Short Papers

Optimal Deployment for Target-Barrier Coverage Problems in Wireless Sensor Networks

Pengju Si, Shuaishuai Wang, Lei Shu, *Senior Member, IEEE*, Rui Ning, and Zhumu Fu

***Abstract*—Target-barrier coverage problems are a new emerging issue in wireless sensor networks. However, it is a challenge to achieve target barriers for randomly distributed targets in the surveillance region. In this paper, we propose a deterministic deployment algorithm to find the minimum number of required sensors for a given region. The algorithm first constructs a target-barrier circle for each target. Then, it utilizes the merged properties of target-barrier circles to derive the shortest length of target barriers. Our extensive experiments demonstrate that the proposed algorithm can construct target-barrier coverage effectively with minor deployment costs.**

***Index Terms*—Coverage, target barrier, wireless sensor networks (WSNs).**

NOMENCLATURE

Symbol	*Description*
$\mathcal{T}$	Set of targets.
t_i	ith target in $\mathcal{T}$.
m	Number of targets in $\mathcal{T}$.
$d_{t_i t_j}$	Distance between targets t_i and t_j.
$\mathcal{S}$	Set of sensors.
s_j	jth sensor in $\mathcal{S}$.
n	Number of sensors in $\mathcal{S}$.
$d_{t_i s_j}$	Distance between target t_i and sensor s_j.
r	Sensing radius of each sensor.
d_t	Distance constraint of target barrier.
$\mathcal{B}$	Set of target barriers.
b_k	kth target barrier in $\mathcal{B}$.
l	Number of target barriers in $\mathcal{B}$.
$\mathcal{S}(\mathcal{B})$	Set of sensors to construct the set $\mathcal{B}$.
$\mathcal{S}(b_k)$	Set of sensors in target barrier b_k.
$\mathcal{T}(b_k)$	Set of targets enclosed by target barrier b_k.
$\lvert\mathcal{S}(\mathcal{B})\rvert$	Number of sensors in $\mathcal{S}(\mathcal{B})$.
$\lvert\mathcal{S}(b_k)\rvert$	Number of sensors in $\mathcal{S}(b_k)$.
$\lvert\mathcal{T}(b_k)\rvert$	Number of targets in $\mathcal{T}(b_k)$.
$c(t)$	Target-barrier circle of target t.
$\mathcal{L}_(b_k)$	Perimeter of target barrier b_k.

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I. INTRODUCTION

The traditional coverage problem in wireless sensor networks (WSNs) can be classified into three categories: area, target, and barrier, which characterize different monitoring quality of WSNs [1]. For applications in defense surveillance region, we deploy a certain number of sensors for intrusion detection from outside region and prevention of inner barrier breaching. For instance, applications of WSNs in special terrains or hazardous zones include nuclear leak detection [2] and infectious disease monitoring [3]. Due to the unique requirement, these applications exhibit different characteristics and calls for different design considerations than by traditional coverage measures in WSNs. Besides, in these practical applications, sensors must be deployed over a closed curve that has a certain distance between this curve and targets. Then, Cheng and Wang [4] addressed the new coverage problem, which is defined as the target-barrier coverage problem.

However, compared to the other types of coverage, there are two contradictory features in the target-barrier coverage problem. First, the target-barrier coverage problem has a distance constraint that all deployed sensors cannot approach the enclosed region. Such that, we can schedule a large number of sensors around the enclosed region with a larger radius than the distance constraint. On the other hand, to minimize the cost of WSNs, we should search for the minimum number of sensors to form target-barrier coverage of the enclosed target. These two contradictory features drive us to deploy sensor nodes evenly on the circle with center being the target and radius the distance constraint. The crucial question is that: How many sensors are needed and where we deploy them such that the total cost is minimized for many targets? Besides, there would be many targets random distributed in the surveillance region in some applications [5]. Thus, in the target-barrier coverage problem, the most fundamental and critical issue is how to develop a deployment strategy of sensors to satisfy the requirement of all targets.

In this paper, we first formulate the minimization problem. Then, we derive an optimal merged algorithm based on our analysis of target-barrier circles and its properties. In the algorithm, we resort to Kruskal algorithm and Graham algorithm to find the target-barrier coverage set with minimum sensors. Finally, extensive simulations are conducted to evaluate the performance of the proposed algorithm.

