Energy-efficient Barrier Coverage in WSNs with Adjustable Sensing Ranges

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***Abstract*—Energy-efficient barrier coverage is an important issue in wireless sensor networks. In this paper we study the problem of how to maximize the lifetime of a barrier, where sensors have adjustable sensing ranges. In our approach, each node is divided into some virtual sub-nodes according to the available sensing ranges. For small-scale sensor networks, we construct a barrier coverage graph where a link exists between two sub-nodes in two different nodes, if their sensing ranges overlap. We propose to use a linear programming optimization method based on the exhaustive search of all possible barriers in the constructed graph to find the optimal barriers and their respective operation times. For large-scale sensor networks, we propose two distributed heuristics: one is to randomly select, from its neighboring sub-nodes, a next sub-node to construct barriers; another is to greedily select a next sub-node to best match the lifetime of the barrier constructed before choosing this sub-node. Simulation results show that compared with the randomized one, the greedy scheme can achieve longer lifetime and lower message overhead.**

***Index Terms*—barrier coverage, energy-efficiency, lifetime maximization, wireless sensor networks**

I. Introduction

Barrier coverage is an important issue in wireless sensor networks (WSNs) [1] [2] [3]. In order to detect intruders as they traverse a protected area, a chain of sensors should be constructed across the region with the sensing areas of adjacent sensors overlapping with each other. This chain of sensors is referred to as a barrier to detect intruders attempting to cross the network. Applications of barrier coverage include country border control, critical infrastructure (e.g.,ports, nuclear powerplants) protection and etc. All these applications require sufficient number of sensors to be active for barrier construction. An important issue in sensor networks is power scarcity, driven in part by battery size and weight limitations.

Mechanisms that optimize sensor energy utilization have a great impact on prolonging the network lifetime. Power saving techniques can generally be classified into two categories: scheduling the sensor nodes to alternate between active and sleep mode, and adjusting the transmission or sensing range of the sensor nodes. Sensor scheduling can be used to select an active sensor set with adjustable sensing ranges such that different barriers can work successively to maximize the barrier lifetime. A sensor can participate in multiple sensor sets, but the sum of the energy spent in each set is constrained by the initial energy. For some practical reasons, such as, uneven load, different recharging rate, unanticipated failures, additional deployment and etc, the deployed sensors may have different initial energy (referred as the heterogeneous lifetime). Therefore, multiple power levels with different power consume rates can greatly prolong the lifetime of barrier coverage in the heterogeneous lifetime case.

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In this paper we consider sensors with adjustable sensing range that are deployed under the line-based deployment strategy [5] to monitor a rectangle region. The goal is optimizing sensor energy utilization in order to extend the lifetime of barrier coverage over the rectangle. We propose a novel adaptive node scheduling algorithm: each node is divided into some virtual sub-nodes with different sensing ranges, and a sub-node is assumed to be able to cover a disk area centered at itself with a sensing range r. For a small-scale sensor network, we exhaustively search all possible barriers and a linear programming solution is then adopted to schedule their operational times such that the barrier lifetime can be maximized. Moreover, two heuristics are proposed. The contributions of this paper are: (1) introduce the maximizing barrier lifetime problem where sensors have adjustable sensing range in the heterogeneous lifetime case and mathematically model the optimal solution to this problem for small-scale sensor networks; (2) design efficient distributed heuristics to solve this problem, using random and greedy neighboring selection techniques; and (3) analyze the performance of our approaches through simulations.

The rest of this paper is organized as follows. We discuss the related work in Section II and model the problem in Section III. In section IV, we present our schemes to maximize the barrier lifetime. Performance evaluation results are shown and analyzed in Section V. Conclusions are draw in Section VI.

II. Related Work

Coverage is one of the most important issues of the WSNs [4]. Since sensors have limited battery life, wireless sensor networks are characterized by high node density. It is not necessary to have all sensor nodes operate simultaneously in active mode and different scheduling methods are used to ensure energy-efficient coverage and connectivity.

