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Maximizing Strong Barriers in Lifetime-Heterogeneous Directional Sensor Network

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***Abstract*—Directional sensor network (DSN) has been widely used to detect intrusions and provide fine-grained border surveillance. Despite that barrier coverage in DSN has been intensively studied in recent years under numerous assumptions, various lifetimes of sensor nodes haven't been taken into account. In reality, the lifetimes of sensors are generally different, and the lifetime heterogeneity does affect the surveillance performance since the failure of a single node in a sensor barrier leads to blind areas in surveillance regions. In this paper, we focus on solving a strong barrier coverage problem with lifetime-heterogeneous rotatable directional sensors. Taking into account the non-uniform lifetimes of sensor nodes, we innovatively construct an extended directional barrier graph to model the problem. An efficient algorithm using two-round maximum flow algorithm (TMFA) is proposed to find the maximum barrier number, which in turn maximizes the life span of surveillance. Extensive simulations show that TFMA achieves near-optimal performance and outperforms other heuristic methods.**

***Index Terms*—barrier coverage; directional sensor; wirless sensor network; lifetime; maximum flow.**

I. INTRODUCTION

Barrier coverage, which requires much fewer sensors than full coverage, is known to be an appropriate model of coverage for movement detection applications such as intrusion detection [1]. Since first introduced into wireless sensor network (WSN) in [2], it has received considerable attention [3-7]. In WSN, a series of sensor nodes whose sensing regions or horizontal projections of sensing regions overlap, form a barrier for intruders and guarantee the detection of penetrating behaviors in vertical direction. Critical applications of barrier coverage in WSN include deploying sensors along country borders to detect illegal instruction, around prisons to avoid escaping, and around grasslands to detect the migration of wild animals.

Directional sensors, such as ultrasound, infrared, and video sensors are widely used in many surveillance applications of WSN. They enable the perception of extra dimensional information and thus provide more precise surveillance than the traditional WSN. WSN consisting of directional sensors is referred to as directional sensor network (DSN). Since the first introduction of DSN [7], barrier coverage with directional sensors has drawn extensive interest.

Barrier coverage can be classified into weak barrier coverage and strong barrier coverage [8]. In the weak barrier coverage, the horizontal projections of sensing regions overlaps and this can only guarantee to detect the movements along vertical traversing paths as illustrated by the dash lines in Fig. 1(a). As shown in the same figure, if an intruder knows the deployment map of sensor nodes in advance, it may adopt a polygonal path indicated by the solid line, avoiding being detected. By contrast, the strong barrier coverage, which provides a continuous coverage, ensures to detect every intrusion since any crossing path needs to traverse a barrier. As shown in Fig. 1(b), despite following a polygonal path, the intruder can be detected by the barrier on the top.

In addition, based on the characteristics of barriers, barrier coverage can be classified into other categories such as 1-barrier and k-barrier, any-view coverage and full-view coverage, coverage with mobile sensors and coverage with stationary sensors, etc. As illustrated by Fig. 1(b), if a mobile sensor (indicated by the white sector) is used and moved to the position indicated by the dash lines, it would form a 2-barrier coverage in hybrid DSN which means both mobile and stationary sensors are used.

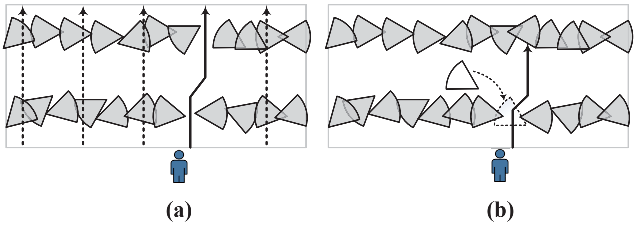
(a) (b)

Fig. 1. Weak and strong barrier coverage in DSN. (a) Weak barrier coverage. (b) Strong barrier coverage.

