Fault Tolerant Barrier Coverage for Wireless Sensor Networks

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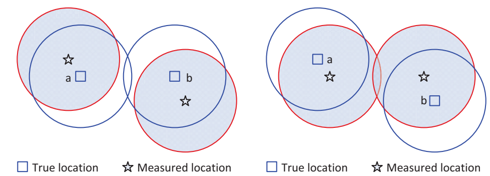
***Abstract*—Barrier coverage is a critical issue in wireless sensor networks for security applications (e.g., border protection), the performance of which is highly related with locations of sensor nodes. Existing work on barrier coverage mainly assume that sensor nodes have accurate location information, however, little work explores the effects of location errors on barrier coverage. In this paper, we study the barrier coverage problem when sensor nodes have location errors and deploy mobile sensor nodes to improve barrier coverage if the network is not barrier covered after initial deployment. We analyze the relationship between the true distance and the measured distance of two stationary sensor nodes and derive the minimum number of mobile sensor nodes needed to connect them with a guarantee when nodes location errors. Furthermore, we propose a fault tolerant weighted barrier graph, based on which we prove that the minimum number of mobile sensor nodes needed to form barrier coverage with a guarantee is the length of the shortest path on the graph. Simulation results validate the correctness of our analysis.**

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 region of interest (ROI), we need to deploy a set of sensor nodes[1] that can provide coverage of the ROI, a problem that is often referred to as *barrier coverage* [11], where sensor nodes form *barriers* for intruders.

Deterministic and random deployment are the two most popular ways of deploying nodes to the ROIs. For the ROIs with friendly environment, deterministic deployment can be used to deploy nodes to the exact locations as we expect. However, in general, the ROIs are in harsh environment and difficult for human being to reach, which makes random deployment (e.g., dropped by aircraft) the only way to deploy nodes. When only stationary nodes are used, after the initial random deployment, it is highly possible that nodes could not form a barrier due to the gaps in their coverage, which would allow intruders to cross the ROIs without being detected. Therefore, it is necessary to deploy more nodes to form a barrier. In fact, it is difficult if possible at all to improve barrier coverage for sensor networks consisting of only stationary nodes. Fortunately, with recent technological advances, practical mobile nodes (e.g., Robomote [5], Packbot [20]) have been developed, which provides us a way to improve barrier coverage performance after sensor networks have been deployed.

[1]We use sensor nodes or nodes interchangeably in this paper.



(a) overlap → no overlap (b) no overlap → overlap

Fig. 1. The effects of location errors. According to the measured locations, (a): two overlapping nodes are considered as no overlapping; (b): two no overlapping nodes are considered as overlapping

Location information of nodes serves the basis of lots of applications, such as navigation and target tracking. However, it is cost-expensive to equip GPS receivers on each node. Therefore, the location information of nodes are unknown when they are randomly deployed. To obtain the location information of each node, a lot of localization algorithms have been proposed including the range-based (e.g., TOA [9], TDOA [16] and RSSI [1]) and the range-free (e.g., DV-HOP [15] and APIT [8]) localization algorithms. However, none of them can provide the accurate locations and therefore inevitably has location errors.

The existence of location errors can significantly affect the quality of barrier coverage provided by sensor networks. In reality, we can only know the measured locations instead of true locations of sensor nodes. As shown in Figure 1(a), although node a and node b actually overlap with each other, due to the location errors, we think they do not overlap and need to deploy more mobile nodes between them to prevent intruder from crossing without being detected, which increases the cost of deployment. In contrast, as shown in Figure 1(b), based on the measured locations, we think node a and node b overlap with each other and all intruders crossing the line segment ab can be detected. However, since they actually do not overlap, intruders can cross the line segment ab without being detected. Therefore, location errors cannot only increase the cost of node deployment but also increase the miss rate of intruders.

A lot of work has been done on barrier coverage, however, little considers the effects of location errors of sensor nodes. In this paper, we study the barrier coverage problem when nodes have location errors.

First, how can we know whether the network provide barrier coverage or not after initial random deployment when nodes have location errors? The problem is challenging because the true locations of nodes are unknown. Even the network with measured locations provide barrier coverage for the ROI, it does not mean the network really can. Therefore, it is necessary to find an efficient way to decide whether the network provides barrier coverage or not with a guarantee. When the ROI is not barrier covered, mobile nodes can be deployed to form barrier coverage. However, the manufacturing cost of mobile nodes are usually more expensive than stationary nodes, which demands the usage of as few mobile nodes as possible. Therefore, the second problem is to find the minimum number of mobile nodes needed to form barrier coverage when nodes have location errors. To solve this problem, we need to first find the minimum number of mobile nodes needed to connect two stationary nodes with a guarantee when nodes have location errors, which is challenging because the number of mobile nodes calculated from the measured locations may not be enough in reality. Moreover, there are too many ways of deploying mobile nodes to form barrier coverage and how to find the optimal way using the minimum number of mobile nodes is also challenging.