A range of problems related to energy-efficient barrier coverage have been investigated in the recent years [6] [7] [8]. A widely proposed technique to extend the network lifetime is to use sleep-wakeup sensor scheduling [9] [10]. With this technique, a sleeping schedule for sensors is computed such that at any given time only one subset of sensors are active. The remaining sensors are put to sleep. The challenge is to design a sleeping schedule that maximizes the network lifetime while maintain the desired quality of monitoring. The sleep-wakeup problem, that determines a sleeping schedule for sensors to maximize the network lifetime, is polynomial-time solvable for barrier coverage even when sensor lifetimes are not equal [10]. Kumar et al. [9] develop optimal algorithms to appropriately exploit the redundancy of network so that the lifetime of network is maximized for both homogeneous and heterogeneous lifetimes. While, the sensing power of sensors were assumed to be fixed in their work. Wu and Yang [8] propose two density control models

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for designing energy conserving protocols in sensor networks, using the adjustable sensing range of several levels. Yang et al. [11] studied the minimum energy cost of k-barrier coverage problem in which each sensor has $l + 1$ sensing power levels and formulated the problem into a minimum cost flow problem with side constraints. They use the classical Lagrangian algorithm to find a lower bound of the total energy cost and then proposed two heuristic algorithms for this problem.

In this paper, based on multiple sensing power levels model, we study the problem of maximizing the lifetime of a barrier in a sensor network to determine what sensing power level assignment and sleep-wake-up schedule can be used to make the network last beyond the lifetime of an individual sensor node so that the network lifetime is maximized. A major limitation of the barrier coverage model is that individual sensors can't locally determine whether a network provides barrier coverage, making it impossible to develop localized algorithms. Consequently, many algorithms developed so far for barrier coverage are centralized. Distribution and localization are important properties of a node scheduling mechanism, as it adapts better to a scalable and dynamic topology. In this paper we will concern with designing distributed and localized algorithms (see section V).

III. Network Model and Problem Description

We assume that a set of sensors, $\mathcal{S} = \{s_1, s_2, \cdots, s_N\}$, are deployed under a line-based deployment [5] in a two-dimensional (2D) rectangle with length R_L and width R_W. Under the line-based deployment, sensors are evenly deployed along a specified horizontal line, e.g., $y = 0$. The horizontal coordinate of the ith target landing point is given by

$$x_i = \frac{(2i-1)R_L}{2N}, 1 \leq i \leq N$$

The offset distances of sensor s_i in the horizontal and vertical directions are denoted as δ_i^x and δ_i^y, respectively. The actual landing point of sensor s_i can be modeled by $(x_i+\delta_i^x, \delta_i^y)$, where we assume that the random offset distances follow Gaussian distributions with zero mean and σ^2 variance, i.e., $\delta_i^x, \delta_i^y \sim N(0, \sigma^2)$. In this paper, we assume that each sensor knows its own coordinate $(x_i, y_i), i = 1, 2, ...N$.

In this paper, we consider a disk sensing (coverage) model: If an event happens at a distance less than or equal to the sensing range r from the sensor location, the sensor can detect the event; otherwise, it cannot detect the event. Generally, the sensor's energy consumption (power level) is a function of it's sensing range. For example, in [12], it is assumed that the power level is proportional to r_s^2; while in [13] the power level is proportional to r_s^4. In this paper, we use following power consumption model:

$$p(r_s) = a \cdot r_s^{\alpha} \tag{1}$$

where $a > 0$ and $\alpha > 0$ are constants.

In this paper, we assume that each sensor node s_i has K different sensing ranges $0 < r_1 < r_2 < \cdots < r_K$, and the corresponding power levels are $0 < p_1 < p_2 < \cdots < p_K$. Note that a sensor can choose to be inactive such that its sensing range is 0 and consumes no energy. As illustrated in Fig.1, each sensor has three sensing ranges, r_1, r_2, r_3. When the sensor s_i chooses to use the sensing range r_3, and the sensor s_j uses r_2 or r_3, then their coverage disks have overlapped area and the two sensors form a piece of barrier. However, the two sensors can form no barrier at all, if, say for example, both s_i and s_j use r_1 as their respective sensing range.