With directional sensor nodes, barriers possess stronger monitoring capabilities due to the introduction of extra dimensional information. However, the unique characteristics of directional sensor nodes, such as angle of view, working direction, and line of sight, have brought in new challenges such as the needs for using more parameters to model the directional sensors and the increasing complexities of solving the barrier coverage problem.

In [5], which is the most relevant to our work, the authors have conducted exploratory research work on strong barrier

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coverage with directional sensors. Using the directional non-overlapping model, they construct a directional coverage graph to model the connectivity relations of sensor nodes. In this way, the problem of finding a continuous barrier in DSN turns into finding a path linking two special vertexes in the directional coverage graph. Two paths are said to be conflicting if they share a vertex that corresponds to the same sensor. This paper first applies the maximum flow algorithm to calculate all the potential paths and then develops heuristic algorithms to choose the non-conflicting ones, which can work alternately to extend the barriers' lifetime. Yet it is worth noting that the lifetimes of sensor nodes are set equal, and this is not realistic since sensor nodes usually have different lifetimes and energy-consumption rates.

In [9], to improve the computational efficiency, the authors analyze the orientation and the locations of sensor nodes, and simplify the procedure of constructing directional barrier graph. In particular, they also propose solutions to minimizing the total and the maximum rotation angles of all the directional sensors after a strong barrier is found. As seen from these research works, designing appropriate directional barrier graph plays a significant role in solving the barrier coverage problem

All the studies reviewed so far, however, haven't taken into account the various lifetimes of sensor nodes. In reality, the energy consumption of different nodes in a network is generally uneven, and this may have a critical influence on maintaining barriers. To be specific, previous studies all assumed that the lifetime of each sensor node is uniform. However, as a consequence of uneven energy consumption owing to different workloads, the lifetimes of all sensor nodes are not equal in reality. If a sensor in a barrier runs out of energy, then the barrier will not maintain anymore. Thus, the various lifetimes of different nodes must be considered in constructing the sensor barriers to maximize the barriers' lifetime.

In this paper, we study the barrier coverage problem in lifetime-heterogeneous DSN in which sensor nodes have different lifetimes. The main contributions of our work are described as follows:

1) To the best of our knowledge, we are the first to study the strong barrier coverage problem in lifetime-heterogeneous DSN and show that the existing barrier coverage algorithms do not produce optimal results if sensors have different lifetimes.
2) We innovatively construct an extended directional barrier graph to model the problem. The graph allows for the lifetimes of sensor nodes, and can be used to find the non-conflicting paths.
3) We propose an algorithm called two-round maximum flow algorithm (TMFA) to find the maximum barrier number. TMFA can achieve near-optimal solutions and satisfy the lifetime constraints of sensors.

The remainder of this paper is organized as follows. Section II introduces system model and problem statement. In Section III, we present the extended directional coverage graph and two-round maximum flow algorithm (TMFA). Simulation work and numerical results are presented in Section IV and we conclude the paper in Section V.

II. MODLES AND PROBLEM STATEMENT

We consider a DSN with n lifetime-heterogeneous rotatable directional sensors $S = \{s_1, s_2, \ldots, s_n\}$ deployed to monitor a belt region B. Similar to [5], the non-overlapping sensing model, shown in Fig. 2, is adopted. For a sensor node, the coverage areas of different orientations are not overlapping. We represent a directional senor with a sector denoted by a 4-tuple $s_i = \langle P, R, a, \vec{V} \rangle$, where P is the coordinate of a sensor in a two-dimension monitoring plane; R is the maximum sensing radius and a is the sensing offset angle; $\vec{V} = \{\vec{V}_1, \vec{V}_2, \ldots, \vec{V}_m\}$ is a set of unit direction vectors, representing the set of possible sensing orientations. Particularly, the angle between any two $\vec{V}_i$ should be greater than $2a$ if the sensing model is non-overlapping. Only one orientation can be assigned for each node on a barrier.