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

- To the best of our knowledge, our work is the first to explore the effects of location errors on barrier coverage.
- We theoretically analyze the relationship between the true distance and the measured distance of two stationary nodes, and derive the minimum number of mobile nodes needed to connect two stationary nodes with a guarantee when nodes have location errors.
- We propose a fault tolerant weighted barrier graph to model the barrier coverage formation problem, based on which we prove that the minimum number of mobile nodes needed to form barrier coverage with a guarantee is the length of the shortest path on the graph.

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 system model in Section III. We study the barrier coverage problem when only stationary nodes have location errors in Section IV and the barrier coverage problem when both stationary and mobile nodes have location errors in Section V. The performance evaluation of our work is presented in Section VI. Finally, we conclude the paper in Section VII.

II. Related Work

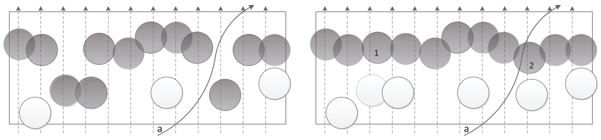
The concept of barrier coverage first appeared in [6] in the context of robotic sensing. Kumar et al. [11] firstly defined the notion of k-barrier coverage as well as weak and strong barrier coverage for WSNs. Chen et al. [3] introduced the notion of local barrier coverage and devised localized sleep-wakeup 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. [18] 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. A novel full-view coverage model was introduced in [23] for camera sensor networks. With the full-view coverage model, Wang et al. [22] 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. [21] 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. [19] studied the energy efficient relocation problem for barrier coverage in mobile sensor networks. Keung et al. [10] focused on providing k-barrier coverage against moving intruders in mobile sensor networks. Ban et al. [2] studied the problem on how to relocate mobile sensors to construct k grid barriers with minimum energy consumption. He et al. [7] 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. [17] proposed a greedy algorithm to find barrier gaps and moved mobile sensors with limited mobility to improve barrier coverage. However, to the best of our knowledge, none of existing work has explored the effects of location errors on barrier coverage.

III. System Model

We assume that the ROI is a two-dimensional rectangular belt area and n stationary sensor nodes are randomly deployed in the ROI. The belt region 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 (e.g. path a in Figure 2). A congruent crossing path is a special crossing path that is orthogonal to the upper and lower boundaries of the belt region (e.g., dashed lines in Figure 2). An intruder may attempt to penetrate the area along any crossing path.

We assume that stationary and mobile sensor nodes have the same type of sensors, but mobile sensor nodes have the ability to move. We adopt the most commonly used



(a) Weak barrier coverage (b) Strong barrier coverage

Fig. 2. An illustration of weak and strong barrier coverage

disk model for the sensing ability of sensor nodes, and assume that all sensor nodes have the same sensing range, denoted by r_s. That is, when an intruder is within the distance of r_s of a sensor node, the sensor node can detect the intruder; otherwise, the sensor node cannot detect the intruder. Let $s_i = (x_i, y_i, r_s)$ denote the sensor node i whose true location is $l_i = (x_i, y_i)$. Each node can obtain its location by using suitable localization algorithms, which is called the measured location, denoted by $\tilde{l}_i = (\tilde{x}_i, \tilde{y}_i)$ for s_i. Thus, $d(l_i, \tilde{l}_i)$ is called the location error for s_i, where $d(\cdot)$ represents the Euclidean distance. We assume that the location error is upper bounded by δ where $\delta < r_s$.

Kumar et al. introduced two types of barrier coverage, weak barrier coverage and strong barrier coverage, in [11]. Weak barrier coverage requires the union of sensor nodes form a barrier in the horizontal direction from the left boundary to the right boundary, so that every intruder moving along the congruent crossing paths can be detected. In contrast, strong barrier coverage requires that the union of sensor nodes form a barrier from the left boundary to the right boundary so that every intruder can be detected no matter what crossing path it takes. Figure 2 shows an example of weak and strong barrier coverage, respectively. If a sensor network provides weak (strong) barrier coverage for the ROI, we say that the ROI is weak (strong) barrier covered. Note that weak barrier coverage is a special case of strong barrier coverage. Without loss of generality, we mainly consider strong barrier coverage in this paper.

The notations used throughout the paper are summarized in Table I.