Without loss of generality, we assume to construct a sensor

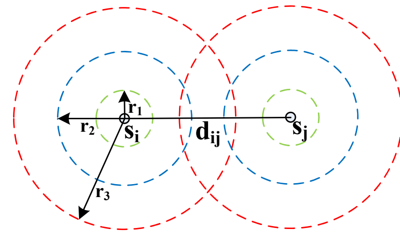

Fig. 1: Sensing discs at different power levels.

barrier from the left side to the right side in the rectangular sensor field. We define a *virtual start sensor* s and a *virtual terminate sensor* t, respectively, located at the left boundary and right boundary of the sensor field. A sensor s_i is said to be connected with s, or there exists a link between s_i and s, if s_i can find at least one sensing range such that its corresponding coverage disk overlaps with the left boundary. Similarly, a sensor s_j connects with t, if one of its coverage disks overlaps the right boundary. A sensor barrier is a chain of sensors, denoted by $\mathbf{B}_M \equiv (s, < s_1, ..., s_m, ...s_M >, t)$, and with their respective sensing range denoted by $\mathbf{R}_M \equiv (r_1, ..., r_m, ..., r_M)$, such that s_1 connects with s, s_M connects with t, and for any two consecutive sensors, their sensing disks overlap with each other, that is,

$$\sqrt{(x_m - x_{m+1})^2 + (y_m - y_{m+1})^2} \leq r_m + r_{m+1}, m = 1, 2, \ldots, M-1$$

Let e_i denotes the residual energy of sensor s_i, and is assumed to follow Gaussian distributions with e_0 mean and ${\sigma_e}^2$ variance, i.e., $e_i \sim N(e_0, {\sigma_e}^2)$. In this paper, we consider a simple energy consumption model where the energy consumption is mainly determined by the sensing task. If a sensor chooses the sensing range r_k and uses the sensing power p_k, it can operate at most $\frac{e_i}{p_k}$ unit time. The lifetime (the maximum operation time) of a barrier $\mathbf{B}_M$, denoted by $L(\mathbf{B}_M)$, is determined by the sensor with the minimum operation time, that is, $L(\mathbf{B}_M) = \min\{\frac{e_m}{p_m}\}, m = 1, ..., M$. However, we can assign a barrier with the operation time t not larger than its lifetime, i.e., $t \leq L(\mathbf{B}_M)$. After this barrier has worked for t unit time, we construct another barrier and assign it a new operation time. This process continues until no barrier can be found. The *network barrier coverage lifetime* can thus be defined as the sum of the operation time from all constructed barriers.

In this paper, we define the following barrier coverage lifetime maximization problem: Given a sensor network, finding a series of barriers and their corresponding operation times such that the network barrier coverage lifetime can be maximized. Different from the problem in [9] where each sensor has a fixed sensing range, our problem considers that each sensor has adjustable sensing ranges. Therefore, we also need to determine the sensor sensing range and its transmission power, when constructing a barrier and assigning its operation times.

IV. An Optimal Solution for Maximizing Network Barrier Lifetime

In order to solve the problem of barrier lifetime maximization with adjustable sensing ranges, we first divide s_i into K sub-nodes $\{q_{i,1}, q_{i,2}, \cdots, q_{i,K}\}$ for each sensor $s_i, i = 1, 2, ..., N$ according to their available sensing ranges. That is, the sub-node $q_{i,k}$ chooses the sensing range r_k and uses the power level p_k, $k = 1, 2, ..., K$. Note that all sub-nodes $q_{i,k}$ have the same coordinates as those of s_i. We denote $L_i^k = \frac{e_i}{p_k}$ as the lifetime of the sub-node $q_{i,k}$.

We next construct an auxiliary network barrier coverage graph

$G = (V, E)$ as follows. In the graph, V is the set of all sub-nodes plus the two virtual nodes s and t. The graph G is a directed graph, and the set of edges E is constructed as follows. 1) There exists a directed edge from s to $q_{i,k}$, if the sensing range r_k used by $q_{i,k}$ intersects with the left boundary; 2) There exists a directed edge from $q_{j,k}$ to t, if the sensing range r_k used by $q_{i,k}$ intersects with the right boundary; 3) For two sub-nodes $q_{i,k}$ and $q_{j,k'}$, if $x_i < x_j$ and the sensing disks of the two sub-nodes overlaps each other, then there exists a directed edge from $q_{i,k}$ to $q_{j,k'}$. An example of the constructed barrier coverage graph is shown in Fig. 2. There are in total 6 distinct paths from s to t, the red edges (dash-dot line) and the blue edges (dash line) represent a path respectively and the green edges (dot line) are their common edges.