The shaded sector shown in Fig. 2 represents the Field of View (FoV) of a sensor node. To construct a strong barrier, a subset of directional sensors and their corresponding orientations, which can guarantee a continuous coverage from the leftmost and the rightmost border of the surveillance regions, should be found. Since no crossing path, which links the entrance side and the exit side of the monitoring region, is allowed in the strong barrier, the FoVs of the neighboring sensors on selected barriers should overlap to eliminate coverage holes.

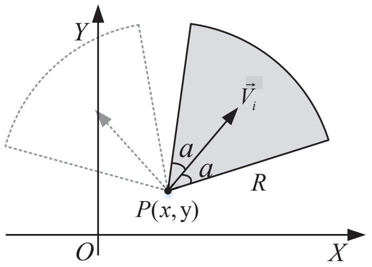


Fig. 2. The sensing model of a directional sensor

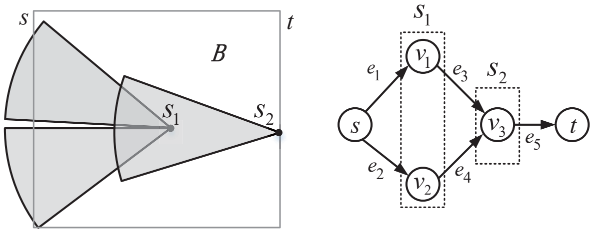
We assume that the sensor nodes in DSN have three lifetime levels: low, medium and high, quantified as one, two and three unit time in our simulation. In reality, more levels can be used to model the lifetimes of the sensor nodes. To provide good coverage and make the best use of the sensors lifetimes, we employ sensors which have the ability to rotate to a set of assigned orientations. This can be realized by using the sensors with actuation unit [9]. Furthermore, we assume that the energy consumption for rotation can be ignored since in our case one sensor may rotate for at most three times.

We assume that the intruder tries to cross the monitoring region from the bottom side to the top side. A directional sensor barrier is an ordered set of sensor nodes whose sensing regions overlap in the horizontal direction and the leftmost and the rightmost sensors can cover the left and right boundaries.

Given a set of N lifetime-heterogeneous rotatable directional sensors which are deployed in a belt region, the objective of this work is to find the maximum number of directional sensor barrier.

As mentioned in the previous section, directional barrier graph [5,9] is an important tool for modeling barrier coverage problem in DSN. We use $G(V, E)$ to denote directional barrier graph (DBG for short). V and E are sets of vertexes and edges respectively. A vertex v_i in V corresponds to a potential sensing sector of a node. In addition, two virtual nodes s and t, corresponding to the left and right boundaries, are added. A directed edge e_k between two vertexes exists if their matching sectors belong to different sensors and overlap in the belt region B. For e_k, the start point is the vertex which corresponds to the sensor close to the left boundary. Additionally, we add an edge linking a vertex and s (or t) if a sensing sector intersects with the left (or right) boundary.

An example is given in Fig. 3 to illustrate how to construct a DBG. In Fig. 3(a), s_1 and s_2 are two sensor nodes deployed in a belt region B. s_1 has two possible sensing sectors while s_2 has only one. Thus, following the definition of DBG, we can get the graph shown in Fig. 3 (b). v_1 and v_2 correspond to the two sensing sectors of s_1 while v_3 stands for s_2. As we can see from Fig. 3, the overlapping relationships between sensor nodes are mapped to the DBG.



(a) (b)

Fig. 3. Construct a DBG. (a) Deployment diagram (b) DBG

For a directional barrier graph $G(V, E)$, if we can find a path (i.e. flow) from s to t, then a barrier exists in the directional sensor network. Unfortunately, not all the paths can be used because of the following reasons: for the problems in [5] and [9], the lifetime for sensor nodes is uniform and each sensor can choose only one working direction (sector) during the whole lifetime, meaning that hidden conflicts may exist between the paths. For our problem, since the lifetime of sensor nodes is non-uniform, we need to consider the lifetime constraints and choose the paths which can make the best use of every rotatable directional sensors to form the maximum number of non-conflict barriers.