IV. Barrier Coverage When Stationary Nodes Have Location Errors

In this section, we consider that only stationary nodes have location errors. We assume that mobile nodes are equipped with GPS receivers, so that they can accurately know their locations without errors. For this case, we first analyze the effects of location errors on the minimum number of mobile sensor nodes needed to connect a pair of stationary nodes, and then propose a progressive method that uses exactly the upper bound of the true minimum number of mobile sensor nodes needed to connect a pair of stationary nodes with a guarantee. Finally, we model the barrier coverage problem as a fault tolerant weighted barrier graph and prove that the minimum number of mobile sensor nodes needed to form barrier coverage with a guarantee is the length of the shortest path on the graph.

TABLE I
Summary of notations

Symbol	Description
L	the length of the belt region
H	the width of the belt region
n	the number of deployed stationary nodes
r_s	the sensing range of each sensor node
δ	the upper bound of location errors and $\delta < r_s$
s_i	the ith stationary sensor node
l_i	$l_i = (x_i, y_i)$ the true location of s_i
$\tilde{l}_i$	$\tilde{l}_i = (\tilde{x}_i, \tilde{y}_i)$ the measured location of s_i
R_i	Location region of s_i
$d(l_i, l_j)$	the true distance between s_i and s_j
$d(\tilde{l}_i, \tilde{l}_j)$	the measured distance between s_i and s_j
$N(s_i, s_j)$	the true minimum number of mobile nodes needed to connect s_i and s_j
$N_s^u(s_i, s_j)$	the upper bound of $N(s_i, s_j)$ when only stationary nodes have location errors
$N_s^l(s_i, s_j)$	the lower bound of $N(s_i, s_j)$ when only stationary nodes have location errors
$N_{sm}^u(s_i, s_j)$	the upper bound of $N(s_i, s_j)$ when both stationary and mobile nodes have location errors
$N_{sm}^l(s_i, s_j)$	the upper bound of $N(s_i, s_j)$ when both stationary and mobile nodes have location errors

A. Minimum Number of Mobile Nodes Needed to Connect Two Stationary Nodes

The basis of barrier coverage is to decide whether two nodes overlap or not and how many mobile nodes are needed when they do not overlap. The problem is easy to answer if each node knows its true location. For example, given two nodes s_i and s_j and their true locations l_i and l_j, they overlap with each other if $d(l_i, l_j) \leq 2r_s$. When $d(l_i, l_j) > 2r_s$, s_1 and s_2 do not overlap with each other and the minimum number of mobile nodes needed to connect them, denoted by $N(s_i, s_j)$, is $\lceil \frac{d(l_i,l_j)-2r_s}{2r_s} \rceil$.

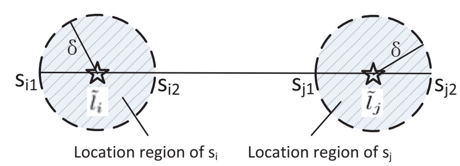


Fig. 3. The location region of a sensor node given its measured location

However, each node does not know its true location but instead the measured location. Suppose the measured locations for s_i and s_j are $\tilde{l}_i$ and $\tilde{l}_j$, respectively. As shown in Figure 3, given a measured location, the true location is within the shaded circle centered at the measured location with the radius of δ, where δ is the upper bound of location errors. We call the shaded circle centered at $\tilde{l}_i$ as the location region of s_i, denoted by R_i. Given the measured location $\tilde{l}_i$, we know that the true location of s_i is in the location region R_i. Therefore,

$$\max(0, d(\tilde{l}_i, \tilde{l}_j) - 2\delta) \leq d(l_i, l_j) \leq d(\tilde{l}_i, \tilde{l}_j) + 2\delta \quad (1)$$

Lemma 1. *Given two stationary nodes s_i and s_j and their measured locations $\tilde{l}_i$ and $\tilde{l}_j$, s_i and s_j overlap with each other with a guarantee when $d(\tilde{l}_i, \tilde{l}_j) + 2\delta \leq 2r_s$.*

Proof: According to Equation (1), when $d(\tilde{l}_i, \tilde{l}_j) + 2\delta \leq 2r_s$, the true distance $d(l_i, l_j) \leq 2r_s$, so s_i and s_j overlap with each with a guarantee. ∎

Lemma 2. *Given two stationary nodes s_i and s_j and their measured locations $\tilde{l}_i$ and $\tilde{l}_j$, the minimum number of mobile nodes needed to guarantee the connection of s_i and s_j is $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$.*

Proof: Recall that $N(s_i, s_j) = \lceil \frac{d(l_i,l_j)-2r_s}{2r_s} \rceil$ denotes the true minimum number of mobile nodes needed to connect s_i and s_j. According to Equation (1), we have

$$\max(0, \lceil \frac{d(\tilde{l}_i, \tilde{l}_j) - 2\delta}{2r_s} \rceil - 1) \leq N(s_i, s_j) \leq \lceil \frac{d(\tilde{l}_i, \tilde{l}_j) + 2\delta}{2r_s} \rceil - 1$$