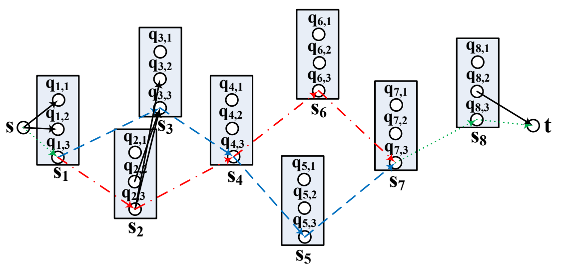

Fig. 2: An auxiliary barrier coverage graph with 6 sensors and 18 sub-nodes. Each sensor has three transmission ranges.

Based on the constructed graph, we use a depth-first search (DFS) algorithm [14] to exhaustively search all possible paths from s to t consisting of sub-nodes (each path is a barrier). The set of all paths is denoted by $\mathcal{B} = \{\mathbf{B}^{(1)}, \mathbf{B}^{(2)}, \cdots, \mathbf{B}^{(J)}\}$, where $\mathbf{B}^{(j)} \equiv (s, < q_{j_1, j_{1k}}, \cdots, q_{j_{m_j}, j_{m_{jk}}} >, t)$ contains m sub-nodes. We assign each path $\mathbf{B}^{(j)}$ a working time t_j, where $t_j \leq \min_{q_{i,k} \in \mathbf{B}^{(j)}} \{\frac{e_i}{p_k}\}$. The network barrier coverage lifetime can be defined by $\sum_{j=1}^{J} t_j$, and each sensor cannot work more than its lifetime. Therefore, our problem can be formulated as the following constrained optimization problem:

$$Maximize \sum_{j=1}^{J} t_j, \tag{2}$$

subject to

$$\sum_{j=1}^{J} E(s_i, \mathbf{B}^{(j)}) \cdot t_j \leq e_i, \quad \text{for all } 1 \leq i \leq n \tag{3}$$

where $E(s_i, \mathbf{B}^{(j)})$ denotes s_i's energy consumption in the path $\mathbf{B}^{(j)}$.

The linear programming method can be used to solve the above optimization problem. The total number of all available paths are in the order of $\mathcal{O}(K^N)$, where N is the number of sensors and K is the number of adjustable power levels. Therefore, the optimal solution is easy to obtained only for small-scale networks with small values of N and K. Besides, the optimal solution is centralized, thus some heuristic distributed algorithms are required to solve this problem adapting better to a scalable and dynamic topology. In the next section, for large-scale networks, we propose two distributed heuristics to approximately solve our problem.

V. Two Distributed Heuristic Algorithms

In this section, we propose two distributed heuristic algorithms, called Greedy Selection(GS) and Random Selection(RS) algorithm respectively.

A. Main Idea

The main idea about heuristic algorithms is as follows:

1) Initial Sub-node Selection: A sub-node near the left boundary of the field should be selected as an *initial sub-node*. A timer-based competition process is executed to select an *initial sub-node*. Any sub-node with its sensing range intersecting with the left boundary can participate in this competition process, and it sets its timer randomly in the RS algorithm or sets its timer as the inverse of its lifetime (its residual energy divided by its sensing power) in the GS algorithm.

2) Neighboring Sub-node Selection: A sub-node selects, from its neighboring sub-nodes, a next sub-node as its next node of barrier. We always randomly select a neighboring sub-node in RS; While in GS, we try to select a neighboring sub-node $q_{u,m} \in N_v^n$ to minimize $\|L_u^m - LIFE\|$, where $LIFE$ is the life of the barrier constructed so far. The idea behind this strategy is to find the best matching sub-node such that the formed barrier can have a balanced lifetime among the constructing sensors.

3) Go-Back k-Steps: In the barrier construction process, it is possible that one sub-node cannot find a next sub-node, and if this happens, the process goes-back k-steps to re-do the selection process by excluding the previously selected sub-nodes.

B. Protocol Design

We assume a disk transmission model and the communication range r_c is two times larger than the largest sensing range, i.e., $r_c > 2r_K$.