III. TWO-ROUND MAXIMUM FLOW ALGORITHM

In this section, we modify the directional barrier graph to take into account the lifetime constraints. Based on the extended DBG, we present an integer linear programming formulation (ILP) whose solution will serve as a benchmark, and we propose our two-round maximum flow algorithm.

A. Extended Directional Coverage Graph

The extended directional barrier graph (EDBG) $G(V, E, C, L)$ is constructed as follows. V and E follow the same definitions and rules as those in DBG. $L = \{l_1, l_2, \ldots, l_n\}$ is the set of lifetimes for all the senor nodes, and $C = \{c_1, c_2, \ldots, c_k, \ldots, c_n\}$ represents the set of capacities for edges $E = \{e_1, e_2, \ldots, e_k, \ldots, e_n\}$ in the graph. If e_k connects two vertexes which separately belong to sensor s_i and s_j, then $c_k = \min\{l_i, l_j\}$. The capacities for s and t are set to infinity.

The maximum time that a node can work on a direction is the lifetime of that node, and the life span of a sensor barrier is restricted by the shortest lifetime of all the sensors on it. Thus, in the corresponding graph, c_k equals to the smaller value of l_i and l_j, and determines an upper bound for the flow that can pass through this edge. For instance, if we find a flow with value 2 from s to t, then all the sectors, which correspond to the vertexes on the flow, can be utilized for at most two unit time.

We add parameters C and L to the DBG in Fig. 3(b) to get the EDBG. The lifetimes of s_1 and s_2 are set to 3 and 2 individually. Following the rules of constructing the EDBG, we can get $c_1 = c_2 = 3$, $c_3 = c_4 = 2$, and $c_5 = 2$. Using Edmonds-Karp algorithm [11] in the Ford-Fulkerson Method for the graph in Fig. 3(b), we can simply find a maximum flow $s - v_1 - v_3 - t$ with flow value 2, which means we can use sector v_1 and v_3 for two unit time to build barriers.

B. ILP Formulation

Based on EDBG model, we develop an ILP formulation for our problem. The ILP formulation also serves as a benchmark since it always provides the optimal solutions. In the following formulation, f_{e_i} is the flow on edge e_i in the EDBG; $E_{v_j}^{in}$ and $E_{v_j}^{out}$ stand for the sets of inwards and outward edges of vertex v_j in V; Particularly, E_t^{in} represents the sets of inwards edges of vertex t; v_j belongs to the set S_q if v_j represents a potential sensing sector of the sensor node s_q.

$$\max \sum_{e_i \in E_t^{in}} f_{e_i} \tag{1}$$

s.t.

$$\sum_{e_i \in E_{v_j}^{in}} f_{e_i} = \sum_{e_i \in E_{v_j}^{out}} f_{e_i} \ , \ \forall v_j \in V \backslash \{s, t\}; \tag{2}$$

$$\sum_{e_i \in E_{S_q}^{out}} f_{e_i} \leq l_q \ , \ \forall q \in \{1, 2, \ldots, n\}; \tag{3}$$

$$f_{e_i} \leq c_{e_i} \ , \ \forall e_i \in E. \tag{4}$$

To be specific, the object function (1) concerns finding the maximum number of directional sensor barriers. When a flow on the path from s to t with value 1 can be found, then there will be a barrier with the lifetime of one unit time. Particularly, we count a barrier for n times if it can work for n unit time. Constraint (2) is a flow conservation equation, which arises from the fact that the flows on the inward edges of a vertex (except for s and t) increases equally with those on the outward edges. Furthermore, with the lifetime limitations, constraint (3) guarantees that the maximum times a sensor node can be used are always bounded by the lifetime of that sensor. Finally, constraint (4) ensures that the maximum times an edge can be used are less than the minimum lifetime of two connected sensors.

