Finding and Mending Barrier Gaps in Wireless Sensor Networks

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***Abstract*—Constructing sensing barriers using wireless sensor networks has important applications in military operations and homeland security. The goal of forming a sensing barrier is to detect intruders attempting to cross the network. Early studies often assume that sensors remain static once deployed. We note that barrier gaps may occur at deployment if sensors are deployed at random. Barrier gaps may also occur in an existing barrier if some sensors used to form the barrier start malfunctioning or run out of power. We present an efficient solution to solve this problem. In particular, we devise an efficient algorithm to find sensing gaps and relocate mobile sensors to form a new barrier while balancing the energy consumption among mobile sensors. We also investigate the related design issues and performance tradeoffs. Simulation results show that our algorithms can effectively improve the barrier coverage of a wireless sensor network under a wide range of deployment parameters. These results provide insights and guidelines to the deployment, design, and performance of mobile wireless sensor networks for barrier coverage.**

I. INTRODUCTION

Barrier coverage using wireless sensor networks aims at detecting intruders that attempt to cross the network. It requires a chain of sensors with overlapping sensing areas across the entire deployed region. Each independent chain of sensors is referred to as a sensing barrier, or simply barrier. It acts as a "trip wire" to detect intruders attempting to cross the network. Barrier coverage has critical applications in military operations and homeland security.

Barrier coverage has been studied intensively in recent years. Critical conditions for achieving barrier coverage have been obtained, and the effect of different deployment strategies, sensor collaboration schemes, dimensionality on barrier coverage, and the construction and monitoring of barrier coverage have been studied [1], [2], [3], [4], [5], [6], [7], [8], [9]. However, little effort has been made to explore effective mechanism to improve barrier coverage of a wireless sensor network. We note that sensing gaps may occur at deployment if sensors are deployed at random, or in an already formed barrier if some sensors used to form the barrier start malfunctioning or run out of power.

Recent technology advances have made it possible to deploy mobile sensors in practical applications. A number of mobile sensor platforms have been developed [10], [11], [12], providing a powerful mechanism to improve various coverage measures in hostile environments including battlefields and hazardous areas. While there have been extensive studies on how to efficiently relocate mobile sensors to improve the area coverage of a wireless sensor network [13], [14], [15], [16], [17], the impact of sensor mobility on barrier coverage is yet to be explored.

In this work we study how to use mobile sensors to improve barrier coverage and investigate its design issues and performance tradeoffs. In particular, we would like to find sensing gaps and relocate mobile sensors to the desired locations to form new barriers. This task faces a number of challenges because of the unique features of barrier coverage and the resource constraints of wireless sensor networks.

First, barrier coverage is a global property, for it requires a chain of sensors with overlapping sensing ranges across the entire length of the network. Using mobile sensors to connect local sensor clusters do not necessarily result in the formation of a global barrier. It may require multiple mobile sensors be relocated to certain desired locations at the same time.

Second, each mobile sensor has a limited moving range due to its energy constraints. Its movement is confined within its moving range and it may not be relocated to arbitrary locations in the network. Moreover, it is highly desirable to balance the energy consumption among mobile sensors to prolong the network lifetime.

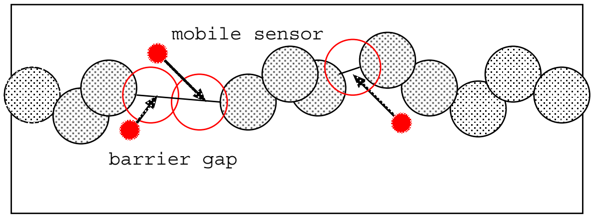

Fig. 1. A two-phase algorithm to improve barrier coverage by first finding barrier gaps and then mending them with mobile sensors.

We consider the scenario where sensors are deployed at random along a line (e.g., sensors are dropped from an aircraft along a specific path) [6]. Due to wind and other environmental factors, these sensors may be scattered around along the deployed line with random offsets, which may result in gaps between different sensor clusters as illustrated in Figure 1.

We devise a two-phase algorithm that can efficiently find barrier gaps and relocate mobile sensors to form new barriers while balancing the energy consumption among the mobile sensors. In the first phase, the algorithm scans the network from left to right to find barrier gaps, as illustrated in Figure 1. In the second phase, the algorithm computes which mobile sensors should be relocated to fill the gaps such that the maximum moving distance among all sensors is minimized.