A sub-node $q_{v,n}$ locally stores PD_v^n and PR_v^n, indicating the sub-node $q_{PR_v^n, PR_v^n}$ is the previous sub-node of $q_{v,n}$ in the constructed barrier, L_v^n indicates the working lifetime of sub-node $q_{v,n}$, and a variable A_v^n indicates whether sub-node $q_{v,n}$ is useable ($A_v^n = 1$) or unusable ($A_v^n = 0$). We denote the virtual start and terminate sub-node by, respectively, $s = q_{s,0}$, $t = q_{t,0}$, that is, the sensing range of s and t is 0. A neighboring sub-node list

$$N_v^n = \{q_{i,j} | \sqrt{(x_i - x_v)^2 + (y_i - y_v)^2} \leq r_j + r_n, x_i > x_v, L_i^j > 0\}$$

There are two types of message(*FORWARD* and *BACKWARD*), whose structures are both shown in Fig.3. *FORWARD* message is sent from sub-node $q_{v,n}$ to its neighboring sub-node $q_{u,m}$, and *BACKWARD* message is sent from a neighboring sub-node $q_{u,m}$ of $q_{v,n}$ to $q_{v,n}$. *SUCCESS* field be 1 means a barrier is found. We will update local variables based on the values in the broadcast message from sub-node q_u^m. The details of this

FORWARD message

1 bit	1 bit				
FORWARD	src_ID	src_range	dest_ID	dest_range	LIFE

BACKWARD message

1 bit	1 bit			
BACKWARD	SUCCESS	dest_ID	dest_range	LIFE

Fig. 3: Structures of *FORWARD* and *BACKWARD* message.

mechanism including subroutines are showed in **Alg.1** and **Alg.2**. After deployment, all sub-nodes boot up and initialize. After initialization, all sub-nodes keep on waiting for an incoming message (MSG) to be processed. When sub-node $q_{v,n}$ receives a *FORWARD* message from sub-node $q_{u,m}$, it follows the steps in **Alg.1** to process it: if there exists $q_{i,j} \in N_{v,n}|A_i^j = 1$, it will send *FORWARD* message to one of its useable neighboring sub-node and let $q_{u,m}$ be the previous node of $q_{v,n}$; if no such neighboring sub-node exists, it will send a *BACKWARD* message to $q_{PR_v^n, PR_v^n}$. When a *BACKWARD* message from $q_{u,m}$ to $q_{v,n}$, $q_{u,m}$ will check the *SUCCESS* bit to see whether it should update L_u^i with $L_u^i - LIFE$ $(1 \leq i \leq l)$. If *SUCCESS* bit is 0, that is there no $q_{i,j} \in N_{v,n}|A_i^j = 1$, then $q_{v,n}$ will try to send a *FORWARD* message to another unuseable sub-node, the details are shown in **Alg.2**.

Algorithm 1: Process 1 MSG(FORWARD, src_ID, src_range, dest_ID, dest_range, LIFE)

```
if v == dest_ID and n == dest_range then
  if exists a useable node in N_v^n then
    choose a useable node q_{u,m}(A_u^m = 1) from N_v^n;
    A_v^n = 1; PD_v^n = src_ID; PR_v^n = src_range;
    L_v^n = min(LIFE, L_v^n);
    if m == 0 then
      MSG(BACKWARD, 1, PD_v^n, k, LIFE), 1 <= k <= l;
    else
      MSG(FORWARD, v, n, u, m, L_v^n);
    end if
  else
    A_v^n = 0;
    MSG(BACKWARD, 0, PD_v^n, PR_v^n, LIFE);
  end if
end if
```

Algorithm 2: Process 2 MSG(BACKWARD, SUCCESS, dest_ID, dest_range, LIFE)

```
if v == dest_ID and n == dest_range then
  if SUCCESS == 1 and n != 0 then
    L_v^n = L_v^n - LIFE;
    MSG(BACKWARD, 1, v, n, PD_v^n, PR_v^n, LIFE);
  else if SUCCESS == 0 then
    if n == 0 then
      algorithm terminate;
    else
      choose a useable node q_{u,m} from N_v^n;
      MSG(FORWARD, v, n, u, m, L_v^n);
    end if
  end if
end if
```

