A Greedy Algorithm for Target Coverage Scheduling in Directional Sensor Networks*

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Abstract

The wireless sensor networks have emerged as a promising tool for monitoring the physical world. Recently directional sensor networks (DSNs) consisting of directional sensors have gained attention. DSNs comprise a large number of sensors equipped with limited angles of sensing range and a limited battery. In DSNs, maximizing network lifetime while covering all the targets in a given area is still a challenge problem. A major technique to save the energy power of sensors is to use a node wake-up scheduling protocol by which some sensor nodes stay active to provide sensing service, while the others are inactive for conserving their energy. In this paper, we first address the MSCD (Maximum Set Cover for DSNs) problem that is known as NP-complete and then present a new target coverage scheduling scheme to solve this problem with a greedy algorithm. To verify and evaluate the proposed scheme, we conduct simulations and show that it can contribute to extending the network lifetime largely. By the simulations, we also present an energy-efficient strategy to choose a sensor in order to organize a scheduling set in the greedy scheme.

1 Introduction

Wireless sensor networks (WSNs) have been employed in various application fields, such as environmental monitoring, battlefield surveillance, smart spaces, and so on [2]. WSNs are typically composed of a great number of sensors that have sensing, data processing, and communication functionalities. In WSNs, *coverage* determines how well an area (or points) of interest is monitored or tracked by sensors [8]. There are three types of coverage classified based on what is to be covered, namely area coverage, target (discrete point) coverage and barrier coverage. In this paper, we focus on the target coverage [3, 4] in a randomly deployed sensor network where the density of sensor nodes is enough high to monitor most targets.

For the target coverage problem, it is essential that sensors should monitor all the targets continuously for a long time as possible. Once sensors are randomly scattered, it is hardly possible to replace their

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battery by a new one or be recharged [13, 9]. Accordingly, under such circumstances, the problem of maximizing the network lifetime while covering all the targets is an important issue. To achieve this purpose, each sensor should minimize its battery consumption in an energy-efficient manner. Typically, the radio state of sensors falls into four kinds of states: transmit, receive, idle, and sleep [3, 4]. We can denote transmit, receive, and idle states as an active state, because these three states consume more energy than a sleep one. Therefore, a scheduling scheme to properly alternate between active and sleep states will be a promising method to extend the network lifetime.

There have been a lot of works to maximize the network lifetime by alternating sensors between active and sleep states. In particular, these works have assumed that WSNs have omni-directional sensors, each of which can sense an omni-directional range at every instance [3, 4, 11]. Recently, directional sensors such as camera sensors, ultrasonic sensors, infrared sensors, etc. have emerged in sensor markets due to the constraints of manufacturing techniques, size and cost [1, 12]. The networks consisting of such sensors, i.e., directional sensor networks (DSNs), are widely used. The most distinguishing characteristic of them is the limited sensing angle. Each directional sensor can sense only a sector of the disk, centered at itself, with the radius being equal to the sensing range. Rotation enables directional sensors' working in distinct directions so as to facilitate cooperation between neighboring directional sensors. Unlike WSNs, target coverage in DSNs is determined by both location and direction of sensors. This feature of DSNs makes a target coverage scheduling more complex. As a result, maximizing the network lifetime of DSNs is still a challenge problem. Nevertheless, there are few works dealing with the target coverage problem in DSNs.

In this paper, we study a problem of target coverage scheduling in DSNs, in which directional sensors have limited battery capacity and are randomly and densely deployed to cover all targets. We describe the *MSCD (Maximum Set Covers for DSNs) problem* that finds the cover sets monitoring all the targets in an energy-efficient way and maximizes the network lifetime by assigning different scheduling time to each cover set. As referred in [1], this problem is known as NP-complete. To solve the problem, we first devise a greedy heuristic algorithm which has the advantage of finding a solution faster than other heuristic ones. Simulation results verify that the proposed algorithm can solve the MSCD problem efficiently. By the simulation, we also present an energy-efficient strategy to choose a sensor in order to organize a scheduling set in the greedy algorithm.

The rest of this paper is organized as follows. In Section 2, we formally define the MSCD problem. In Section 3, our greedy algorithm to solve the problem is given. In Section 4, we present the performance evaluation of the proposed scheme with simulations. Section 5 concludes the paper.

