Barrier Coverage in Hybrid Directional Sensor Networks

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***Abstract*—Barrier coverage is a critical issue in wireless sensor networks for security applications (e.g., border protection) where directional sensors (e.g., cameras) are becoming more popular and advantageous than omni-directional scalar sensors for the extra dimensional information they provide. However, barrier coverage can not be guaranteed after initial random deployment of sensors, especially for directional sensors with limited sensing angles. In this paper, we study how to efficiently achieve barrier coverage in hybrid directional sensor networks by moving mobile sensors to fill in gaps and form a barrier with stationary sensors. In specific, we introduce the notion of directional barrier graph to model the barrier coverage formation problem. We prove that the minimum number of mobile sensors required to form a barrier with stationary sensors is the length of the shortest path from the source node to the destination node on the directional barrier graph. We then formulate the problem of minimizing the cost of moving mobile sensors to fill in the gaps on the shortest path as a minimum cost bipartite assignment problem, and solve it in polynomial time using the Hungarian algorithm. Both analytical and experimental studies demonstrate the effectiveness of the proposed algorithm.**

I. Introduction

Wireless sensor networks (WSNs) have been widely used as an effective surveillance tool for security applications, such as battlefield surveillance, border protection, and airport intruder detection. To detect intruders who penetrate the regions of interest (ROI), we need to deploy a set of sensor nodes that can provide coverage of the ROI, a problem that is often referred to as *barrier coverage* [11], where sensors form *barriers* for intruders. When only stationary sensors are used, however, after the initial random or manual deployment, it is possible that sensors could not form a barrier due to gaps in their coverage, which would allow intruders to cross the ROI without being detected. In fact, it is difficult if possible at all to improve barrier coverage for sensor networks consisting of only stationary sensors. Fortunately, with recent technical advances, practical mobile sensors (e.g., Robomote [6], Packbot [18]) have been developed, which provides us a way to improve barrier coverage performance after sensor networks have been deployed.

Directional sensors (e.g., camera, radar) have been widely used for security applications. For example, the FREEDOM system [1], deployed on the border between Mexico and United States, uses cameras to detect illegal intruders (e.g., drug dealers and illegal immigrants). The SBInet project [2] uses cameras, radar, and ground sensors to construct a virtual fence to detect illegal intruders. Different from omni-directional scalar sensors, although directional sensors provide extra dimensional information, they usually have limited angle of views and facing directions, which therefore decrease the probability of barrier formation after initial random deployment.

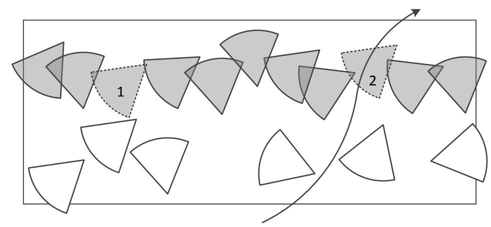


Fig. 1. An example of a strong barrier formation for hybrid directional sensor networks. Mobile sensors 1 and 2 fill in the gaps between stationary sensors and form a strong barrier for the ROI.

In this paper, we study the barrier coverage formation problem in hybrid directional sensor networks which consist of both stationary and mobile sensors with directional sensing model. In particular, we consider a two-phase deployment: in the first phase, after stationary sensors are deployed, their barrier gaps are identified and the number of mobile sensors needed can be calculated; in the second phase, mobile sensors are deployed and move to desired locations to fill in these gaps to form a barrier. Figure 1 shows an example of forming a strong barrier using mobile sensors. Mobile sensors 1 and 2 fill in the gaps between stationary sensors and form a strong barrier with pre-existing stationary sensors for the ROI.

A lot of work has been done on barrier coverage. However, most of existing work mainly focus on critical condition analysis and barrier construction for stationary sensors with omni-directional sensing model [11], [4], [13], [16], little effort has been made to explore how to efficiently use mobile sensors to form barrier coverage with stationary sensors, especially for directional sensors. Saipulla et al. [15] used mobile sensors with limited mobility to form a barrier for omni-directional sensors. Our work is different from their's in the following aspects. First, we study the barrier coverage formation problem on directional sensors rather than on omni-directional sensors. Second, we want to find the minimum number of mobile sensors needed to form a barrier. To the best of our knowledge, we are the first to study how to efficiently form barrier coverage in hybrid directional sensor networks.

There are lots of challenging issues in the barrier coverage formation problem of hybrid sensor networks. First, how to determine whether two sensors overlap with each other and calculate the distance between sensors is complicated due to the limited angle of views and variation of facing directions of directional sensors. Second, sensors are randomly deployed, therefore, it is challenging to determine whether the sensors already form a barrier after initial deployment or not. Third, the manufacturing cost of mobile sensors is much higher than the stationary sensors [6], which motivates us to use as few mobile sensors as possible. It is therefore challenging to find the minimum number of mobile sensors required to form barrier coverage with the deployed stationary sensors. Finally, mobile sensors should move to expected locations to fill in the gaps between stationary sensors. However, sensor movement costs a lot of energy and mobile sensors are often power limited. Therefore, another challenging issue is how to schedule and move mobile sensors to expected locations so that the total moving cost is minimized.

In this paper, we systematically address the aforementioned problems, and the main contributions of this paper are summarized as follows:

- To the best of our knowledge, we are the first to study the barrier coverage problem in hybrid directional sensor networks with both stationary and mobile sensors.
- We introduce a directional barrier graph to model the barrier coverage problem. We prove that determining the minimum number of mobile sensors required to form a barrier is equivalent to finding the shortest path from the source node (left boundary) to the destination node (right boundary) on the directional barrier graph.
- We formulate the problem of relocating mobile sensors to form a barrier while minimizing the total moving cost as a minimum cost bipartite assignment problem, and solve it in polynomial time using the Hungarian algorithm.