C. The Proposed Algorithm

Despite providing optimal solutions, ILP is NP-hard which means we need to find more efficient ways to solve the problem. The maximum flow algorithms such as Edmonds-Karp algorithm [11] can calculate the maximum flow of a network in polynomial time, and it is chosen in this work to calculate the maximum paths and eliminate the conflicts between these paths. Two or more paths are said to have conflicts if they share a common sensor node, and the times for using that node are more than its lifetime. The proposed algorithm has two steps:

1) Calculate the potential paths: For an EDBG, we can form a barrier if there is a path from s to t in the graph. Since a sector may be used for the whole lifetime of a sensor, all sub-sectors are assumed to have the same values as the lifetime of sensors. Employing the maximum flow algorithms such as Edmonds-Karp algorithm [11] in the Ford-Fulkerson method, we can get all the paths, where each path represents a potential directional barrier. However, due to the lifetime constraints for sensor nodes, not all the paths are feasible for maintaining barriers. Therefore, we need to choose the feasible solutions.

2) Eliminate conflicting paths: We construct a new graph to eliminate conflicting paths. In the new graph, we add two virtual nodes s and t which correspond to the left and the right boundaries. For a path found in the previous step, if it doesn't share any common sensor node with others, we directly add an edge in the new graph linking s and t.

For the paths with conflicts, we first sort out those sensors which are utilized by two or more paths. Assuming that s_i is one of those sensors, then we add two vertexes $s_i^{'}$ and $s_i^{''}$, and an inner edge $e_{s_i}^{in}$ between them to the graph. The capacity of $e_{s_i}^{in}$ is set equal to the lifetime of s_i. Particularly, we don't need to add vertexes for the sensors used just by one path. Then, we add edges to connect vertexes and form new paths linking s and t. The order in which these vertexes appear in the new path is consistent with the sensors' appearing orders in the path of the previous step. Thus, a new path corresponds to an original one. Except for the inner edge, the capacities for other newly-added edges are set equal to the smallest capacity of all the edges on the original path, ensuring that the flow value on the new path remains consistent with that on the original one.

Fig. 4 illustrates the new graph of this step. w_1 is a non-conflicting path while paths w_2 and w_3 has common vertexes $s_i^{'}$ and $s_i^{''}$ which come from the same sensor s_i, indicating that we need to choose proper flow value on the paths to satisfy the lifetime constraints of s_i. Supposing that the lifetime for s_i and the flow values on w_2 and w_3 are 2, then we can simply keep path w_3 after applying Edmonds-Karp algorithm on the new graph. The capacity on the inner edge $e_{s_i}^{in}$ sets an upper bound for the times that s_i can be used. Thus, the paths with lifetime conflicts can be removed utilizing the maximum flow algorithm once again.

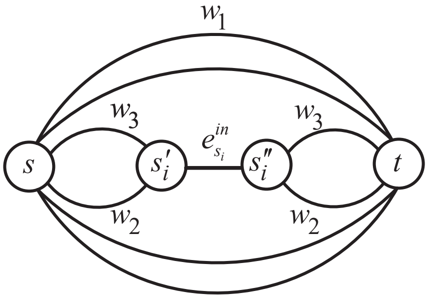


Fig. 4. The graph to calculate non-conflicting paths

Supposing that the network has n sensor nodes and each node has at most m possible sensing orientations, then the complexity for building an EDBG is $O(n^2m^2)$. Step 1) can be done in $O(n^5m^5)$ if Edmonds-Karp algorithm is adopted. After the first step, we can get at most nm paths and n vertexes (except for s and t) for step 2). In the worst case, there are n inner edges, $n^2/2$ edges between vertexes, $2*nm$ edges between s (or t) and vertexes. Similarly, if we use EdmondsKarp algorithm, the running time will be at most $O(n^5+n^2m^2+n^4*m)$. Hence, the time complexity of TMFA is $O(n^5m^5)$.

D. Modified Disjoint Path Algorithms

For the purpose of comparison, we modify the centralized algorithms in [5] to make them applicable for the lifetime-heterogeneous directional networks.