2 Related Works

The target coverage concept is one of the fundamental measures of the quality of service (QoS) of the sensing function. The goal is to have each target in the physical space of interest within the sensing range of at least one sensor. A survey on target coverage problems in wireless sensor networks is presented in [6, 5]. The initial works relevant to our study in this paper are [3, 4]. [3] introduced the target coverage problem, where disjoint sensor sets are modeled as disjoint cover sets, such that every cover set completely monitors all the targets. The problem was called *MSC (Maximum Set Covers)*. The MSC problem was proved to be NP-complete in the study. The MSC problem was reduced to a maximum flow problem, which was then modeled as mixed integer programming. This problem was further extended in [4], where sensors was not restricted to participation in only disjoint sets, that is, a sensor could be active in more than one set. [4] proposed two heuristic algorithms to solve the MSC problem: LP (linear programming)-MSC and Greedy-MSC. The authors showed that the Greedy-MSC has lower complexity and running time than the LP-MSC and also that the Greedy-MSC increases the network lifetime more than the LP-MSC. [7] proposed a new sensor scheduling algorithm for the MSC problem based on the branch and bound approach. The heart of proposed algorithm was to find cover sets covering the minimum number of overlapped targets. An overlapped target is the target sensed by adjacent sensors at the same time. When a cover set for the MSC problem contains the sensors covering many overlapped targets, the energy wasted by such sensors become much. The bound step in the branch and bound algorithm has the rule which reflects this energy-saving strategy. The authors compared the performances of the proposed branch and bound algorithm and the Greedy-MSC and got the results that the proposed algorithm is better than the Greedy-MSC in terms of both network lifetime and runtime of execution. [10] considered both the overlapped target and sensors' residual energy at the same time and updated the Greedy-MSC so that it produced more number of cover sets.

This paper is an extension of the MSC problem addressed in [3, 4, 7, 10], for the case when sensor nodes can be directional. Compared to omni-directional sensors, directional sensors are obviously in that the coverage region of a directional sensor is determined by both its location and orientation. The initial work relevant to the coverage issue in DSNs is presented in [1]. The authors formulated the MCMS (Maximum Coverage with Minimum Sensors) problem in which coverage in terms of the number of targets to be covered is maximized whereas the number of sensors to be activated is minimized. They also presented two approximate greedy algorithms: a centralized greedy algorithm (CGA) and a distributed greedy algorithm (DGA). Our work differs from this work because the MSC problem to be solved in this paper is different from the MCMS one. While an optimal configuration of directional sensors and orientations at any instant was formulated by a solution of the MCMS problem, our solution of the MSC problem will produce cover sets as many as possible and thus maximize the network lifetime.

3 Maximum Set Cover Problem in DSNs

Let us consider a DSN composed of N sensors, each of which has W directions and operates only one direction with a uniform sensing range at any instance. We also consider that all sensors are randomly scattered to cover M targets in a two-dimensional plane. We define $S = \{s_1, s_2, \dots, s_N\}$ as the set of N sensors and $R = \{r_1, r_2, \dots, r_M\}$ as the set of M targets. Unlike a sensor network composed of omni-directional sensors, a DSN should additionally consider the definitions concerned with sensor directions.

- $D_{i,j}$: the jth direction of a sensor s_i ($i = 1, 2, \dots N$ and $j = 1, 2, \dots, W$). We assume that a sensor s_i has not any overlap between two neighbor directions.
- D: the collection of $D_{i,j}$ for $i = 1, 2, \dots, N$ and $j = 1, 2, \dots, W$.
- C_k ($\subseteq D$): the kth set of the directions that cover all targets in R such that every element in C_k covers at least one element in R and every two elements in C_k cannot belong to the same sensor in S. We call this set C_k a *cover set*.
- R_m ($\subseteq D$): the set of the directions that cover a target r_m ($m = 1, 2, \dots, M$).
- L_i: the lifetime of a sensor s_i. We assume that a sensor s_i spends a uniform energy regardless of its direction and the number of covered targets when it is active.
- t_k: the allocated active time for the kth cover set ($0 \leq t_k \leq 1$).

