to inform that they are the new cluster heads. Once the sensor nodes receive the advertisement message, they determine the cluster to which they want to belong for that round based on the signal strength of the advertisement message from the cluster heads.

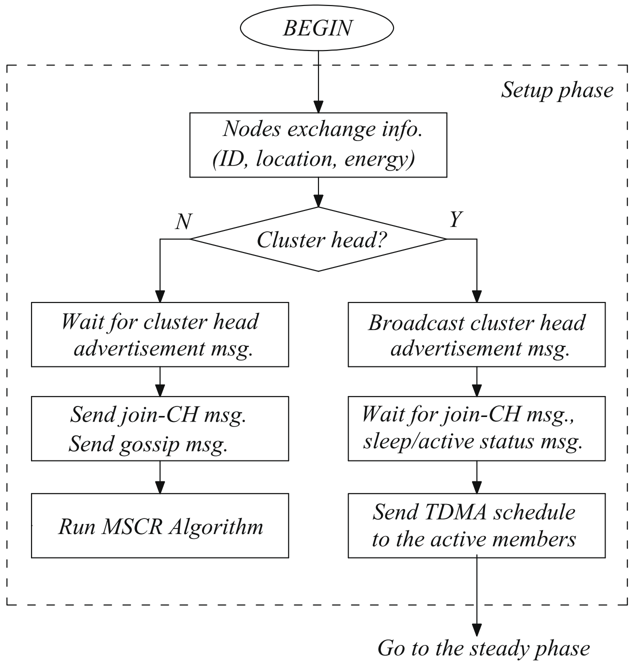

Fig. 4. The flowchart of the MSCR-LEACH protocol in the setup phase.

And then, based on the application requirements (e.g., area monitoring, connectivity, sensing coverage requirement), sensor nodes run the MSCR algorithm Algorithm 1 to exchange their sensing coverage information. This algorithm allows eligible redundant nodes to sleep while others remain active. Every sensor node informs the corresponding cluster head that it will be a member of the cluster by sending its current status to the cluster head. Once all the nodes are classified into clusters, each cluster head creates a TDMA schedule for the nodes in its cluster based on their status and sends this information back to the nodes. This schedule allows the radio component of each non-cluster-head node to be turned off at all times except during its transmission time. Thus, our method minimizes the energy dissipated in the individual sensors. In each cluster, only a small subset of nodes is on-duty while the rest of nodes are off-duty.

5.2.2. Steady phase

During the steady phase, all active nodes can begin sensing the environment and transmitting sensed data to the cluster heads. The cluster heads receive data from all their active members, do signal processing functions on the received data (e.g., data aggregation), and transmit the data to the remote base station. After a certain period of time spent in the steady phase, the network goes into the setup phase again and enters another round of activity.

6. Performance evaluation

6.1. Simulation setup

We develop a simulation program based on [23] to evaluate the performance of our MSCR-LEACH algorithm and compare it with the original LEACH. In our simulation, we use the same network model and radio model mentioned in [3]. Table 1 shows the simulation parameters. In the simulations, a set of sensor nodes is deployed randomly in a square area. The sensors are provisioned an energy level of 2 J at startup. They can sense within a radius of sensing range set for each simulation. Each on-duty sensor senses the physical environment, generates a data packet at a regular rate, and sends it to its cluster head. The cluster head waits to receive the packets from all the active members, aggregates them, and sends the aggregated data packet to the base station. All the results in this subsection are based on ten runs with different random network topologies.

6.2. Result analysis

Our work concentrates on the most important aspect: energy efficiency. The simulations aim to evaluate the performance of the MSCR algorithm, and the effect of the MSCR algorithm on the LEACH routing protocol concerning energy efficiency, energy balance, and system lifetime.

6.2.1. MSCR algorithm

The MSCR algorithm is a distributed algorithm designed to deal with the sensing coverage problem by turning off eligible redundant nodes to conserve energy in wireless sensor networks. To evaluate the performance of the MSCR algorithm for its ability to find eligible redundant nodes, we run different simulations with different sensor nodes uniformly dispersed in a square field with dimension $400 \times 400\ \text{m}^2$.