For sensor nodes with non-uniform lifetimes, the modified disjoint path algorithm 1 and 2 (MDPA1 and MDPA2 for short) are executed in a multi-round way: in each round, we assume that all sensor nodes have one unit time lifetime and construct a regular DBG; then, the original algorithms are executed to find the maximum disjoint paths. If any sensor node runs out of energy after the previous round, then we remove the vertexes and edges in DBG that are related to it. The same operations are repeated in each round until no disjoint path can be found. Then, the sum of all the disjoint paths is the maximum number of barriers.

In addition, we also develop two simple heuristic algorithms (HA1 and HA2 for short) for the purpose of comparison. In both algorithms, we first execute the phase 1) in TMFA to find all the paths. Then, HA1 heuristically selects the paths which both have the minimum hop counts and satisfy the lifetime constraints. HA2 works similarly, except that in the heuristic path selection procedure, it will choose the paths with the fewest conflicts.

IV. EVALUATION

In this section, we evaluate the performance of TMFA via extensive simulations in terms of barrier number. The purposes of the simulations are twofold: to prove the effectiveness of TMFA in comparison with other algorithms which do not consider lifetime heterogeneity, and to evaluate the effect of some important parameters (such as the sensor node number, sensing radius and the number of possible sensing orientations) on barrier number.

Without loss of generality, directional sensors are uniformly deployed in a belt region with the dimension of 300 × 150m. The lifetime of each node is randomly and uniformly chosen from 1, 2 or 3 unit time. Similar as in [5], we assume that the sensor nodes use the non-overlapping sensing model. Assigning an initial orientation randomly, each node has $p = \pi/a$ sensing orientations with angle increments $2a$. In the following scenarios, we mainly evaluate the effects of node number (n), sensing radius (R) and sensing orientation number (q) on performance by setting them to different values. All simulation results are the statistical average of 100 simulations.

In scenario 1, $R = 40$m, $p = 4$, and n ranges from 50 to 300 with 50 as the step increment. As we can see from Fig. 5, barrier numbers of all the algorithms increase monotonically with the increase of node number. The reason is that increasing the number of sensor nodes will result in an increase of node density, thus enhancing the connectivity of networks and leading to a big number of barriers. In particular, TMFA achieves a close-to-optimal solution and outperforms other algorithms since it fully considers the lifetime heterogeneity. In addition, MDPA1 which chooses the paths with minimum hop count performs better than MDPA2 but still has a big gap from TMFA, indicating that the average performance of traditional algorithms in [5] are worse than our algorithm and they are not suitable to the DSN with lifetime-heterogeneous sensors. Two heuristic algorithms HA1 and HA2 get relatively worse results since in the procedure of heuristic path selection, there is no effective scheduling for choosing paths.

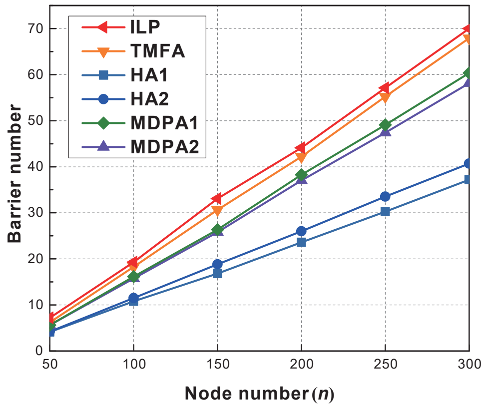


Fig. 5. The effect of node number on barrier number in scenario 1

In scenario 2, $n = 150$, $p = 4$, and we change the sensing radius R from 25m to 55m with 5 as the step size. Similarly, we can observe from Fig. 6, that barrier numbers increase with the sensing radius, since bigger sensing radius provides a bigger chance for sensor nodes to overlap with each other and form barriers. In both of the two scenarios, TMFA outperforms other algorithms and approaches the ILP solution.