Before formally formulating the target coverage problem in DSNs, we show an example of a DSN. In Fig. 1, $r_m (1 \leq m \leq 5)$ is a target and $s_i (1 \leq i \leq 3)$ is a directional sensor. $D_{i,j} (1 \leq i, j \leq 3)$ represents the sensing direction of s_i, and thus $D = \{D_{1,1}, D_{1,2}, D_{1,3}, D_{2,1}, D_{2,2}, D_{2,3}, D_{3,1}, D_{3,2}, D_{3,3}\}$. Also, $D_{i,1}$, $D_{i,2}$, and $D_{i,3}$ denote the three directions of s_i. A target can be monitored only when it is within the

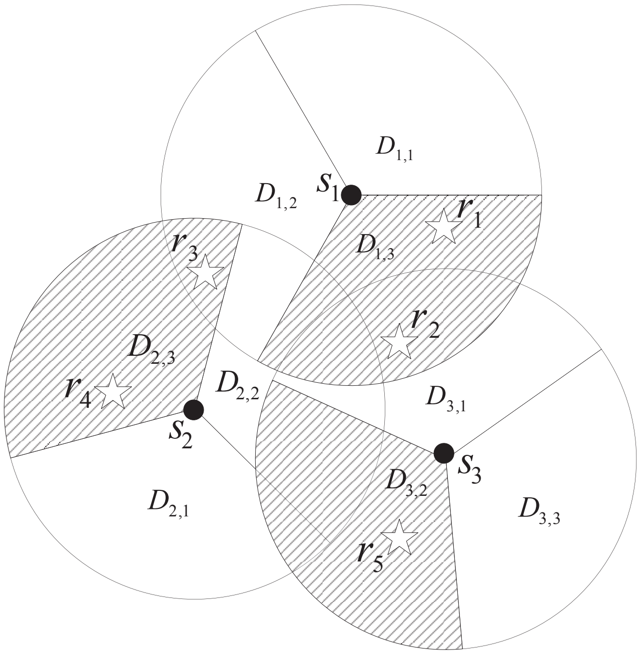

Figure 1: An illustrative example for a directional sensor network with five targets of interest.

current sensing directional of at least one sensor. We can know that $R_1 = \{D_{1,3}\}$, $R_2 = \{D_{1,3}, D_{3,1}\}$, $R_3 = \{D_{1,2}, D_{2,3}\}$, $R_4 = \{D_{2,3}\}$ and $R_5 = \{D_{3,2}\}$. Currently, $\{r_1, r_2\}$, $\{r_3, r_4\}$ and r_5 are monitored simultaneously by s_1, s_2 and s_3 (more specifically by $D_{1,3}$, $D_{2,3}$ and $D_{3,2}$), respectively. Therefore, $\{D_{1,3}, D_{2,3}, D_{3,2}\}$ can represent a cover set C_i.

We organize the directions in D into K cover sets, where K is the maximum number of cover sets for a given coverage relationship between S and R. Since $D_{i,j}$ can belong to multiple cover sets until the lifetime L_i of a sensor s_i completely runs down, we can define a boolean variable $x_{i,j,k}$ as in [1]:

$$x_{i,j,k} = \begin{cases} 1 & \text{if } D_{i,j} \in C_k \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

We define the *MSCD (Maximum Set Covers for DSNs) problem* as follows.

$$\text{Maximize} \quad \sum_{k=1}^{K} t_k \tag{2}$$

$$\text{subject to} \quad \sum_{k=1}^{K} \sum_{j=1}^{W} x_{i,j,k} \cdot t_k \le L_i, \forall s_i \in S \tag{3}$$

$$\sum_{j=1}^{W} x_{i,j,k} \le 1, \forall s_i \in S, k = 1, 2, \ldots, K \tag{4}$$

$$\sum_{D_{i,j} \in R_m} x_{i,j,k} \ge 1, \forall r_m \in R, k = 1, 2, \ldots, K \tag{5}$$

$$\text{where} \quad x_{i,j,k} = \{0, 1\} \text{ and } t_k \ge 0. \tag{6}$$

Equation (3) guarantees that the time allocated for each sensor s_i, across all cover sets, is not larger than L_i, which is the lifetime of each sensor. Equation (4) guarantees that one directional sensor in a cover set has at most one orientation depending on whether it is activated or not. Finally, Equation (5) guarantees that each target is covered by at least one direction in a cover set.