Fig. 5 shows a snapshot of a scenario with $k = 2$. In this figure, the square nodes are active nodes, the circle nodes are redundant nodes, and the cube nodes are cluster heads. Fig. 6 plots the percentage of redundant nodes versus sensing ranges with sensing coverage level varying from 1 to 4. To evaluate the performance of MSCR algorithm with varying network density, we run the simulation with the k-coverage level set to 2 while varying the number of sensor nodes in the same field; the sensing range and communication range are set to 30 m and 90 m respectively. The results are plotted in Fig. 7. Clearly seen from this plot, we can schedule a significant number of nodes to be off-duty while guaranteeing k-coverage requirement.

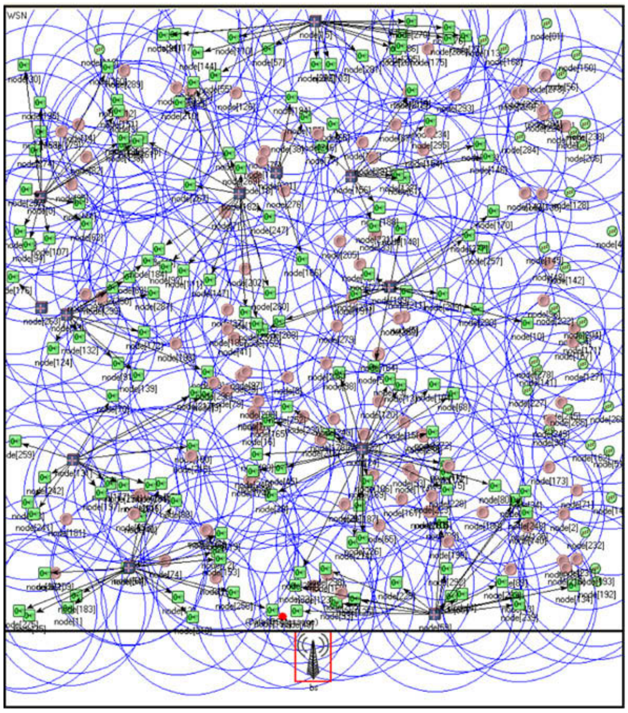

Fig. 5. A snapshot of the MSCR-LEACH protocol with $k = 2$ (the square nodes are active nodes, the circle nodes are redundant nodes, and the cube nodes are cluster heads).

Table 1
Simulation parameters.

Parameter	Value
Initial energy ($E_{initial}$)	2 J
Data packet size	500 byte
Broadcast packet size	25 byte
Packet header size	25 byte
Data frames	30
Energy of transceiver electron (E_{elec})	50 nJ/bit
Energy for transmission in free space model (E_{fs})	10 pJ/bit/m^2
Energy for transmission in multi-path model (E_{mp})	0.0013 pJ/bit/m^4
Threshold distance (d_0)	75 m

6.2.2. Energy efficiency

To evaluate the energy performance and network lifetime, in the next experiment, we compare the MSCR-LEACH with the original LEACH. The performance metrics used to evaluate the system lifetime are the number of surviving nodes and the average energy remaining per round of activity. The overall network lifetime is the continuous operational time of the system before a certain number of nodes dies or the average residual energy drops below a specified threshold. In these simulations, we stop the simulation after 70% of nodes die or the threshold of 10% for average residual energy is reached. In these simulations, a number of sensor nodes are uniformly and randomly deployed within a square area $400 \times 400\ \text{m}^2$ with a difference of k-coverage and sensing range parameters.

Fig. 8 shows the average residual energy in the whole system versus the network lifetime in rounds with different k-coverage. The simulation runs with 1500 sensor nodes deployed within a $400\ \text{m} \times 400\ \text{m}$ area. The communication range and sensing range are set to 60 m and 20 m respectively. In the original LEACH, the system lifetime is only 800 rounds because the majority of nodes have run out of energy. The MSCR-LEACH runs longer than the original LEACH with lifetime up to about 1400 rounds (with coverage level $k = 1$) before the predefined threshold expires. The MSCR-LEACH achieved better performance than the original LEACH as a smaller subset of active nodes consumed less energy than the whole nodes in each cluster. As a result, we can extend the overall system lifetime from