Simulation results show that our algorithm can effectively improve the barrier coverage of a wireless sensor network. We show that, as mobile sensors are added to the deployment, after a certain point the barrier coverage probability starts to increase and a barrier is formed. This can be explained as follows. When the number of mobile sensors is not sufficient to fill all the barrier gaps, no new barriers can be formed and the barrier coverage probability remains unchanged. After a certain point, there is a positive probability that the mobile sensors can fill all the gaps to form a barrier, and the probability increases as more mobile sensors are added. When there are enough mobile sensors such that all the gaps can be filled almost surely, the barrier coverage probability will reach one.

As the number of mobile sensors increases, the required minimum moving range to achieve barrier coverage decreases. This demonstrates a tradeoff between the number of mobile sensors and the required moving ranges to achieve barrier coverage. If there are enough mobile sensors, the moving range of each sensor may remain small and still achieve barrier coverage. Otherwise, the moving range will need to be enlarged to compensate for the shortage of mobile sensors.

The results obtained in this paper provide important guidelines and insights into the deployment, mobile sensor relocation, and the performance of wireless sensor networks for barrier coverage.

The rest of the paper is organized as follows. Section II reviews previous work on barrier coverage of wireless sensor networks. Section III describes the network model used in our study. In Section IV we present a two-phase algorithm to find and mend the barrier gaps in the network. Section V evaluates the performance of our proposed algorithm. Finally, we conclude the paper in Section VI.

II. RELATED WORK

The notion of barrier coverage, first introduced in the context of robotic sensors [18], concerns a sensor network's capability to detect intruders crossing from one side of the network to the opposite side.

Liu and Towsley [1] first studied the barrier coverage problem on two-dimensional plane and two-dimensional strip sensor networks using percolation theory. Recently, Liu, Dousse, Wang, and Saipulla derived the critical conditions for the existence of barrier coverage and devised efficient algorithms to construct sensor barriers [3]. Barrier coverage of three-dimensional underwater sensor networks is studied by Barr et. al. [8]. In [9], [7], Yang and Qiao studied the effects of sensor collaboration and multi-round deployment on barrier coverage.

Kumar, Lai, and Arora [2] introduced the notion of weak coverage and derived the critical conditions for the existence of weak barrier coverage in a randomly deployed sensor network. Later, Chen, Kumar, and Lai [19] devised a localized algorithm that guarantees the detection of intruders whose trajectory is confined to a slice of the belt region of deployment. In [4], Chen, Lai, and Xuan studied how to measure and ensure the quality of barrier coverage in wireless sensor networks.

Most of the early studies assume that the sensor locations follow a Poisson point process where sensors are distributed in a large area uniformly at random. Saipulla, Westphal, Liu, and Wang first considered a more realistic application scenario where sensors are dropped along certain lines with random offsets, and established analytical results for the barrier coverage probability [5], [6].

The effects of sensor mobility on intrusion detection have been investigated in previous studies. In [20] the authors proposed an optimization framework for selecting sensor positions to detect mobile targets traversing a given area. Chellappan et al [17] studied the issue of relocating mobile sensor with limited moving range to minimize the variance in number of sensors among the regions and simultaneously minimize the sensor movements. In [21], the authors proposed a virtual force based heuristic algorithm to relocate mobile sensors to form barriers. Using a game theoretic approach, sensor movement strategies are studied to defend against intrusions in wireless sensor networks [22], [23].

III. NETWORK MODEL

A combination of n_s stationary and n_m mobile sensors are dropped along a straight line across a rectangular deployment region of size $l \times w$. We assume that sensors are evenly distributed along the deployed line. Let $n = n_s + n_m$ be the total number of sensors, and $\zeta = l/(n+1)$. The horizontal coordinate of the i-th sensor's target landing point is

$$x_i = \frac{il}{n+1} = i\zeta, \ 1 \le i \le n.$$

Because of mechanical inaccuracy, wind, terrain constraints, and other environmental factors, the actual landing point of each sensor may deviate from its target location by a random offset. Denote by δ_i^x and δ_i^y the offsets of sensor s_i in the horizontal and vertical directions, respectively. The actual landing point of sensor s_i is thus $(x_i + \delta_i^x, \delta_i^y)$.