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Greedy algorithm for the MSCD problem $(S, D, R, t)$
1:  set $L_i$ of each sensor to 1
2:  $SENSORS = S$
3:  $DIRECS = D$
4:  $K = 0$
5:  while each target is covered by at least one direction in $DIRECS$ do
6:     $K = K + 1$
7:     $C_K = \emptyset$
8:     $TARGETS = R$
9:     while $TARGETS \neq \emptyset$ do
10:       $D_c = \emptyset$
11:       find a critical target $r_c \in TARGETS$
12:       find all directions $\in DIRECS$ that cover $r_c$ and insert them into $D_c$
13:       select a direction $D_{s,t} \in D_c$ with the greatest contribution
14:       $C_K = C_K \cup \{D_{s,t}\}$
15:       for each direction $D_{i,j} \in DIRECS$ do
16:          if $i = s$ then
17:             $DIRECS = DIRECS - \{D_{i,j}\}$
18:          end if
19:       end for
20:       for each target $r_i \in TARGETS$ do
21:          if $r_i$ is covered by the direction $D_{s,t}$ then
22:             $TARGETS = TARGETS - \{r_i\}$
23:          end if
24:       end for
25:    end while
26:    for each direction $D_{x,y} \in C_K$ do
27:       $L_x = L_x - t$
28:       if $L_x \leq 0$ then
29:          $SENSORS = SENSORS - \{s_x\}$
30:       end if
31:    end for
32:    $DIRECS = \cup_{j=1}^{W} \{D_{i,j}\}$ for each sensor $s_i \in SENSORS$
33: end while
34: return $K$-number of cover sets and the cover sets $C_1, C_2, \ldots, C_K$
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Figure 2: Greedy algorithm to solve the MSCD problem

4 The Proposed Greedy Algorithm to Solve The MSCD Problem

Fig. 2 describes the details of the greedy algorithm devised to solve the MSCD problem by using a same active time t for all cover sets. It is similar to the one proposed in [4], but modified to capture the characteristics of DSNs. Our algorithm takes as the input parameters S (the set of directional sensors), D (the set of directions), R (the set of targets), and t (the allocated active time of each cover set) As known from the last parameter, $t = t_1 = \cdots = t_K$ in our algorithm. The algorithm consists of the following steps:

Step 1 Initialize the energy of each sensor and the variables $SENSORS$, $DIRECS$, and k. (lines $1 \sim 4$).

Step 2 Increase k by one and initialize the kth cover set and the variable $TARGETS$ (lines $6 \sim 8$).

Step 3 Initialize the variable D_c and a *critical target* r_c is selected (lines 10 ∼ 11). The critical target is defined as the one which a sensor constituting the current cover set should cover due to increase the energy efficiency. We will explain how to select the critical target in Section 5.1.

Step 4 Once the critical target r_c has been selected, our algorithm selects the direction $D_{s,t}$ with the greatest contribution that covers the critical target (lines 12 ∼ 13). Various contribution functions can be defined. In this paper, we use the following function F:

$$F(D_{i,j}, r_c) = \alpha \cdot N_{i,j,c} + (1-\alpha) \cdot L_i, \ 0 \le \alpha \le 1. \tag{7}$$

$$D_{s,t} = \arg\max_{D_{i,j}} F(D_{i,j}, r_c). \tag{8}$$

where $N_{i,j,c}$ denotes the number of targets which the direction $D_{i,j}$ covers while $D_{i,j}$ already covers the target r_c. By choosing a proper value of α, the direction $D_{s,t}$ will be selected such that it covers a larger number of uncovered targets and the sensor s_s with the selected direction has more residual energy available.

Step 5 Once a direction $D_{s,t}$ has been selected, it is added to the current cover set C_k (line 14), and other directions of the same sensor s_i are removed from the *DIRECS* set (lines 15 ∼ 19).

Step 6 All targets additionally covered by $D_{s,t}$ are removed from the *TARGETS* set (lines 20 ∼ 24). When all targets are covered, the new cover set was formed. The condition in line 9 guarantees that a new cover set will cover all targets.