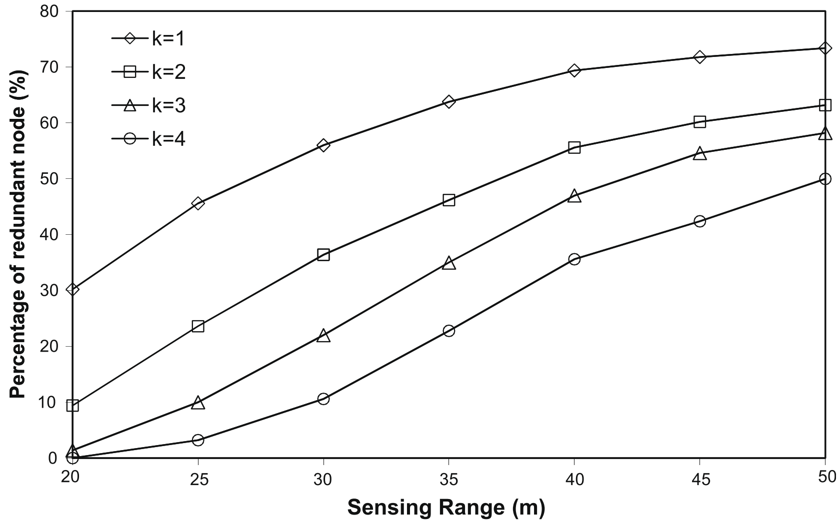

Fig. 6. Percentage of redundant nodes versus sensing ranges with different sensing coverages (600 sensor nodes in an 400 m × 400 m area).

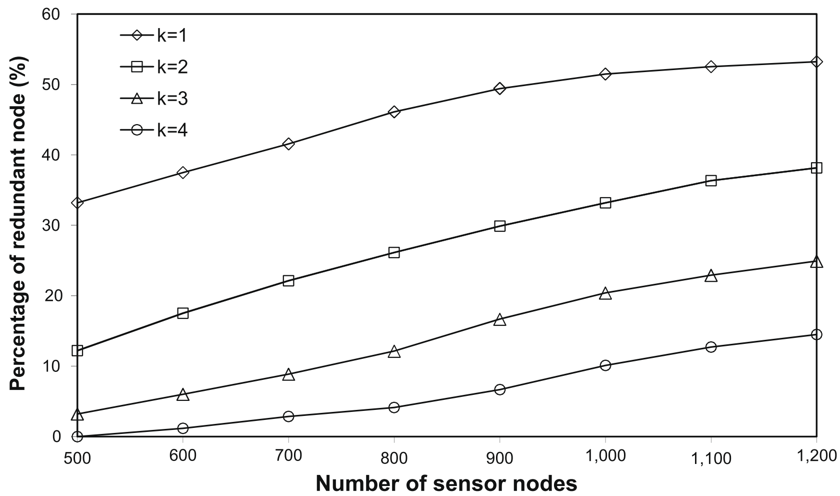

Fig. 7. Percentage of redundant nodes versus network densities with different sensing coverages (up to 1200 sensor nodes in a 400 m × 400 m area, sensing range 30 m).

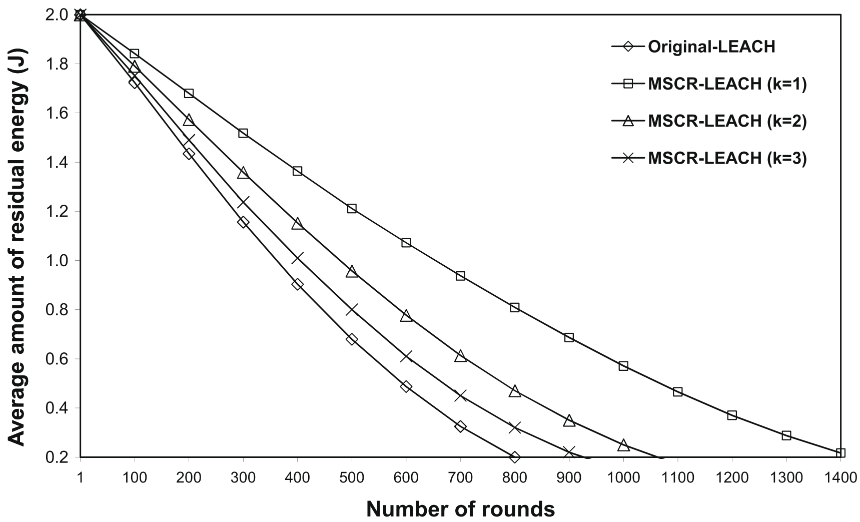

Fig. 8. The average amount of residual energy versus rounds with different sensing coverages (1500 sensor nodes in a 400 m × 400 m area, sensing range 20 m).