The remainder of the paper is organized as follows. We give a brief discussion about the literature of barrier coverage in Section II. We present the network model and the sensing model in Section III. The barrier coverage problem for directional sensor networks is formulated in Section IV. We present our directional barrier coverage algorithm in Section V. The performance evaluation of our algorithm is presented in Section VI. Finally, we conclude the paper in Section VII.

II. Related Work

Kumar et al. [11] firstly defined the notion of k-barrier coverage for WSNs and proposed an efficient algorithm to determine whether a belt region is k-barrier covered or not. They also introduced two notions of probabilistic barrier coverage - weak barrier coverage and strong barrier coverage. Chen et al. [4] introduced the notion of local barrier coverage and devised localized sleep-wakeup algorithms that provide near-optimal solutions. Liu et al. [13] devised an efficient distributed algorithm to construct multiple disjoint barriers for strong barrier coverage in a randomly deployed sensor network on a long irregular strip region. Saipulla et al. [16] studied the barrier coverage of the line-based deployment rather than the Poisson distribution model, and a tight lower-bound for the existence of barrier coverage was established. Li et al. [12] proposed an energy efficient scheduling algorithm for barrier coverage with probabilistic sensing model.

Recently, barrier coverage in directional sensor networks has gradually received more and more attention. Zhang et al. [22] studied the strong barrier coverage problem for rotationally directional sensors. A novel full-view coverage model was introduced in [21] for camera sensor networks. With the full-view coverage model, Wang et al. [20] further proposed a novel method to select camera sensors from an arbitrary deployment to form a camera barrier. The minimum camera barrier coverage problem was studied in camera sensor networks [14]. Tao et al. [19] investigated the problem of finding appropriate orientations of directional sensors such that they can provide strong barrier coverage.

With the development of mobile sensors, node mobility is exploited to improve barrier coverage. Shen et al. [17] studied the energy efficient relocation problem for barrier coverage in mobile sensor networks. Keung et al. [9] focused on providing k-barrier coverage against moving intruders in mobile sensor networks. Ban et al. [3] studied the problem on how to relocate mobile sensors to construct k grid barriers with minimum energy consumption. He et al. [8] studied the cost-effective barrier coverage problem when there are not sufficient mobile sensors and designed sensor patrolling algorithms to improve barrier coverage. Saipulla et al. [15] proposed a greedy algorithm to find barrier gaps and moved mobile sensors with limited mobility to improve barrier coverage.

Compared to these aforementioned works on barrier coverage, this paper is the first to study barrier coverage problem in hybrid directional sensor networks. With the unique features of directional sensing, we explore how to take advantage of mobile sensors to form a barrier.

III. System Model

In this section, we present system model including the network model and the sensing model for directional sensors, and introduce several terminologies related with barrier coverage.

We assume that the ROI is a two-dimensional rectangular belt area and n stationary sensors are randomly deployed in the belt region. τ mobile sensors are deployed further after the minimum number of mobile sensors required is calculated. We assume that stationary and mobile sensors are the same type of sensors except that mobile sensors have the ability to move. Let $S = \{s_1, s_2, \cdots, s_n\}$ denote the set of stationary sensors.

As shown in Figure 2, the area with the length of L and the width of H is generally a long and thin strip. A crossing path is a path that crosses the complete width of the area from the lower boundary to the upper boundary. A congruent crossing path is a crossing path that is orthogonal to the two boundaries. The path a and path b shown in Figure 2 demonstrate a congruent crossing path and a random crossing path, respectively. An intruder may attempt to penetrate the area along any crossing path.

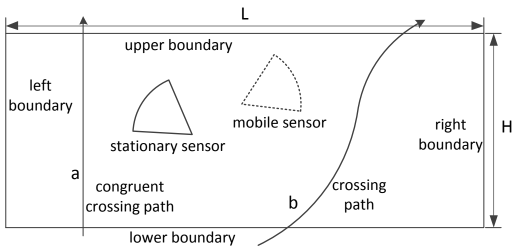
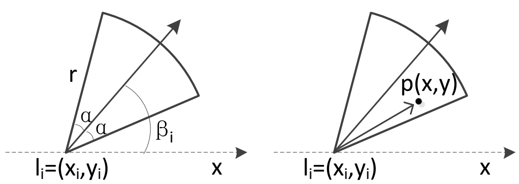


Fig. 2. An illustration of belt region (the square area), crossing paths, and directional sensors.

Unlike an omni-directional sensor, a directional sensor has a limited angle of view and an orientation. Therefore, as shown in Figure 3(a), a sector is commonly adopted to represent the sensing model of directional sensors. Let s_i denote the directional sensor i, then it can be represented by a 5-tuple $<x_i, y_i, r, \alpha, \beta_i>$, where $l_i = (x_i, y_i)$ is the two-dimensional location of the center of sensor i, r is the sensing range and α is half of the sensing angle of a sensor. We assume that each sensor has the identical sensing range and sensing angle. Based on the ground truth data in [7], the sensing angle of directional sensors, 2α, is usually less than π. β_i is the orientation or the facing direction of sensor i. We assume that β_i is uniformly distributed in $[0, 2\pi)$, e.g., $\beta_i \sim U(0, 2\pi)$. Note that omni-directional sensing model is a special case of directional sensing model when $2\alpha = 2\pi$.



(a) (b)

Fig. 3. (a) The sector sensing model for directional sensors; (b) A point p is covered by the sensor s_i.