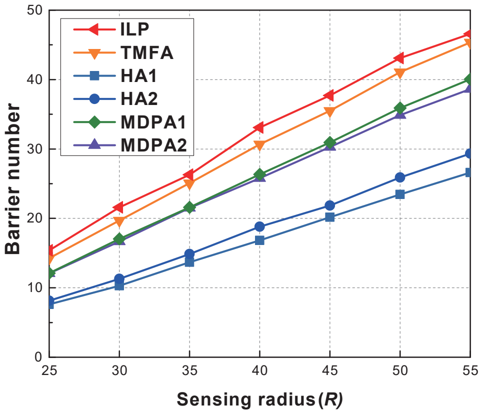


Fig. 6. The effect of sensing radius on barrier number in scenario 2

In scenario 3, $n = 150$, $R = 40$ m and p is changed from 1 to 6 with an increment of 1. Observing Fig. 7, all the algorithms has a downward trend when increasing the sensing orientation number, since having more orientations means smaller sensing area and a smaller chance for sensors to overlap with each other which consequently leads to fewer barriers. When $p = 1$, all the algorithms have the same barrier number since the sensing model becomes omnidirectional and we don't need to consider the path conflicts. We also notice that the performance of TMFA is slightly worse than MDPA1 and MDPA2 when $p = 2$. The reason is that when $p = 2$, TMFA will not get enough paths to conduct effective scheduling. However, with the increase of p, TMFA has more feasible paths to choose, leading to a better performance which is very close to the optimal solution. Although the performance is not good enough when $p = 2$, TMFA still achieves a 92.1% of the optimal value and outperforms HA1 and HA2.

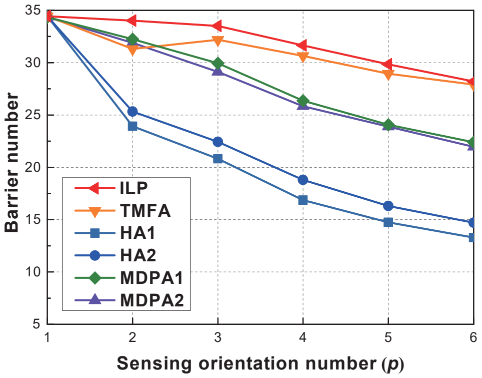


Fig. 7. The effect of sensing orientation number on barrier number

In scenario 4, we compare the effect of using overlapping and non-overlapping sensing models. In this case, we assume that the non-overlapping model has 4 sensing orientations and the overlapping models has 8 orientations with $2a = 2{*}\pi/8 = 4$ as the angle increments. Results shown in Fig. 8 indicates TMFA still suits the scenarios using overlapping model (such as in [9]) and, to monitor the same regions, the overlapping model achieves better performance than that of the than non-overlapping model since it provides more sensing orientations to choose from.

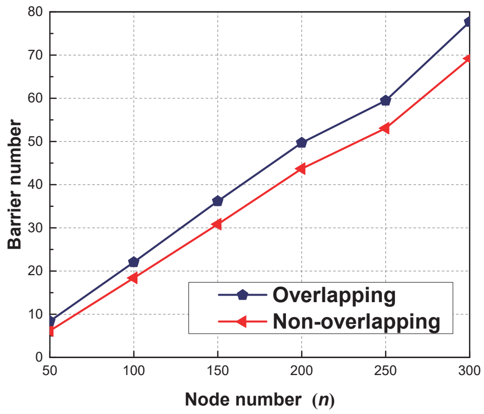


Fig. 8. The effect of using overlapping and non-overlapping sensing model

V. CONCLUSIONS

In this paper, we studied the maximum strong barrier coverage problem using lifetime-heterogeneous rotatable directional sensors. First, we innovatively constructed an extended barrier coverage graph to model the problem which considers the various lifetimes of sensor nodes. We developed the ILP formulation for the problem which serves as the performance benchmark. We proposed an efficient two-round maximum flow algorithm to find the feasible solutions which can find the maximum barrier numbers subject to the lifetime constraints. Simulations results show that the lifetime heterogeneity of sensor nodes has a critical effect on barrier number and demonstrate the effectiveness of TMFA.

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