Step 7 After a cover set C_k has been formed, the lifetime of each sensor in C_k is updated (lines 26 ∼ 31). Once a sensor finishes its lifetime, it is removed from the set of available sensors, *SENSORS*.

Step 8 Before going to line 5 to find a new cover set, the set of available directions *DIRECS* is updated based on the set *SENSORS* (line 32).

The algorithm returns K (the number of cover sets) and the cover sets $C_1, C_2, \cdots, C_K$. The network lifetime is computed as $K \times t$. The complexity of the algorithm is $O(KN^2W^2M^2)$ where N is the number of sensors, W is the number of directions, and M is the number of targets. The variable K is upper-bounded by d/t, where d is the number of directions that cover the most sparsely covered target at the initial deployment. Because t is a constant and $d < NW$, the heuristic runtime is $O(dN^2W^2M^2)$. This computational cost is not so high as it appears to be since the values of N, W and M are not large.

5 Simulations

In this section, we conduct the simulations to evaluate and analyze the performance of the proposed scheme with various simulation parameters.

5.1 Simulation environments

To conduct simulations, we implemented a simulator with JDK 6.0. Using the simulator, we constructed the simulation environments to build a directional sensor network environment.

Our simulation environment assumes that the different numbers of targets (M=5 and 15) are uniformly deployed in a region of $500 \times 500m$. On the region, the different numbers of directional sensors are randomly scattered to cover the targets. It also assumes that all directional sensors can sense one of the three directions; *i.e*, they have a direction angle of $\frac{2\pi}{3}$ ($W = 3$). In our simulations, the initial lifetime (L_i) of all directional sensors is set to 1.0 and the active time of all cover sets (t) is set to 0.1.

Our greedy algorithm is evaluated with the following three selection criteria.

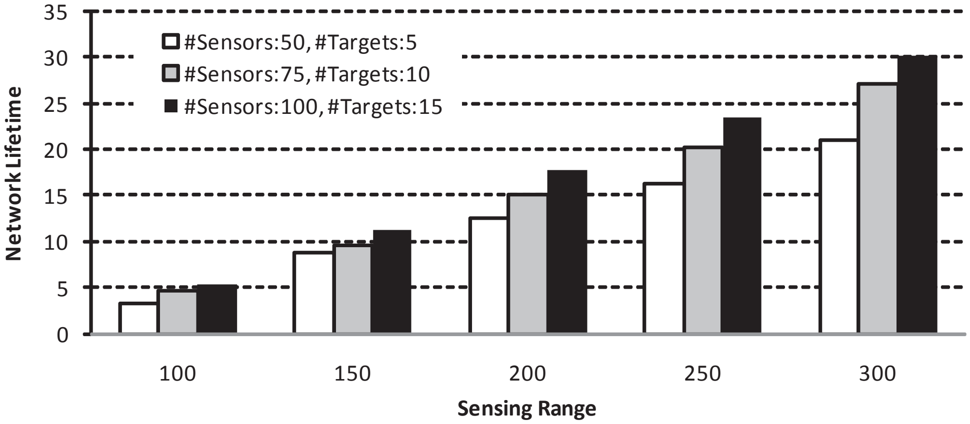


Figure 3: Effect of sensing ranges on the network lifetime

- Sensing range: this is used to investigate the performance of our scheme on various sensing ranges of directional sensors. As the sensing range grows narrower, the target coverage of directional sensors becomes shrunk. We can expect that the wider sensing range leads to more numbers of cover sets than the narrower one.
- Critical target: how to select the critical target is likely to have an effect on the energy efficiency of our scheme. We consider the following three ways to select a critical target and investigate the effect of this on the performance of our scheme.
  - *MIN*: the target most sparsely covered in terms of the number of sensors.
  - *MAX*: the target most densely covered in terms of the number of sensors.
  - *ANY*: any target that is randomly chosen.
- Direction with the greatest contribution: we defined the contribution function F in Section 3. As the value of α in the function F, we select one of the following three criteria, each of which represents different strategies when selecting a direction with the greatest contribution:
  - $\alpha = 0.0$: consider only the residual energy of directional sensors.
  - $\alpha = 0.5$: consider both the number of covered targets and the residual energy of directional sensors at the same time.
  - $\alpha = 1.0$: consider only the number of covered targets.