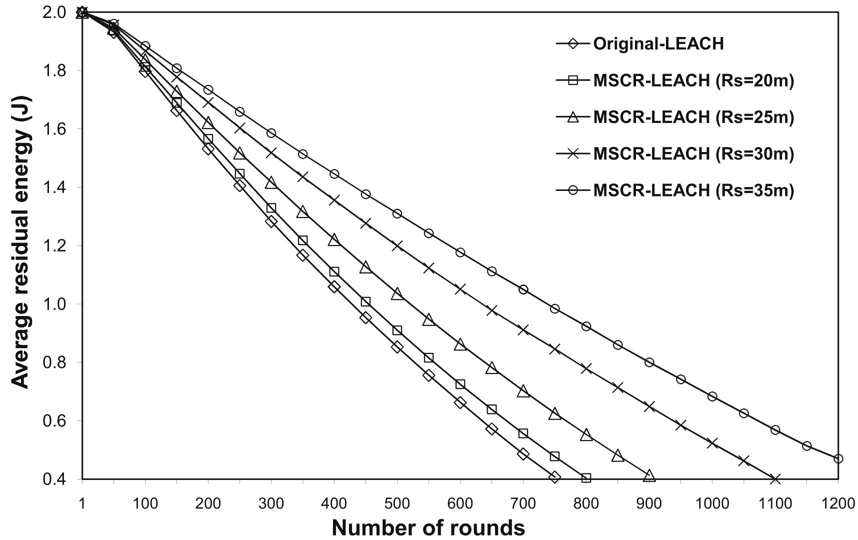

Fig. 9. The average amount of residual energy versus rounds with different sensing ranges (800 sensor nodes in a 400 m × 400 m area, $k = 2$).

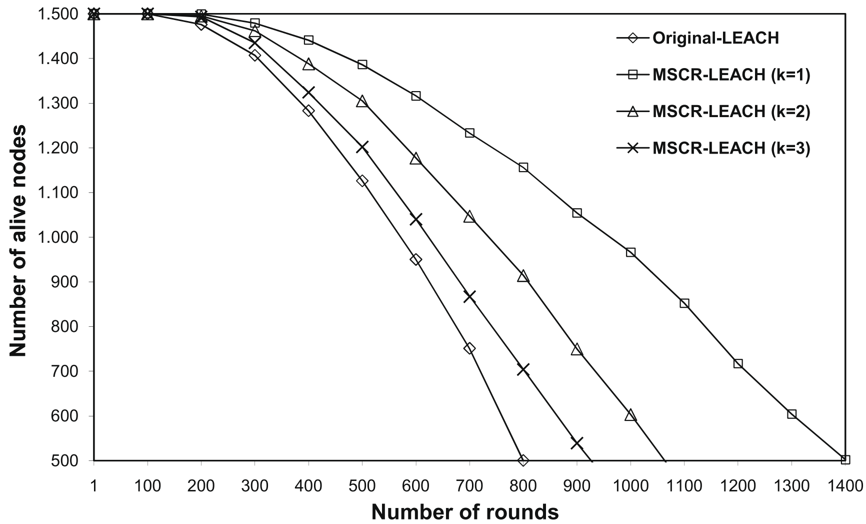

Fig. 10. Number of alive nodes versus the number of rounds with different sensing coverages (1500 sensor nodes in a 400 m × 400 m area, sensing range 20 m).

15% up to 75% depending on k from the k-covered requirement.