While in practice the random offsets of nearby sensors may correlate, to simplify the analysis and provide insights, we assume that the random offsets are independently and identically distributed (i.i.d.) with a normal distribution of zero mean and variances σ_x^2 and σ_y^2, respectively, i.e.,

$$\delta_i^x \sim N(0, \sigma_x^2), \ \delta_i^y \sim N(0, \sigma_y^2).$$

We adopt the widely-used binary disk sensing model. Each sensor has a sensing range r and can detect any intruders within its sensing range. For each mobile sensor, we assume it has a maximum moving range d due to energy constraint.

We assume that the intruders attempt to cross the region from top to bottom. A *crossing path* is a path that connects one side of the region to the opposite side. A path is said to be covered if it is intercepted by at least one sensor. A sensor network is barrier covered if any possible crossing path is covered, i.e.,

Definition 1: A sensor network is barrier covered if

$$P(\text{any crossing path is covered}) = 1 \text{ w.h.p.}$$

A sensor network is barrier covered if there exists a set of sensors that can be ordered as a chain across the horizontal direction such that the sensing ranges of adjacent sensors overlap and the sensing range at both ends of the chain intersects both boundaries of the rectangular area. It is evident that no intruders can cross such a sensing barrier without being detected, regardless of the path being taken.

IV. FIND AND MEND BARRIER GAPS

We present a two-phase algorithm that can efficiently relocate mobile sensors to form new barriers while balancing the energy consumption among the mobile sensors. In the first phase, the algorithm scans the network from left to right and find barrier gaps. In the second phase, the algorithm computes which mobile sensors should be relocated to what locations such that the maximum moving distance among all sensors is minimized. This will have the effect of balancing energy consumption.

A. Find Barrier Gaps

Starting from the left boundary, the algorithm greedily looks for a connected cluster of static sensors that extends farthest to the right direction. It then finds the sensor node (marked as y) that is located to the right of the cluster and closest to the rightmost node of the cluster (marked as x). The space between these two sensors is marked as a barrier gap, denoted by (x,y). The process is repeated from sensor y until it reaches the right boundary of the area. This is illustrated in Figure 2.

Recall that the sensing range of each sensor is denoted by r, and use P to store all the barrier gaps found in the process. The details of the algorithm are described as follows:

FIND-GAPS(N, r)

1) Initialize $P = \emptyset$.
2) Construct a connectivity graph $G(V,E)$ $(V = N \cup s \cup t)$ as follows, where each vertex in N represents a static sensor, and s and t are two virtual nodes representing left and right boundary of the area. $E = \{(u,v),(v,u) | u \in N, v \in N, \text{and } dist(u,v) <= 2r\} \cup \{(u,s),(s,u) | u \in N, \text{and dist}(u, \text{left-boundary}) <= r\} \cup \{(u,t),(t,u) | u \in N, \text{and dist}(u, \text{right-boundary}) <= r\}$.
3) Starting at s, perform a depth-first search for t in G. If successful, the algorithm terminates, and returns P. Otherwise, mark the rightmost node appeared in the search as x, and mark node that is to the right of and closest to x as y. Mark the space between x and y as a barrier gap, and add the gap (x,y) to P.
4) Remove all nodes to the left of y and their associated edges, and set s to y. Repeat from step 3.

After the algorithm terminates, P contains a set of gaps by filling which a new barrier will be formed.

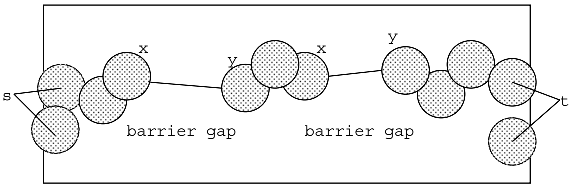

Fig. 2. Illustration of FIND-GAPS algorithm.

B. Mend Barrier Gaps with Mobile Sensors

For each gap obtained in the first phase, we relocate mobile sensors to fill the gap and minimize the maximum moving distance among all sensors to balance the energy consumption. When all gaps are mended, a new sensing barrier will be formed.

Consider a gap between node x and node y. The minimum number of sensors needed to fill the gap is $g = \lceil \frac{dist(x,y)-2r}{2r} \rceil$. Divide the segment (x,y) evenly with g grid points. These grid points represent a set of locations where if each of them is occupied by a mobile sensor, the whole network will be barrier covered.