Definition 1. *A two-dimensional point $p = (x, y)$ is said to be covered by a directional sensor $s_i = <x_i, y_i, r, \alpha, \beta_i>$ if and only if the following two conditions are satisfied.*

- $(x - x_i)^2 + (y - y_i)^2 \leq r^2$,
- $ang(\overrightarrow{l_i p}) \in [\beta_i - \alpha, \beta_i + \alpha]$, *where $ang(\cdot)$ denotes the angle of $(\cdot)$.*

The largest coverage range of a directional sensor, denoted by l_r, is the longest line in its sensing sector. Since the longest line is either the sensing radius or the longest chord of the sector, then we have

$$l_r = \begin{cases} \max(r, 2r\sin\alpha) & \text{for } 0 \leq \alpha < \frac{\pi}{2}, \\ 2r & \text{for } \frac{\pi}{2} \leq \alpha \leq \pi. \end{cases}$$

A. Terminologies

Two types of barrier coverage: *weak barrier coverage* and *strong barrier coverage*, were introduced in [11]. Weak barrier coverage requires that the union of sensors form a barrier in the horizontal direction from the left boundary to the right boundary, so that every intruder moving along congruent crossing paths can be detected. Figure 4 shows an example of weak barrier coverage. However, weak barrier coverage can not guarantee the detection of intruders following any crossing path (e.g., path a). In contrast, strong barrier coverage requires that the union of sensors forms a barrier from the left boundary to the right boundary so that every intruder can be detected no matter what crossing path it takes. An example of strong barrier coverage is shown in Figure 1. In this paper, we address the barrier coverage formation problem for both weak and strong barrier coverage.

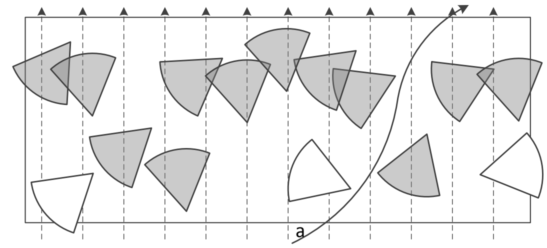


Fig. 4. An example of weak barrier coverage formed by sensors in grey color. A weak barrier can detect intruders following congruent crossing paths, however, can not guarantee the detection of intruders following any crossing path (e.g., path a).

IV. Problem Formulation and Analysis

In this section, we present the formulation and analysis of the barrier coverage problem for hybrid directional sensor networks.

A. Preliminaries

The fundamental problem for weak barrier coverage is to decide whether two directional sensors overlap in the horizontal direction or not, while the fundamental problem for strong barrier coverage is to decide whether two directional sensors overlap at all or not. This problem is easy to answer for omni-directional sensors of disk sensing model. However, it is much harder for directional sensors due to their different orientations and limited angle of views. For example, we can claim that two omni-directional sensors overlap with each other if the Euclidean distance between their centers is smaller than or equal to $2r$. However, two directional sensors might not overlap even when they are very close to each other, e.g., two cameras can be side by side but looking at opposite directions. Therefore, using only distance information would not work for directional sensors.

In the following, we first provide some preliminaries concerning weak barrier coverage. Considering a directional sensor $s_i = <x_i, y_i, r, \alpha, \beta_i>$. Let $[x_i^L, x_i^R]$ denote the coverage region of s_i in the horizontal direction, where x_i^L and x_i^R are the x-coordinates of the leftmost point and the rightmost point of the sector, respectively.

Definition 2. *Directional sensors s_i and s_j are said to be* weakly connected *directly if $x_i^L \leq x_j^L \leq x_i^R$ or $x_j^L \leq x_i^L \leq x_j^R$. Directional sensors s_i and s_k are said to be* weakly connected through intermediate sensor *s_j if s_i and s_k are* *not weakly connected directly but both of them are weakly connected directly to s_j.*

As shown in Figure 5(a), sensor b are weakly connected directly with sensor a and sensor c. Although sensor a and sensor c are not weakly connected directly, they are weakly connected through sensor b.

Definition 3. *A* weakly connected cluster *is the union of a set of directional sensors where each sensor is weakly connected with the rest of sensors in the set either directly or through one or multiple intermediate sensors.*

Lemma 1. *Given a belt region with length L, a weak barrier is formed if there is a weakly connected cluster whose coverage region in the horizontal direction is $[0, L]$.*

The proof is straightforward and omitted due to space limitation.

The following preliminaries are related to strong barrier coverage. For two strongly connected sensors, they overlap with each other if there exists a point covered by both sensors. However, there are many points in each sensing sector. Therefore, checking the coverage for each point is computationally prohibitive. Observing that a sector is uniquely characterized by its two radii and the arc, we propose the following lemma to efficiently detect overlaps between two sensors.

Lemma 2. *Directional sensors s_i and s_j overlap with each other if and only if there exists at least one intersection between the two radii and the arc of s_i and the two radii and the arc of s_j.*

Proof: $\Rightarrow$. If there exists an intersection between the two radii and the arc of s_i and the two radii and the arc of s_j, there must exist one point covered by both s_i and s_j. Therefore, s_i and s_j overlap with each other.

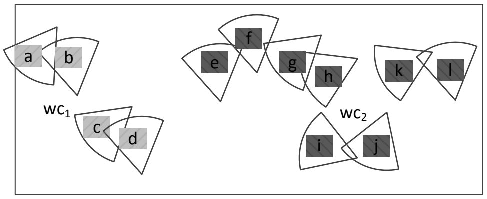
$\Leftarrow$. If s_i and s_j overlap with each other, there exists at least one point covered by both s_i and s_j. Since the point is bounded by the two radii and the arc of each sensor, there must exist at least one intersection between the two radii and the arc of s_i and the two radii and the arc of s_j. ■

Based on Lemma 2, the problem of deciding whether two sensing sectors overlap or not can be simplified to check the intersections between line-line, line-circle, and circle-circle.