II. System Model and Problem Formulation

A. System Model

Assume $\mathcal{T}$ represents the target set that we need to protect continuously. There is m targets $\mathcal{T} = \{t_1, t_2, \ldots, t_m\}$ randomly distributed in the surveillance region, which is a flat Euclidean space. Each target is static with a known location. Let $d_{t_i t_j}$ denote the distance between two targets t_i and t_j. To protect all targets in $\mathcal{T}$, we resort to a set of $\mathcal{S} = \{s_1, s_2, \ldots, s_n\}$ to construct a target-barrier coverage network. Besides, all sensors have the same parameters and adopt the disk sensing model with the sensing radius r. Note that the sensing radius r is much less than the distance constraint d_t of the target in general, i.e., $r \ll d_t$. $d_{t_i s_j}$ denotes the distance between target t_i and sensor s_j. Let $\mathcal{B}$ denote a target-barrier set, which can provide target-barrier coverage service for all targets in $\mathcal{T}$. Now, we construct l target barriers $\mathcal{B} = \{b_1, b_2, \ldots, b_l\}$ in the surveillance region. Obviously, the maximum target barriers is the number of targets, i.e., $l \leq m$. Assume $\mathcal{S}(b_k)$ denotes the set of sensors in the target barrier b_k, and $\mathcal{T}(b_k)$ is the set of targets enclosed by the target barrier b_k. Besides, the number of sensors in $\mathcal{S}(b_k)$ and the number of targets in $\mathcal{T}(b_k)$ are denoted by $|\mathcal{S}(b_k)|$ and $|\mathcal{T}(b_k)|$, respectively. The set of sensors to construct a set of target barriers of all targets is denoted by $\mathcal{S}(\mathcal{B})$, where $|\mathcal{S}(\mathcal{B})|$ is the number of sensors. The notations used in this paper is given in nomenclature.

Definition 1. (Target-barrier coverage [4]): A target-barrier is a continuous circular barrier formed around the target. The target barrier has a d_t constraint that is set depending on applications and needs. d_t defines the minimum distance between the target and sensors constructing the barrier.

B. Problem Formulation

Our goal is to deploy the minimum total number of sensors to construct target-barrier coverage for all targets as

$$\min \quad |\mathcal{S}(\mathcal{B})| \tag{1}$$

$$\text{s.t.} \quad d_{s_i t_j} \geq d_t \quad \forall s_i \in \mathcal{S}(b_k), t_j \in \mathcal{T}(b_k), b_k \in \mathcal{B} \tag{2}$$

$$d_{s_i s_{i+1}} \leq 2r, s_{|\mathcal{S}(b_k)|} = s_1 \quad \forall s_i \in S(b_k), b_k \in \mathcal{B} \tag{3}$$

$$\sum_{k=1}^{l} |\mathcal{T}(b_k)| = m \quad \forall b_k \in \mathcal{B}. \tag{4}$$

Constraint (2) imposes that the constructed target barrier for each target should have a minimum distance of d_t from the target. Constraint (3) indicates that the sensing regions of sensors overlap with each other in each target barrier. Constraint (4) defines that the set of target barriers should cover all targets, and the number of targets is denoted by m.

III. Optimal Solution

A. Discussion

To find the minimum required sensors, we should take full advantage of the sensing region of each sensor, which implies that the constraint (3) is tight. Then, for the minimization problem to be bounded, how to find the minimum required sensors is converted into how to construct a set of target barriers with the shortest length. We first discuss the minimum required sensors to form the target barrier of a single target.

Definition 2. (Target-barrier circle): A target-barrier circle, denoted by $c(t)$, is a circle such that the center is the target t and the radius is the distance constraint d_t.

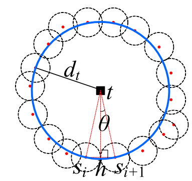

Fig. 1. Illustration of a target-barrier coverage.

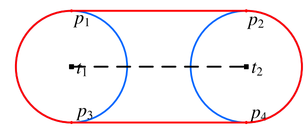

Fig. 2. Illustration of a merged target barrier.