C. Greedy Selection and Random Selection

The techniques of these two schemes are summarized as follows: Firstly, an sub-node is selected as *initial sub-node* according to *Initial Sub-node Selection*. Secondly, according to *Neighboring Sub-node Selection*, we can construct a barrier one by one from *initial sub-node*. Note that in the barrier construction process, it is possible that one sub-node $q_{v,n}$ can't find any neighboring sub-node, and if this happens, the process goes-back 1-steps to re-do the selection process by excluding $q_{v,n}$. Obviously, the lifetime of the obtained barrier is the minimal lifetime of these sub-nodes constructing the barrier. During the barrier construction, the operation time t is also computed (and modified, if necessary), and each selected sub-node will work for t time unit. Thirdly, after t time unit operation, the barrier construction process will be executed again. If the energy of any sub-node in the barrier is exhausted, the corresponding sensor node will be picked out, and an new initial sub-node should be selected again. These steps will be repeated until no any barrier can be constructed. Apparently, the total lifetime of each found barrier is the lifetime of the network.

The main differences between GS and RS are their selection criterions for selecting *initial sub-node* and neighboring sub-node.

VI. Performance Evaluation

In this section, we evaluate the performance of optimal algorithm, greedy selection and random selection. We simulate a stationary network with sensors deployed along the horizontal central line in a rectangle of size 200×20 under line-based deployment, as described in Section III. The energy consumption model is quadratic $(p(r_s) = \Theta(r_s^2))$. Each data point in this section is an average result of 10000 different network deployments.

In the first experiment in Table I, we compare the network lifetime computed by optimal solution, greedy selection and random selection when we vary the number of sensors between 9 and 12 with an increment of 1. Each sensor has three adjustable sensing ranges, 8, 10 and 12. The variance of Gaussian distribution is: $\sigma^2 = \sigma_e^2 = 1$. The total paths obtained by exhaustive search are beyond the maximum dimension of array in MATLAB when $N = 13$. Network lifetime results returned by the greedy heuristic are close to the optimal lifetime ones; while the gap extends to increase with the increase of sensor density. When more sensors are deployed, region is covered by more sensors, thus more barriers can be formed and linear programming can optimize the total lifetime better.

TABLE I: Barrier Lifetime

Number of sensors	9	10	11	12	13
Optimal scheme	33.28	34.47	39.96	47.01	-
Random scheme	33.08	33.40	33.76	33.97	34.23
Greedy scheme	33.21	34.06	35.99	41.41	45.84

To contrast the performance between two heuristic algorithm GS and RS, we vary the number of sensors increasing from 15 to 55 with an increment of 5, and each sensor has three adjustable sensing ranges, 8, 10 and 12. We set σ = 1, 2, and σ_e = 1, 2. Four comparison results on network lifetime are shown in Fig. 4 and Fig.5(a)(b)(c)(d) presents the corresponding message overhead of two heuristic algorithms. Simulation results indicate that the strategies of sub-node selection has great impact both on lifetime and message overhead. As shown, GS has better performance than that of RS, with longer lifetime and less message overhead. Especially, we can see that when $N = 25$, the lifetime of GS is twice as much RS's lifetime; While the message overhead is only two-thirds of RS's. Compared with RS, the GS always tries to select the best suitable sub-node leading a higher probability of constructing barrier (less message overhead) and a more sufficient use of each sub-node's residual energy in the constructed barrier(longer lifetime). In other words, energy-balanced barrier can lead to longer lifetime of network barrier coverage. Moreover, the result curves of lifetime and message overhead are more stable with less undulation for both GS and RS, when $\sigma = \sigma_e = 2$ (as illustrated (d)). We say the model of

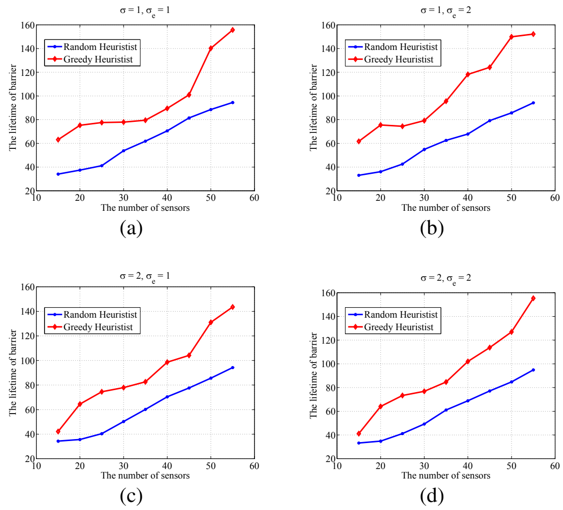

Fig. 4: The comparison of heuristics on network lifetime.