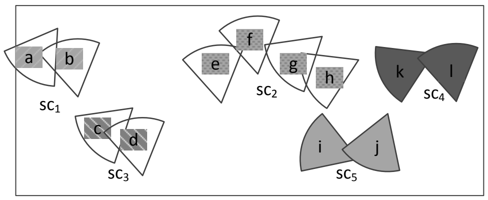
Definition 4. *Directional sensors s_i and s_j are said to be* strongly connected *directly if they overlap with each other. Directional sensors s_i and s_k are said to be* strongly connected through intermediate sensor *s_j if s_i and s_k are not strongly connected directly but both of them are strongly connected directly to s_j.*

As shown in Figure 5(b), sensor f are strongly connected directly with sensor e and sensor g. Although sensor e and sensor g are not strongly connected directly, they are strongly connected through sensor b.

Definition 5. *A* strongly connected cluster *is the union of a set of directional sensors where each sensor is strongly connected with the rest of sensors in the set either directly or through one or multiple intermediate sensors.*



(a) Weakly connected clusters



(b) Strongly connected clusters

Fig. 5. An example of connected clusters for directional sensor networks

Lemma 3. *A strong barrier is formed if there is a strongly connected cluster overlapping with both the left boundary and the right boundary of the belt region.*

The proof is straightforward and omitted due to space limitation.

Figure 5 shows an example of weakly connected clusters and strongly connected clusters for the same sensor network. Two weakly connected clusters, wc_1 and wc_2, can be identified. Sensors a, b, c and d form wc_1, while the rest of sensors form wc_2. Meanwhile, five strongly connected clusters can be identified, as represented by sc_1 to sc_5.

B. Minimizing the Number of Mobile Sensors Needed

Due to random deployment and directional sensing features, sensor networks might not form barrier coverage after initial deployment, especially for strong barrier coverage. The usage of mobile sensors can potentially fill in the coverage holes and help achieve barrier coverage. However, the cost of mobile sensors is usually much higher than that of stationary sensors. Therefore, the problem is how to use the minimum number of mobile sensors to reduce the deployment cost.

According to Lemma 1 and 3, forming a barrier actually is equal to forming a connected cluster. Denote the set of connected clusters by $C = \{c_1, c_2, \cdots, c_k\}$. Depending on the application requirement, this could be either a set of weakly connected clusters or a set of strongly connected clusters. Here, we propose the notion of "directional barrier graph" to help us solve the barrier coverage problem, where we consider each connected cluster as a vertex, and the weight of an edge between two vertices as the minimum number of mobile sensors required to connect the two disjoint clusters into a new connected cluster. Further, we denote the left boundary and right boundary of the belt region by virtual vertices s and t, respectively. s is called the source node and t is called the destination node.

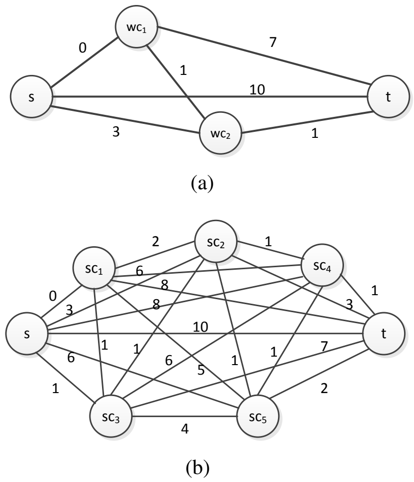


Fig. 6. Directional barrier graph representation for: (a) weak barrier coverage of Figure 5(a); (b) strong barrier coverage of Figure 5(b).

Definition 6. *A* directional barrier graph $G = (V, E, W)$ *of a sensor network is constructed as follows. The set* V *consists of vertices corresponding to the left boundary (s), connected clusters (C) and the right boundary (t) of the belt region, that is,* $V = \{v_1, v_2, \cdots, v_{k+2}\} = \{s \cup C \cup t\}$. $E = \{e(v_i, v_j)\}$ *is the set of edges between any pair of vertices.* $W : E \rightarrow \mathbb{R}$ *is the set of weights of each edge, where the weight* $w(v_i, v_j)$ *of edge* $e(v_i, v_j)$ *is the minimum number of mobile sensors required to connect* v_i *and* v_j.

Let $d_w(v_i, v_j)$ denote the *weak distance* between two vertices v_i and v_j for weak barrier coverage. When none of v_i and v_j is a boundary, $d_w(v_i, v_j) = v_j^L - v_i^R$ given the assumption that $v_j^L > v_i^R$. While if v_i is a boundary, $d_w(v_i, v_j) = 0$ if v_j intersects the boundary; otherwise, $d_w(v_i, v_j) = v_j^L$ if v_i is the left boundary s and $d_w(v_i, v_j) = L - v_j^R$ if v_i is the right boundary t. When v_i is the left boundary s and v_j is the right boundary t, $d_w(v_i, v_j) = L$. x_i^L and x_i^R is the left coverage boundary and the right coverage boundary of v_i in the horizontal direction. Therefore, the weight $w(v_i, v_j)$ in the directional barrier graph for weak barrier coverage is:

$$w(v_i, v_j) = \lceil \frac{d_w(v_i, v_j)}{l_r} \rceil \quad (1)$$

Figure 6(a) shows the directional barrier graph for weak barrier coverage, which is constructed based on weakly connected clusters shown in Figure 5(a). The weight of edge (s, wc_1) is 0 because wc_1 intersects the left boundary.

Let $d_s(v_i, v_j)$ denote the *strong distance* between two vertices v_i and v_j for strong barrier coverage. When none of v_i and v_j is a boundary, $d_s(v_i, v_j) = \min(d(p_i, p_j))$ where p_i and p_j are points on v_i and v_j, respectively, and $d(p_i, p_j)$ is the Euclidean distance between p_i and p_j. When any of v_i and v_j is a boundary, $d_s(v_i, v_j) = d_w(v_i, v_j)$. Therefore, the weight $w(v_i, v_j)$ in the directional barrier graph for strong barrier coverage is:

$$w(v_i, v_j) = \lceil \frac{d_s(v_i, v_j)}{l_r} \rceil \quad (2)$$

Figure 6(b) shows the directional barrier graph of strong barrier coverage, which is constructed based on those strongly connected clusters shown in Figure 5(b).