Fig. 9 shows the average residual energy in the whole system versus the round time with different sensing range. In this simulation, 800 sensor nodes are deployed in the $400 \times 400\ m^2$. The parameter k-coverage is set to 2. Our method MSCR-LEACH achieves better performance than the original-LEACH. Especially, the method achieves greater advantage as the number of sensors or network density increases.

6.2.3. Energy balance

Figs. 10 and 11 show the number of surviving nodes versus the system lifetime. The MSCR-LEACH has more live nodes than the original LEACH protocol at any time. This is mainly because active nodes and redundant nodes are scheduled alternately by rounds. That means they can share load or spread energy consumption out to every node over the whole network. In the case of the original LEACH protocol, all sensor nodes are active at the same time. The density of active nodes in the network is higher than the MSCR-LEACH, sensing areas widely overlapped. However, note that a larger number of active nodes do not necessarily imply a better network sensing coverage. The performance of the network is lower due to wasting energy for sensing and processing redundant data.

In summary, the above results show that our algorithm can balance energy, reduce energy consumption, and extend significantly network lifetime.

6.3. Discussion on other attributes

In our method, there is no negative impact caused by reducing the redundancy that exists in the network. We will discuss here how the method impacts network attributes such as coverage, application quality, delay,

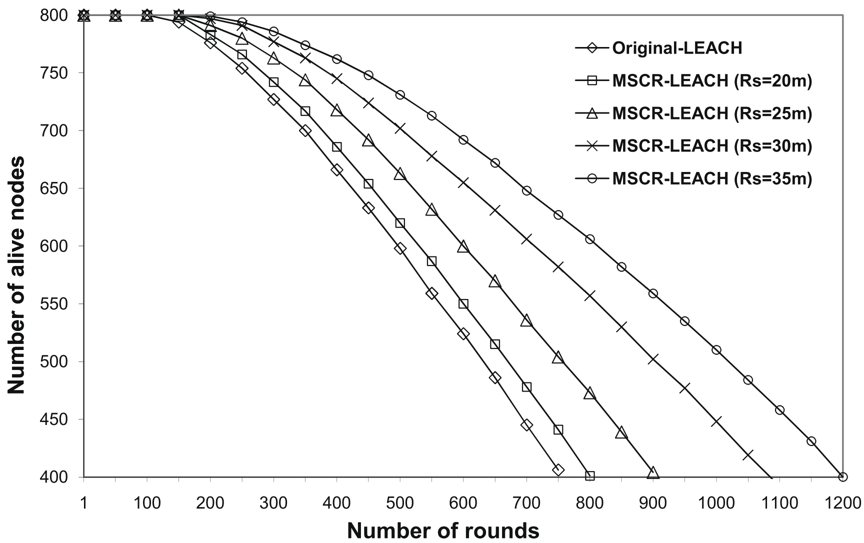

Fig. 11. Number of alive nodes versus the number of rounds with different sensing ranges (800 sensor nodes in a 400 m × 400 m area, $k = 2$).

and connectivity. The other factors such as energy efficiency, load balance, and network lifetime are our positive impacts that were shown clearly in the previous subsection.

As described in Section 4, our method identifies redundant nodes in high-density networks and then assigns them an off-duty operation mode without losing coverage requirement. This means that a sensor should not be sleeping unless its sensing area is sufficiently covered by its active neighbors. In other words, the sensing or application quality is absolutely guaranteed. Moreover, together with the advantage of gossiping itself, reducing the number of redundant nodes will also reduce the collision and overhead. Therefore, the reduction of the proposed method does not impact time delay.

As we assumed that the communication range of a sensor R_c is at least twice its sensing range R_s, k-coverage can guarantee k-connectivity [10,14,19]. Clearly, in our simulation, the percentage of redundant nodes depends on the network density. In case of networks that have a low density of nodes, our method just has low or no improvement. The network connectivity of both LEACH and MSCR-LEACH are the same. Therefore, we do not compare packet losses or any other failures during the run of the MSCR-LEACH protocol.

7. Conclusion

In this paper, we have defined the maximum sensing coverage region problem for randomly distributed WSNs and proposed a gossip-based sensing-coverage-aware algorithm to solve this problem. Simulation results confirmed that our method reduced total energy consumption in the whole system and significantly increased network lifetime.

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