In the next subsection, we present the simulation results to analyze how the choices for these three criteria make an effect on the network lifetime.

5.2 Simulation results

Our simulations were conducted according to the diverse numbers of randomly-deployed directional sensors when some targets with a fixed location were deployed, respectively. The simulations run 10 times for each of three selection criteria.

1) *Effect of sensing ranges*: When 50, 75, and 100 directional sensors are respectively used to cover 5, 10, and 15 targets, the sensing ranges of directional sensors from 100*m* to 300*m* are evaluated. In this

Table 1: Comparison of selection ways of the critical target in nine <number of sensors, number of targets> deployments

<NumOfSensors, NumOfTargets>	Selection Ways		
	MIN	*MAX*	*ANY*
$< 50, 5 >$	20.73	20.75	21.21
$< 75, 5 >$	32.65	33.24	33.26
$< 100, 5 >$	42.36	42.38	43.01
$< *, 5 >$: *Average*	31.91	32.12	32.49
$< 50, 10 >$	17.37	17.43	17.87
$< 75, 10 >$	25.57	25.66	25.98
$< 100, 10 >$	36.70	36.73	36.87
$< *, 10 >$: *Average*	26.55	26.61	26.91
$< 50, 15 >$	14.93	14.97	15.12
$< 70, 15 >$	22.73	22.93	23.41
$< 100, 15 >$	29.70	29.92	30.10
$< *, 15 >$: *Average*	22.45	22.61	22.88
Average	26.97	27.11	27.42

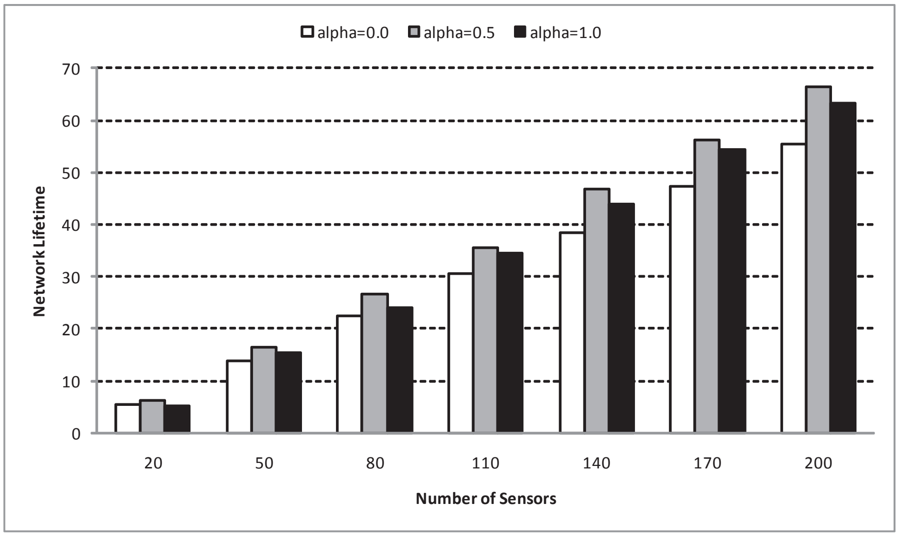
simulation, we use *ANY* as a way of selecting a critical target and set 0.5 to α as a criterion of a direction with the greatest contribution.

Figure 3 shows the effect of sensing ranges on the performance of our scheme. From the results presented in this figure, we can observe that the network lifetime increases almost linearly when the sensing range increases. This is not surprising; the wider sensing range can cover a greater number of targets than the narrower one. The wide sensing range also makes a cover set have a small number of directional sensors, but cover a great number of targets. By finding as many such cover sets as possible, the overall network lifetime can be extended. Therefore, we can see that the wider sensing range causes the network lifetime to be extended in DSNs.