Theorem 4. *The minimum number of mobile sensors required to form a barrier with stationary sensors, denoted by* γ, *is exactly the length of the shortest path from* s *to* t *on the directional barrier graph* G. *That is,* $\gamma = \sum_{e(v_i, v_j) \in sp(G,s,t)} w(v_i, v_j)$, *where* $sp(G, s, t)$ *denotes the shortest path from* s *to* t *on the graph* G.

Proof: According to the definition of directional barrier graph G, if we want to form a barrier, we only need to choose a path from s to t, and put exactly the number of mobile sensors needed on each edge of the path. That is, for a chosen path, the number of mobile sensors required to form a barrier is equal to the sum of weights of all edges on the path, which is the length of the path. Therefore, the minimum number of mobile sensors required to form a barrier is the length of the shortest path from s to t on graph G. ■

Theorem 5. *A region is barrier covered if and only if the length of the shortest path from* s *to* t *on the directional barrier graph is* 0.

Proof: $\Rightarrow$. If the length of the shortest path from s to t on the directional barrier graph is 0, there exists at least one connected cluster that overlaps with both the left boundary and the right boundary of the belt region. Therefore, the region is barrier covered.

$\Leftarrow$. If the region is barrier covered, there exists one connected cluster that overlaps with both the left boundary and the right boundary of the belt region. Then weights are 0 from s to the connected cluster and from the connected cluster to t. Therefore, there exist one path from s to t with a length of 0, which obviously is also the shortest path. ■

The following Theorem provides an upper bound for the number of mobile sensors deployed to form a barrier.

Theorem 6. *Given a belt region with length* L, *the minimum number of mobile sensors required to form a barrier is upper bounded by* $\lceil \frac{L}{l_r} \rceil$, *where* l_r *is the largest coverage range of a sensor.*

Proof: The edge $e(s, t)$ means to deploy mobile sensors directly from the left boundary to the right boundary of the belt region. The optimal way to deploy sensors is to deploy them continuously in a horizontal straight line. Therefore, the minimum number of mobile sensors required to connect the left boundary and the right boundary directly is $\lceil \frac{L}{l_r} \rceil$, that is $w(s, t) = \lceil \frac{L}{l_r} \rceil$. The path containing only the edge $e(s, t)$ could either be the shortest or not. If it is not the shortest path, according to Theorem 4, the minimum number of mobile sensors required is smaller than $\lceil \frac{L}{l_r} \rceil$; otherwise, the minimum number of mobile sensors required is equal to $\lceil \frac{L}{l_r} \rceil$. Therefore, the minimum number of mobile sensors required to form a barrier is always upper bounded by $\lceil \frac{L}{l_r} \rceil$. ■

Theorem 4 proves that the minimum number of mobile sensors required to form a barrier is exactly the length of the shortest path from s to t on graph G, which can be found by the classical Dijkstra's algorithm [5]. The shortest path shown in Figure 6(a) for weak barrier coverage is $s \to wc_1 \to wc_2 \to t$, the length of which is $0+1+1=2$. Therefore, the region is not weak barrier covered after initial deployment, and at least 2 mobile sensors are needed to form a weak barrier. As for strong barrier coverage, the shortest path shown in Figure 6(b) is $s \to sc_1 \to sc_2 \to sc_4 \to t$, the length of which is $0+2+1+1=4$. That is, the region is not strong barrier covered after initial deployment, and at least 4 mobile sensors are needed to form a strong barrier. There are three gaps on the shortest path: $sc_1 \to sc_2$, $sc_2 \to sc_4$, and $sc_4 \to t$, which requires 2, 1 and 1 mobile sensors, respectively.

C. Minimum Cost Barrier Formation (MCBF)

In order to fill in the gaps and form a barrier, the mobile sensors need to be dispatched to the desired locations along the shortest path, which also consumes a lot of energy. In general, the energy consumed by mobile sensors is proportional to the moving distance. In order to prolong the lifetime of mobile sensors, the total moving distance should be minimized. In the following, we formulate the problem of how to assign a set of mobile sensors to fill in barrier gaps and form a barrier while minimizing the total moving cost. We refer to it as the minimum cost barrier formation (MCBF) problem.

Suppose the minimum number of mobile sensors required is γ. Then there are γ target locations for γ mobile sensors to move to. Denote the set of target locations by $T = \{t_1, t_2, \cdots, t_\gamma\}$. In order to form a barrier, τ ($\tau \geq \gamma$) mobile sensors are deployed. Let δ_{ij} denote a decision variable, where $\delta_{ij} = 1$ if mobile sensor m_i is assigned to target location t_j, $\delta_{ij} = 0$ otherwise. d_{ij} is the distance for mobile sensor m_i to move to target location t_j. Then the MCBF problem can be formulated as how to assign γ out of τ mobile sensors to γ target locations while minimizing the total moving distance.

$$\text{Minimize} \quad \sum_{i=1}^{\tau}\sum_{j=1}^{\gamma} d_{ij}\delta_{ij} \tag{3}$$

$$\text{subject to} \quad \sum_{i} \delta_{ij} = 1, \forall j = 1, 2, \cdots, \gamma. \tag{4}$$

$$\sum_{j} \delta_{ij} \leq 1, \forall i = 1, 2, \cdots, \tau. \tag{5}$$

$$\delta_{ij} = 0 \text{ or } 1, i = 1, 2, \cdots, \tau; j = 1, 2, \cdots, \gamma.$$

The objective function is to minimize the total moving distance. The first constraint restricts that any target location must be assigned with one and only one mobile sensor. The second constraint restricts that each mobile sensor can be assigned to at most one target location. The formulated problem is indeed a minimum cost bipartite assignment problem, which can be solved optimally by the Hungarian algorithm [10].