Obviously, the circumstance of a target-barrier circle is $\mathcal{L}_{c(t)} = 2\pi d_t$. Note that we call a part of a target-barrier circle as target-barrier arc. As shown in Fig. 1, the blue circle is the target-barrier circle of target t. It is essential to know that the least number of sensors happens where those sensors are all located on the target-barrier circle with its center at the target. As shown in Fig. 1, both s_i and s_{i+1} are deployed on the target-barrier circle of the target t. It is easy to know $d_{ts_i} = d_{ts_{i+1}} = d_t$. h is the connection point of sensing range of s_i and s_{i+1}, and $d_{s_i h} = d_{s_{i+1} h} = r$. Thus, $\Delta t s_i s_{i+1}$ is an isosceles triangle, and $th \perp s_i s_{i+1}$. Then

$$\sin\theta = \frac{hs_{i+1}}{ts_{i+1}} = \frac{r}{d_t} \tag{5}$$

where θ is the angle between ts_{i+1} and th.

As shown in Fig. 1, the minimum required sensors to construct the target-barrier of a target is

$$|\mathcal{S}(b)| = \left\lceil \frac{\pi}{\arcsin \frac{r}{d_t}} \right\rceil. \tag{6}$$

If all sensors are deployed on the target-barrier circle of each target in T, each target barrier is independent from others in the target-barrier coverage system. The required number of sensors to form the target-barrier set for all targets is $|\mathcal{S}(\mathcal{B})| = m\lceil \frac{\pi}{\arcsin \frac{r}{d_t}} \rceil$. However, when targets are scattered densely that a target has a short distance away from another one target, the number of sensors can be further reduced by merging some target-barrier circles into a large target barrier to enclose a part of targets in $\mathcal{T}$. Let us begin by examining how to merge two target-barrier circles.

Theorem 1: Two target-barrier circles can be merged when the distance between these two targets is less than πd_t.

Proof: It is a simple geometry property. We know that the circumference of a target-barrier circle is $2\pi d_t$. Furthermore, if $d_{t_1 t_2} = \pi d_t$, the perimeter $\mathcal{L}_b$ of merged target barrier (red convex hull in Fig. 2) equals to two circumferences of a target-barrier circle. Thus, if the distance between two targets is less than πd_t, the perimeter of merged target barrier is less than the circumferences of two target-barrier circles (i.e., $\mathcal{L}_b < 4\pi d_t$). ■

Theorem 2: The length of all target-barrier arcs in a merged target barrier is a fixed value.

Proof: As for a single target, the target-barrier is a target-barrier circle, which length is $2\pi d_t$. As for two targets, the length of two target-barrier arcs is $2\pi d_t$, since each target-barrier arc is a semicircle, which is shown in Fig. 2.

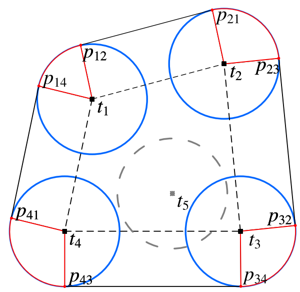

Fig. 3. Illustration of a merged target barrier.

As for $m (m > 2)$ targets, as shown in Fig. 3, the sum angles of m target-barrier circles is $2m\pi$. Sum m interior angles of m polygon, whose vertices are m targets, is equal to $(m-2)\pi$. Furthermore, there are m tangent lines for every two target barriers, and it will exert $m\pi$ angles for all target-barrier circles. Then, sum of all the m target-barrier arcs equals $2m\pi - (m-2)\pi - m\pi = 2\pi$.

Thus, the length of all target-barrier arcs in a merged target barrier is a fixed value, which is $2\pi d_t$. ■

B. Algorithm

Based on the above-mentioned discussion, we propose an optimal merged algorithm for finding a target-barrier set with the minimum sensors. The first step is to generate the target barrier as the optimal target-barrier set $\mathcal{B}_{\min}$, which encloses all targets. According to Theorem 2, we conclude that the perimeter $\mathcal{L}_b$ of a merged target barrier b is

$$\mathcal{L}_b = \mathcal{L}_{cp} + 2\pi d_t \tag{7}$$

where $\mathcal{L}_{cp}$ is the perimeter of the convex polygon with vertices outside targets (e.g., $\{t_1, t_2, t_3, t_4\}$ in Fig. 3). The convex polygon can be generated by the Graham scan algorithm. If each polygon edge moves along the normal line with d_t, we will get the common tangent of two target-barrier circles. The minimum required sensors is

$$|\mathcal{S}(b)| = \left\lceil \frac{\pi}{\arcsin \frac{r}{d_t}} \right\rceil + \left\lceil \frac{\mathcal{L}_{cp}}{2r} \right\rceil. \tag{8}$$