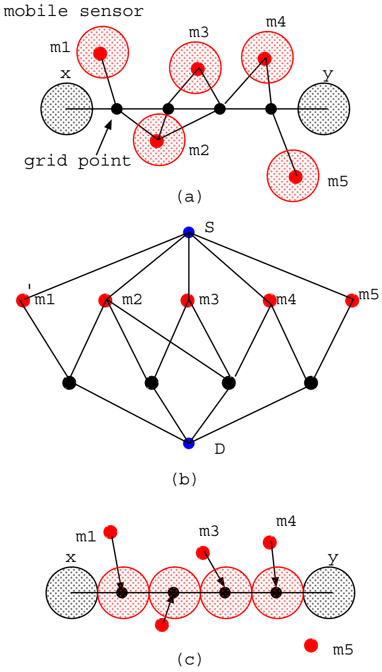

Fig. 3. Illustration of MEND-GAPS algorithm.

Given the set of mobile sensors M, the set of grid points G obtained for all gaps, and the moving range d of mobile sensors, we use a bipartite matching algorithm to compute if every grid point can be occupied by a mobile sensor under the sensor mobility constraint. Should a solution exist, the algorithm also gives the matching between the mobile sensors and the grid points, i.e., an assignment of mobile sensors the grid points. The algorithm is described as follows:

MEND-GAPS(M, G, d)

1) Construct a bipartite graph $G'(V,E)$ ($V = M \cup G$) as follows, where each vertex in M represents a mobile sensor and each vertex in G represents a grid point in a gap. $E = \{(u,v),(v,u) | u \in M, v \in G$, and $dist(u,v) < d\}$.
2) From $G'(V,E)$, construct a flow graph $G^*(V^*,E^*)$ and assign capacity to each edge as follows: $\forall$ u $\in$ V, add u to V^*; $\forall$ (u, v) $\in E$, add (u,v) to E^*. Set $capacity(u,v) = 1$ for $u \in M$ and $v \in G'$. Add a virtual source node S to V^* , and $\forall$ u $\in M$, add an edge (S, u) to E^*, set $capacity(S,u) = 1$; add a virtual sink node D to V^*, and $\forall$ u $\in G$ of $G'(V,E)$, add an edge (u, D) to E^*, set capacity(u, D) = 1.
3) Use a maximum flow algorithm (e.g., Ford-Fulkerson [24]) to compute and return the maximum flow from S to D in G^*.

The main steps of the MEND-GAPS algorithm are illustrated in Figure 3. In part (a), the gap between node x and y is divided evenly by four grid points. Suppose there are five mobile sensors available. We add an edge between a mobile sensor and a grid point if the grid point is within the moving range of the sensor, resulting in a bipartite graph. In part (b), we create a virtual source node S connecting to all mobile nodes, a virtual sink node D connecting to all grid nodes, and assign unit capacity to each edge. We then use a maximum flow algorithm to compute and return the maximum flow. Based on the results, we relocate appropriate mobile sensors to each grid point to fill the gap, as shown in part (c).

When the MEND-GAPS algorithm terminates, if the returned maximum flow from S to D equals the total number of grid points, each grid point will be assigned a mobile sensor and a barrier can be formed. Otherwise, if the returned maximum flow is smaller than the number of grid point, some grid points will not be occupied by sensors, and the gap will not be mended under the mobility constraint. It is straightforward to check that the time complexity of FIND-GAPS is $O(V+E)$, and the time complexity of MEND-GAPS is $O(VE^2)$.

We can use a binary search to find the minimax moving distance among all sensors that is required to find a bipartite match between mobile sensors and grid points in the gaps.

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MINIMAX-MOVING-DISTANCE ($M$, $G$)
1  $last\_success \leftarrow \ell$; $last\_fail \leftarrow 0$; $d_{min} \leftarrow \ell$
2  while ($last\_success$ - $last\_fail \geq \varepsilon$)
3      do $f \leftarrow$ MEND-GAPS($M$, $G$, $d_{min}$)
4         if ($f$ = SIZEOF($G$))
5             then $last\_success \leftarrow d_{min}$
6             else $last\_fail \leftarrow d_{min}$
7         $d_{min} \leftarrow (last\_fail + last\_success)/2$
8  return $d_{min}$
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The above binary search based MINIMAX-MOVING-DISTANCE algorithm terminates in $\Theta(log\ell)$ iterations. When it terminates, it will return the minimum moving distance guaranteeing that every grid point is occupied by a sensor. The ε in line 2 of MINIMAX-MOVING-DISTANCE is a termination threshold. It represents the precision of the d obtained from this algorithm.