V. Directional Barrier Coverage Algorithm

In this section, we present our solution to the barrier coverage problem in hybrid directional sensor networks, referred to as directional barrier coverage (DBC) algorithm. The algorithm is formally presented in Algorithm 1.

Algorithm 1 Directional Barrier Coverage Algorithm (DBC)

Input: $S = \{s_1, s_2, \cdots, s_n\}$
Output: The set of target locations T and mobile sensor assignment vector A_s

identify the set of weakly/strongly connected clusters
calculate the distance between any two connected clusters
calculate the minimum number of mobile sensors required to connect any two connected clusters
construct the directional barrier graph G
find the shortest path sp(G,s,t) using Dijkstra's algorithm
if the length of sp(G,s,t) is larger than 0 **then**
  calculate the set of target locations T
  deploy mobile sensors
  get sensor assignment vector A_s by using the Hungarian algorithm
  move mobile sensors according to A_s and T
else
  Region of interest is already barrier covered
end if

After sensors are deployed, they report their locations and facing directions to the server. The server identifies the set of weakly connected clusters or the set of strongly connected clusters depending on the application requirement. Then it calculates the minimum number of mobile sensors required to connect any two disjoint clusters and constructs the directional barrier graph G. The shortest path can be found using the classical Dijkstra's algorithm. The server uses the Hungarian algorithm [10] to calculate the optimal assignment of mobile sensors and informs them to move to corresponding target locations to fill the gaps on the shortest path.

In the following, we mainly describe the details of two parts in DBC algorithm: identifying the set of weakly/strongly connected clusters and calculating the set of target locations.

A. Connected Clusters Identification

We first describe how to identify the set of weakly connected clusters. Let $C_w = \{wc_1, wc_2, \cdots\}$ denote the set of weakly connected clusters. Based on definition 2, two sensors are weakly connected if they overlap in the horizontal direction. Therefore, we first calculate the coverage region in the horizontal direction of each sensor, and then sort all the sensors in the increasing order according to their left coverage boundary. In this way, we only need to compare the right boundary of a sensor with the left boundary of the next sensor. Initializing a cluster with the first sensor, the left boundary and the right boundary of the cluster are the left boundary and the right boundary of the first sensor, respectively. Starting from the left to the right of the ordered set, if the left coverage boundary of next sensor is smaller than or equal to the right coverage boundary of the cluster, we put the sensor into the cluster and update the right coverage boundary of the cluster; otherwise, we initialize a new cluster with the sensor. The process repeats until all the sensors are compared. Finally, each sensor must belong to one and only one cluster.

We formally present the process of identifying C_w in Algorithm 2. Given n stationary sensors, the running time of the sorting operation in step 5 is $O(n \lg n)$. The running time of the comparison process from step 7 to the end is $O(n)$. Therefore, the running time of this algorithm is $O(n \lg n)$.

Algorithm 2 Weak-Connected-Cluster Identification (WCCI)

Input: $S = \{s_1, s_2, \cdots, s_n\}$
Output: $C_w = \{wc_1, wc_2, \cdots\}$

1: $C_w \leftarrow \emptyset$
2: **for** $i = 1$ to n **do**
3:   calculate x_i^L and x_i^R for sensor s_i
4: **end for**
5: sort S according to x_i^L in the increasing order
6: initialize a queue Q, $Q \leftarrow S$, and $k \leftarrow 0$
7: **while** $Q! = \emptyset$ **do**
8:   $k \leftarrow k + 1$
9:   $s_j \leftarrow Q._{pullFirst}$
10:   $wc_k \leftarrow \{s_j\}$, $wc_k^L \leftarrow x_j^L$, and $wc_k^R \leftarrow x_j^R$
11:   **for** each sensor s_p in Q **do**
12:     **if** $x_p^L \leq wc_k^R$ **then**
13:       $pop(s_p)$
14:       $wc_k \leftarrow wc_k \cup \{s_p\}$, and $wc_k^R \leftarrow \max(wc_k^R, x_p^R)$
15:     **else**
16:       $break$
17:     **end if**
18:   **end for**
19:   $C_w \leftarrow C_w \cup \{wc_k\}$
20: **end while**

We then describe how to identify the set of strongly connected clusters. Let $C_s = \{sc_1, sc_2, \cdots\}$ denote the set of strongly connected clusters. We first initialize a cluster with a sensor. For each newly added sensor s_j in the latest cluster, we check all the rest sensors and put all sensors that are strongly connected with s_j into the cluster. We call this process as the neighbor finding process. If no neighbor can be founded in the neighbor finding process, we initialize a new cluster with a sensor in the rest sensors and perform the neighbor finding process again. Finally, the process terminates when no sensor is left.

We formally present the process of identifying C_s in Algorithm 3. The algorithm performs exactly n rounds of neighbor finding process and the number of sensors to be checked in each round is always smaller than n. Therefore, the running time in the worst case is $O(n^2)$.

Algorithm 3 Strong-Connected-Cluster Identification (SCCI)

Input: $S = \{s_1, s_2, \cdots, s_N\}$
Output: $C_s = \{sc_1, sc_2, \cdots\}$.