Then, a minimum spanning tree $\mathcal{G}$ is constructed by the Kruskal algorithm. Each vertex in $\mathcal{G}$ represents a target, and $e_{t_i t_j}$ denotes the distance between two targets t_i and t_j. Furthermore, all edges are sorted in descending order to facilitate the following calculation.

From the first edge in $\mathcal{E}$, we repeatedly remove each edge and generate two convex polygons by the Graham scan algorithm. Note that we assume a target as a point convex polygon, of which the perimeter is 0. Two targets are set as a line convex polygon, of which the perimeter is two times of the distance of the two targets.

Then, two target barriers are achieved from the two convex polygons and the corresponding target-barrier arcs. If $2\pi d_t$ plus two target barriers is less than the perimeter of $\mathcal{B}_{\min}$, update the optimal target-barrier set $\mathcal{B}_{\min}$. Assuming that there are l elements in the optimal target-barrier set $\mathcal{B}_{\min}$, the minimum required sensors is

$$|\mathcal{S}(\mathcal{B}_{\min})| = l \left\lceil \frac{\pi}{\arcsin \frac{r}{d_t}} \right\rceil + \sum_{k=1}^{l} \left\lceil \frac{\mathcal{L}_{cp_k}}{2r} \right\rceil. \tag{9}$$

The merged algorithm is summarized in Algorithm 1. Since the time complexity of Graham scan algorithm is $\mathcal{O}(m \log m)$, our algorithm can solve the optimal target-barrier problem in $\mathcal{O}(m^2 \log m)$, where m is the number of targets in the surveillance region.

TABLE I
DEFAULT IN SIMULATION EXPERIMENTS

Description	Value
The surveillance region	$1000m \times 1000m$
The sensing radius (r)	$20m$
The distance constraint (d_t)	$50m$
Number of targets (m)	10
Number of sensors (n)	1000
The standard deviation (σ)	20

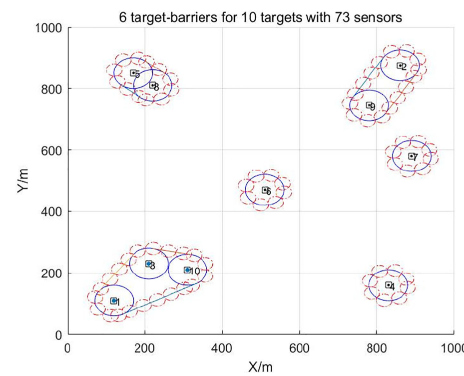

Fig. 4. Example of an optimal merged algorithm.

Algorithm 1: Optimal Merged Algorithm for Target Barrier.

Input: Target set $\mathcal{T}$, distance constraint d_t
Output: Target-barrier set with minimum sensors $\mathcal{B}_{\min}$
Generate the convex polygon cp_0 of all targets
$\mathcal{L}_{b_0} \leftarrow \mathcal{L}_{cp_0} + 2\pi d_t$
$\mathcal{B}_{\min} \leftarrow \{b_0\}$
Construct the minimum spanning tree $\mathcal{G} = (\mathcal{T}, \mathcal{E})$
Sort $e_{t_i t_j}$ in $\mathcal{E}$ in descending order
for each $e_{t_i t_j}$ in $\mathcal{E}$ **do**
  Remove $e_{t_i t_j}$
  Generate two convex polygons cp_i and cp_j
  $\mathcal{L}_{b_i} \leftarrow \mathcal{L}_{cp_i} + 2\pi d_t$ and $\mathcal{L}_{b_j} \leftarrow \mathcal{L}_{cp_j} + 2\pi d_t$
  if $\mathcal{L}_{b_i} + \mathcal{L}_{b_j} + 2\pi d_t < |\mathcal{B}_{\min}|$ **then**
    $\mathcal{B}_{\min} \leftarrow \{b_i, b_j\}$
  end if
end for
return $\mathcal{B}_{\min}$

IV. Evaluation

In this section, we conduct several simulations to evaluate the performance of the proposed algorithm. The default parameter settings can be accessed from Table I.