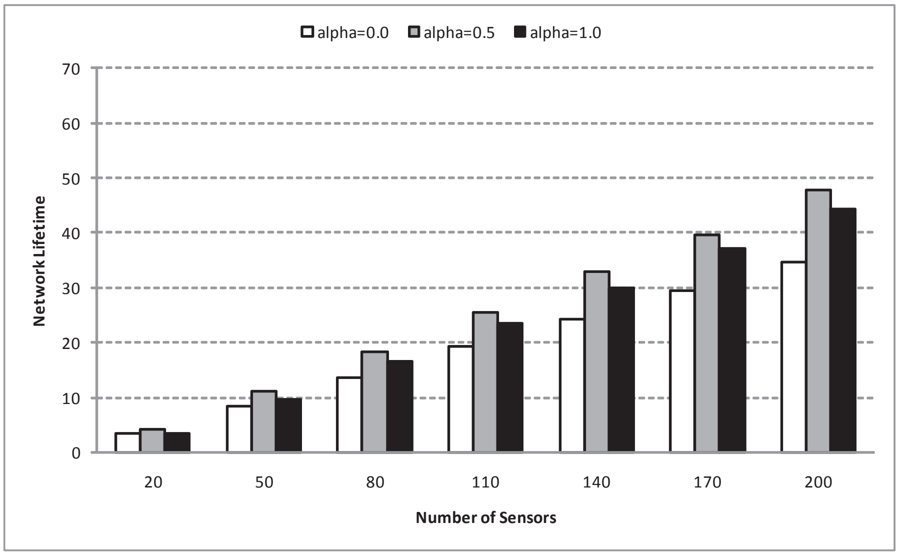
2) *Effect of the critical target*: As shown in Table 1, nine sets of paired sensors and targets are used to investigate this criterion. The three ways of selecting a critical target are used; *i.e.*, *MIN*, *MAX*, and *ANY*. For simplicity of this simulation, we set 250*m* to the sensing range of directional sensors. The value of α used to select the direction with the greatest contribution is set to 0.5. The remaining parameters are the same as in the previous simulation.

From the results presented in the Table 1, we can observe that the way of selecting a critical target has less effect on the performance of our greedy algorithm. However, there are still some difference across the selection ways. The network lifetime obtained when *MAX* is used is somewhat longer than that obtained when *MIN* is used, regardless of the number of directional sensors and targets. Interestingly, when our greedy algorithm uses *ANY* as a way of selecting a critical target, it makes the longest network lifetime as compared with the other two ways.

3) *Effect of the direction with the greatest contribution*: In this simulation, we evaluate the effect of the direction with the greatest contribution on the performance of our scheme. The network lifetimes are compared in accordance with numbers of directional sensors for 5 and 15 targets. The number of directional sensors ranges from 20 to 200. Based on the results of the previous simulation, we use *ANY* as a way of selecting a critical target. For simplicity of this simulation, we set 250*m* to the sensing range of directional sensors. The remaining parameters are the same as in the previous simulation. Three kinds of α to select the direction with the greatest contribution are used in this simulation.



(a) *M*=5



(b) *M*=15

Figure 4: Effect of direction with the greatest contribution sensor on the network lifetime

Figure 4 shows the effect of the direction with the greatest contribution on the performance of our scheme. It is shown that the network lifetime is the longest when α is 0.5, regardless of the number of directional sensors and targets. This indicates that our greedy algorithm can maximally extend the network lifetime when it considers both the number of covered targets and the residual energy of directional sensors at the same time.

6 Conclusions

Contrary to conventional sensor networks, DSNs are composed of numerous directional sensors with limited sensing ranges and directions, and thus a highly sophisticated technique is needed to maximize the network lifetime of a DSN. In this paper, we proposed the greedy algorithm-based target scheduling scheme to solve the MSCD problem. The simulation results showed that our target scheduling scheme can find the cover sets monitoring all the targets by switching directions in an energy-efficient way. Throughout the simulations, the sensing range, critical target, and direction with the greatest contribution were used to investigate their effects on the performance of our scheme. When analyzing the results of simulations on these effects, we can observe that our scheme can solve the MSCD problem regardless of the sensing ranges of directional sensors. In our scheme, the way of selecting a critical target has less effect on the performance. It can moreover maximally extend the network lifetime when it considers both the number of covered targets and the residual energy of directional sensors at the same time.

In this paper, our greedy algorithm is a centralized method and thus a centralized server should execute the proposed algorithm. Recently, distributed greedy algorithms have been proposed in the similar study areas. In the future work, we will devise our distributed greedy algorithm to solve the MDCS problem.

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