$SC \leftarrow \emptyset$, $k \leftarrow 1$
initialize a queue Q, $Q \leftarrow S$
while $Q! = \emptyset$ **do**
  $sc_k \leftarrow Q._{pullFirst}$
  while new sensors are added into sc_k **do**
    for each new added sensor s_j of sc_k **do**
      for each sensor $s_p \in Q$ **do**
        if s_j and s_p are strongly connected **then**
          $pop(s_p)$
          $sc_k \leftarrow sc_k \cup \{s_p\}$
        end if
      end for
    end for
  end while
  $C_s \leftarrow C_s \cup \{sc_k\}$
  $k \leftarrow k + 1$
end while

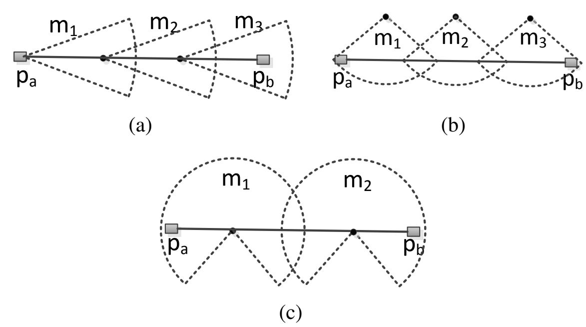


Fig. 7. Illustration of different deployment methods for: (a) $l_r = r$ when $2\alpha < \pi$; (b) $l_r = 2r \sin \alpha$ when $2\alpha < \pi$; (c) $l_r = 2r$ when $2\alpha \geq \pi$.

B. Target Locations Calculation

After finding the shortest path by using Dijkstra's algorithm, we can know all barrier gaps and the number of mobile sensors needed to fill in each gap. The problem that assigning mobile sensors to fill in barrier gaps while minimizing the total moving cost has been formulated as a minimum cost bipartite assignment problem.

Before assigning mobile sensors using the Hungarian algorithm, we should first calculate the set of target locations for mobile sensors to move to. Without loss of generality, we consider the calculation of target locations for strong barrier gaps. The calculation of target locations for weak barrier gaps is simply a special case where only the x-coordinates of target locations for strong barrier gaps are considered.

Given two strongly connected clusters sc_1 and sc_2, the closest pair of points are $p_a = (x_a, y_a)$ on sc_1 and $p_b = (x_b, y_b)$ on sc_2. Thus, the minimum distance between sc_1 and sc_2 is

$$d(sc_1, sc_2) = d(p_a, p_b) = \sqrt{(x_b - x_a)^2 + (y_b - y_a)^2}$$

Then the minimum number of mobile sensors to fill in the gap is $w(sc_1, sc_2) = \lceil \frac{d(sc_1, sc_2)}{l_r} \rceil$. We evenly deploy mobile sensors with their largest coverage distance in its sensing sector along the line segment $p_a p_b$. Therefore, the interval between two mobile sensors is $d_v = \frac{d(sc_1, sc_2)}{w(sc_1, sc_2)}$. As mentioned in Section III, the longest line could either be the radius or the longest chord when $0 \leq 2\alpha < \pi$, or $2r$ when $\pi \leq 2\alpha \leq 2\pi$. Corresponding to these three cases, we have three deployment strategies, as shown in Figure 7.

Let φ denote the direction of $\overrightarrow{p_a p_b}$. Let h denote the height from the center to the longest chord of a sector. Suppose the target locations are $t_i = (t_i^x, t_i^y, t_i^o)$ for $i = 1, 2, \cdots, w(sc_1, sc_2)$, where t_i^x and t_i^y are the x-coordinate and y-coordinate of the target location t_i, and t_i^o is the facing direction of the mobile sensor on t_i. The calculations of target locations for deployments shown in Figure 7(a) and Figure 7(c) are straightforward. Therefore, we mainly describe the calculation of target locations for the deployment shown in Figure 7(b).

$$
\begin{aligned}
t_i^x &= x_a + (i-1)d_v \cos\varphi + \bar{l}\cos(\varphi + \lambda) \\
t_i^y &= y_a + (i-1)d_v \sin\varphi + \bar{l}\sin(\varphi + \lambda) \\
t_i^o &= \varphi + 3\pi/2
\end{aligned}
$$

where $\bar{l} = \sqrt{h^2 + (d_v/2)^2}$, $\lambda = \arctan(2h/d_v)$.

We can calculate the target locations for all the gaps on the shortest path. Thereafter, we use the Hungarian algorithm to find the optimal assignment of mobile sensors to target locations and move sensors accordingly to fill in each gap and form a barrier.

VI. Performance Evaluation

In this section, we conduct simulations using Matlab to evaluate the performance of our proposed directional barrier coverage algorithm.

The ROI is a belt region of length $L = 500m$ and width $H = 100m$. Both stationary sensors and mobile sensors are uniformly deployed in the belt region. The evaluation mainly focuses on three performance metrics: minimum number of mobile sensors required to form barrier coverage, denoted by γ, total moving distance for mobile sensors to form barrier coverage, denoted by d_m, and the probability that the sensor network is already barrier covered after initial deployment, denoted by p_b. p_b is calculated by the ratio of the number of sensor networks barrier covered to the number of experiments performed. Evaluation of these performance metrics is conducted on different parameters, such as the number of stationary sensors, sensing range and sensing angle (or field of view). For all the simulation results presented in this paper, each data point is an average of 100 experiments. According to Theorem 6, $\lceil \frac{L}{l_r} \rceil$ of mobile sensors are deployed in each experiment to guarantee the sensor network will be barrier covered after movement. Both weak barrier coverage and strong barrier coverage are studied.