A. Effectiveness of the Proposed Algorithm

We give an example of toxic gas leak detection to validate the effectiveness of our algorithm. For the industrial application in toxic gas leak detection and monitoring, there may be many gas leak points in gas tanks and pipelines. To monitor intrusion from outside and detect toxic gas from inside, security guards may deploy sensors to form the target-barrier coverage. As shown in Fig. 4, $m = 10$ targets (toxic gas leak points) are randomly distributed, and 10 target-barrier circles are first constructed with the distance constraint $d_t = 50$ m. We find that 8 sensors are required for each target-barrier circle, and 80 sensors are

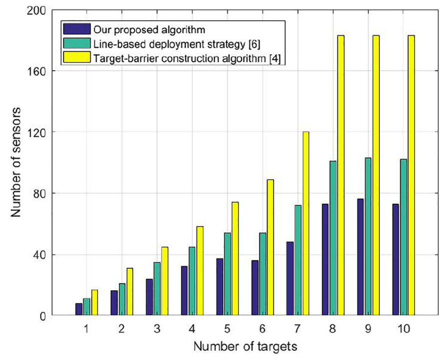

Fig. 5. Number of sensors versus number of targets.

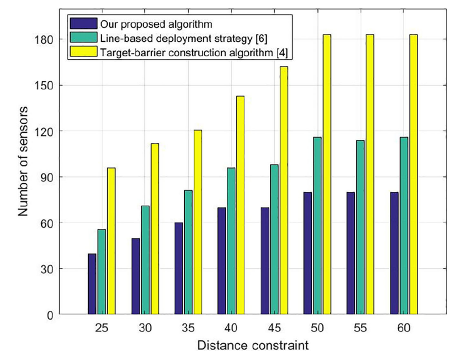

Fig. 6. Number of sensors versus distance constraint.

required for 10 target-barrier circles. After executing the algorithm, 6 target-barriers are formed for 10 targets with 73 sensors.

B. Advantage of the Proposed Algorithm

In the following simulations, we investigate our algorithm over the line-based deployment strategy in [6] and the target-barrier construction algorithm in [4]. Note that both the line-based deployment strategy and the target-barrier construction algorithm are random deployment strategies, and we assume that the random offset of each sensor from its target landing point follows a normal distribution with the standard deviation $\sigma = 20$. In our simulations, 1000 sensors are reserved for the target-barrier construction algorithm.

First, we examine the required number n of sensors with respect to the number m of targets from 1 to 10. We set $d_t = 50$ m as the distance constraint for the target barrier. Our proposed algorithm outperforms other algorithms in terms of constructing target barriers for the different number of targets in Fig. 5. Besides, we observed that the required number of sensors increases with respect to the increasing number of targets. And both our proposed algorithm and the line-based deployment strategy have the same fluctuation. The reason is that we first merge all target-barrier circles to get the optimal set of target barriers.

Second, we examine the required number n of sensors with respect to distance constraint d_t from 25 to 60 m in Fig. 6. In total, 50 targets are randomly distributed in the given region. Our algorithm enables the smaller number of sensors concerning different distance constraints. Since we first merge all target-barrier circles to get the optimal set of target barriers, both our proposed algorithm and the line-based deployment strategy have the same fluctuation. All deployment strategies have the same fluctuation when the distance constraint is less than 50 m. The reason is that the little distance constraint leads to many sparse scenarios. Otherwise, the larger distance constraint leads to more dense scenarios and target barriers are merged by our algorithm.

V. Conclusion

In this paper, we studied the deployment strategy with minimum sensors for target-barrier coverage in WSNs. We introduced target-barrier circles and their properties to convert the problem formulation into minimizing the length of the merged target barriers. We proposed an optimal merged algorithm to find the target-barrier set with minimum sensors for random deployment of targets in the surveillance region. Finally, based on experimental results, we demonstrate that the deployment strategy can minimize the number of sensors for target-barrier coverage.

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