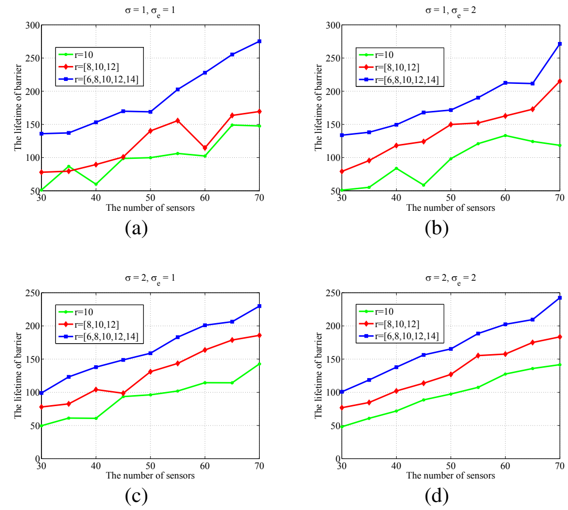

Fig. 6: The lifetime obtained by GS with different levels.

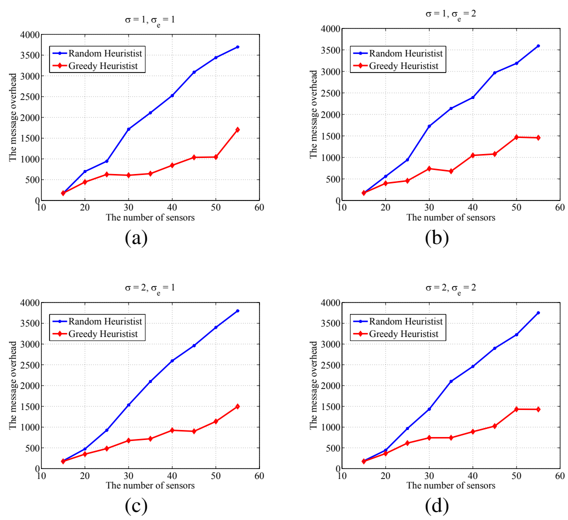

Fig. 5: The comparison of heuristics on message overhead.

three adjustable sensing ranges, 8, 10 and 12 is suitable for the case $\sigma = \sigma_e = 2$.

In the third experiment in Fig. 6, we study the impact of the number of adjustable sensing ranges on network lifetime in GS. We set the number of sensors increasing from 30 to 70 with an increment of 5, and $\sigma = 1, 2$, $\sigma_e = 1, 2$. We compare the network lifetime when sensors support up to 5 sensing range adjustments: $r_1 = 6, r_2 = 8, r_3 = 10, r_4 = 12, r_5 = 14$, and we vary l from 1 to 3 with sensing range centered by 10 spacing 2. Note that $l = 1$ is the case when all sensor nodes have a fixed sensing range with value 10. Simulation results indicate that adjustable sensing ranges have great impact on network lifetime, more multiple levels leading to better performance. This simulation results also justify the contribution of this paper, showing that adjustable sensing ranges can greatly contribute to increasing the network lifetime. Moreover, how to determine right power levels based on σ_e and σ is a new challenge. These conclusions are great guide to future work on network lifetime.

VII. Conclusion

We have studied the maximum network lifetime of 1-barrier coverage problem, and propose an optimal scheme and two effective distributed heuristic algorithms for this problem. We have implemented the proposed algorithms and compared their performance with simulations. Results show that our GS heuristic algorithm is effective. Moreover, a reasonable power consumption model, power levels and sensor deployment based on the realistic application environment can greatly improve the lifetime of network barrier coverage. The results obtained in this paper will provide important guidelines and insights into maximizing lifetime of wireless sensor networks for barrier coverage.

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