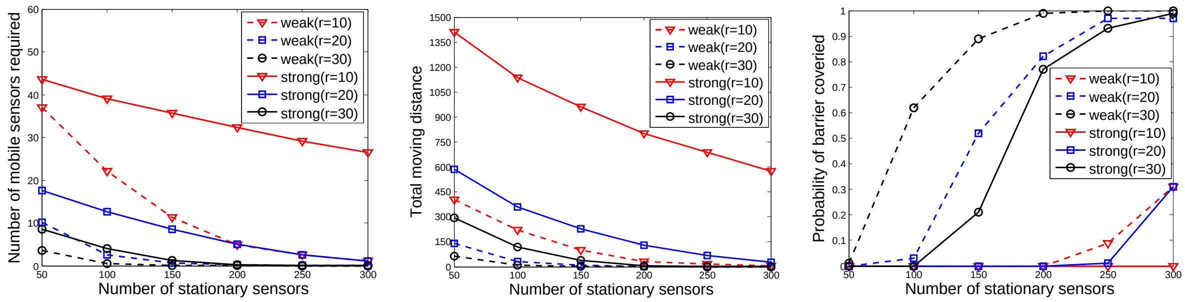
We first explore the effects of the number of stationary sensors on performance metrics. The number of stationary sensors changes from 50 to 300. Figure 8 shows the results when we change the sensing range with $\alpha = \pi/6$ fixed. Figure 9 shows the results when we change the sensing angle with sensing range $r = 20m$ fixed. As shown in Figure 8(a) and Figure 9(a), the minimum number of mobile sensors required decreases quickly as the number of deployed stationary sensors increases. The reason is that more stationary sensors increase the probability of forming larger connected clusters, which results in fewer gaps on the shortest path. The total moving distance, as shown in Figure 8(b) and Figure 9(b), also decreases as the number of stationary sensors increases. The probability of barrier covered for the sensor network, shown in Figure 8(c) and Figure 9(c), increases as the number of stationary sensors increases.

We then explore the effects of sensing range on performance metrics. As shown in Figure 8(a) and Figure 8(b), both the minimum number of mobile sensors required and the total moving distance decreases when the sensing range increases for both weak barrier coverage and strong barrier coverage. The reason is that, larger sensing range increases the probability of forming connected clusters and also enlarges the coverage region of each connected cluster, which results in fewer and smaller gaps on the shortest path. The minimum number of mobile sensors required and the total moving distance for strong barrier coverage are always larger than those for weak barrier coverage given the same sensing range, respectively. An interesting observation is that, even the minimum number of mobile sensors required for weak barrier coverage when the sensing range $r = 10m$ is larger than that for strong barrier coverage when the sensing range $r = 20m$, a reverse result is shown for the total moving distance. This is because mobile sensors only need to move in the horizontal direction for weak barrier coverage. The probability of barrier covered, as shown in Figure 8(c), is always higher for larger sensing range. The probability of weak barrier coverage is always higher than that of strong barrier coverage for the same sensing range.

We also study the effects of sensing angle on performance metrics. As shown in Figure 9(a) and Figure 9(b), the minimum number of mobile sensors required and the total moving distance decrease as the sensing angle increases for both weak barrier coverage and strong barrier coverage. This is because increasing the sensing angle increases the probability of overlapping between sensors, which results in larger connected clusters and less number of gaps on the shortest path. Given the same sensing angle, the minimum number of mobile sensors required and the total moving distance for strong barrier coverage are always larger than those for weak barrier coverage, respectively. The consistent result is also observed in Figure 9(c), where the probability of barrier covered is higher for larger sensing range, and the probability of weak barrier coverage is always higher than that of strong barrier coverage.

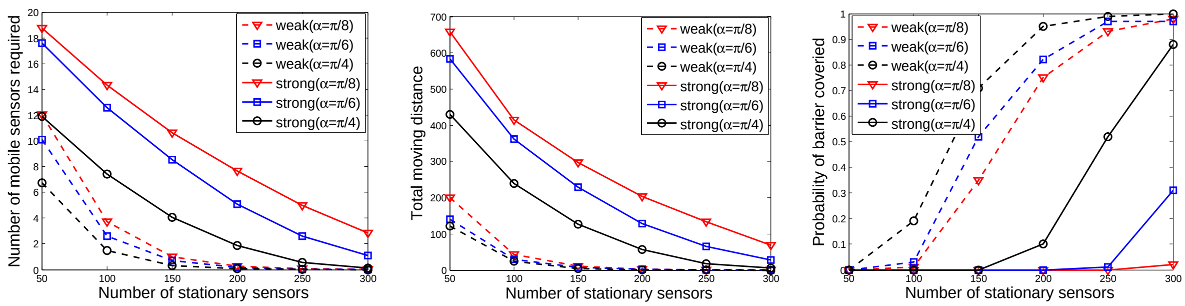
VII. Conclusion and Future Work

In this paper, we studied the barrier coverage problem for hybrid directional sensor networks and explored how to efficiently achieve barrier coverage by taking advantage of the mobility feature of mobile sensors. We introduced the notion of directional barrier graph, and proved that the minimum number of mobile sensors required to form a barrier is the length of the shortest path from the source node to the destination node on the graph. The problem that minimizing the total moving cost of mobile sensors to form a barrier was formulated as the minimum cost bipartite assignment problem,



(a) (b) (c)

Fig. 8. Performance evaluation by varying the number of stationary sensors and the sensing range, $\alpha = \pi/6$ is fixed: (a) minimum number of mobile sensors required to form a barrier; (b) total moving distance; (c) probability of barrier covered after initial deployment.



(a) (b) (c)

Fig. 9. Performance evaluation by varying the number of stationary sensors and the sensing angle, sensing range $r = 20$ is fixed: (a) minimum number of mobile sensors required to form a barrier; (b) total moving distance; (c) probability of barrier covered after initial deployment.

which can be solved in polynomial time by the Hungarian algorithm. Our proof showed that our solution is the optimal for the barrier coverage in hybrid directional sensor networks.

As part of the future work, we plan to seek distributed solutions to the barrier coverage problem. Besides, we also plan to explore the k barriers formation problem in hybrid sensor networks.

ACKNOWLEDGEMENT

This work was supported in part by NSF CNS-1017156 and CNS-0953238, and in part by NSFC 61273079 and ANR-NSFC 61061130563.

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