V. SIMULATION RESULTS

We evaluate the performance of our algorithms via simulation. We deploy sensors along the horizontal central line in a rectangle of size 1000×300. The sensors are deployed on evenly spaced grid points along the line with normally distributed random offsets, as described in Section III. All sensors have a sensing range of 10 and three different random offset variances $\sigma = 10$, 30, and 50 are considered. Each data point in this section is an average of 1000 repeated experiments.

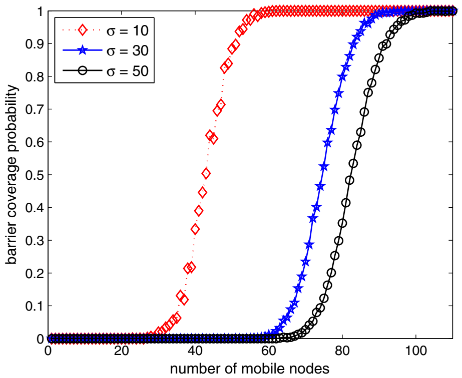

Fig. 4. Barrier coverage probability as a function of the number of mobile sensors.

Figure 4 plots the barrier coverage probability as a function of the number of mobile nodes, where the number of stationary sensors $n_s = 100$ and the number of mobile sensors n_m varies from 0 to 100. We focus on the performance of our algorithms without considering the effect of limited moving range of mobile sensors. In other words, we assume that each mobile sensor can be moved to any location in the network. We will later examine the minimum required moving range to achieve barrier coverage.

The barrier coverage probability is zero initially. As more mobile sensors are added to the deployment, the barrier coverage probability starts to increase quickly after a certain point and converges to 1. When the number of mobile sensors is not large enough to fill all the barrier gaps, no new barriers can be formed and the barrier coverage probability remains unchanged. After a certain point, there is a positive probability that the mobile sensors can fill all the gaps to form a barrier, and the probability increases as more mobile sensors are added. When there are enough mobile sensors such that all the gaps can be filled almost surely, the barrier coverage probability reaches one.

For different deployments with different random offset variances, the larger the variance, i.e., sensors are scattered farther from their target landing points, the more barrier gaps there are and hence more mobile sensors are needed to fill the gaps in order to form a barrier. If the variance $\sigma = 10$, then approximately 45 mobile sensors are needed to form a barrier.

For $\sigma = 30$ and 50, achieving barrier coverage would require approximately 75 and 83 mobile sensors, respectively.

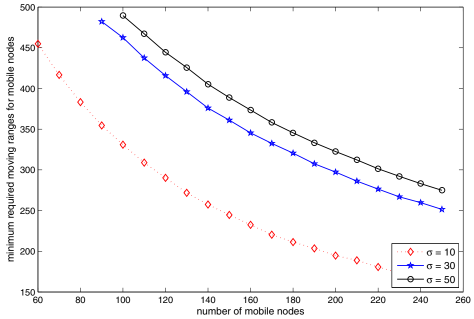

Fig. 5. Minimum required moving range to achieve barrier coverage.

The minimum moving range required for mobile sensors to achieve barrier coverage is shown in Figure 5. As the number of mobile sensors increases, the moving range required to achieve barrier coverage decreases. This demonstrates a tradeoff between the number of mobile sensors and the moving ranges required to achieve barrier coverage. If there are sufficient mobile sensors, mobile sensors may only need to move a small distance to form a barrier. Otherwise, mobile sensors may have to move a larger distance to compensate for the shortage of mobile sensors.

VI. CONCLUSION

In this paper we study the use of mobile sensors to improve the barrier coverage of wireless sensor networks, and investigate the design issues and performance tradeoffs. We devise a two-phase algorithm that first finds barrier gaps in the network, then relocates mobile sensors to desirable locations to fill the gaps while minimizing the maximum energy consumptions among the sensors. Simulation results show that our algorithm can effectively improve barrier coverage of a wireless sensor network under a wide range of deployment parameters. The results obtained in this paper provide guidelines and insights into the deployment, design, and the performance of mobile wireless sensor networks for barrier coverage.

VII. ACKNOWLEDGEMENT

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