In order to guarantee the connection of s_i and s_j, at least $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$ mobile nodes are needed. ∎

Let $N^u_s(s_i, s_j)$ and $N^l_s(s_i, s_j)$ denote the upper and lower bound of $N(s_i, s_j)$, respectively. That is, $N^u_s(s_i, s_j) = \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$ and $N^l_s(s_i, s_j) = \max(0, \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)-2\delta}{2r_s} \rceil - 1)$. Thus, $\triangle N_s(s_i, s_j) = N^u_s(s_i, s_j) - N^l_s(s_i, s_j)$ represents the influence of location error on the minimum number of mobile nodes needed. When $\triangle N_s(s_i, s_j) = 0$, $N(s_i, s_j) = N^u_s(s_i, s_j) = N^l_s(s_i, s_j)$ and therefore the location error would not affect the minimum number of mobile sensor nodes needed to connect s_i and s_j.

Theorem 3. *Given two stationary nodes s_i and s_j and their measured locations $\tilde{l}_i$ and $\tilde{l}_j$, the location error does not affect the minimum number of mobile nodes needed to connect s_i and s_j when $d(\tilde{l}_i, \tilde{l}_j) + 2\delta \leq 2r_s$ or $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)-2\delta}{2r_s} \rceil = \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil \geq 2$.*

Proof: When $N^u_s(s_i, s_j) = N^l_s(s_i, s_j) = 0$, $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$ should be 0. Therefore, $d(\tilde{l}_i, \tilde{l}_j) + 2\delta \leq 2r_s$ is required.

When $N^u_s(s_i, s_j) = \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1 = N^l_s(s_i, s_j) = \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)-2\delta}{2r_s} \rceil - 1 > 0$, $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)-2\delta}{2r_s} \rceil = \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil = k$ is required where k is an integer and $k \geq 2$.

Therefore, when any one of them is satisfied, the location error does not affect the minimum number of mobile nodes needed to connect s_i and s_j. ∎

Theorem 4. *Given a sensor network where only stationary nodes have location errors upper bounded by $\delta < r_s$, at most 2 more mobile nodes are needed to connect any pair of stationary nodes compared to the true minimum number of mobile sensor nodes needed. That is, $\triangle N_s(s_i, s_j) \leq 2$ for any pair of s_i and s_j when $\delta < r_s$.*

Proof: $\triangle N_s(s_i, s_j)$ represents the influence of location error on the minimum number of mobile sensor nodes needed. We prove the theorem from the following cases.

Case 1: When $d(\tilde{l}_i, \tilde{l}_j) + 2\delta \leq 2r_s$, according to Lemma 1, $\triangle N_s(s_i, s_j) = 0$.

Case 2: When $d(\tilde{l}_i, \tilde{l}_j) + 2\delta > 2r_s$ and $d(\tilde{l}_i, \tilde{l}_j) - 2\delta \leq 2r_s$, $N^u_s(s_i, s_j) = \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$ and $N^l_s(s_i, s_j) = 0$. Therefore $\triangle N_s(s_i, s_j) = \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$. Since $d(\tilde{l}_i, \tilde{l}_j) + 2\delta > 2r_s$, $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil \geq 2$. Since $d(\tilde{l}_i, \tilde{l}_j) - 2\delta \leq 2r_s$, $d(\tilde{l}_i, \tilde{l}_j) + 2\delta \leq 2r_s + 4\delta < 6r_s$ and then $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil \leq 3$. Therefore, $1 \leq \triangle N_s(s_i, s_j) \leq 2$.

Case 3: When $d(\tilde{l}_i, \tilde{l}_j) + 2\delta > 2r_s$ and $d(\tilde{l}_i, \tilde{l}_j) - 2\delta > 2r_s$, we have

$$\begin{aligned}\triangle N_s(s_i, s_j) &= \lceil \frac{d(\tilde{l}_i, \tilde{l}_j) + 2\delta}{2r_s} \rceil - \lceil \frac{d(\tilde{l}_i, \tilde{l}_j) - 2\delta}{2r_s} \rceil \\ &< \lceil \frac{d(\tilde{l}_i, \tilde{l}_j) + 2r_s}{2r_s} \rceil - \lceil \frac{d(\tilde{l}_i, \tilde{l}_j) - 2r_s}{2r_s} \rceil = 2\end{aligned}$$

In all cases, $\triangle N_s(s_i, s_j) \leq 2$ which means that at most 2 more mobile nodes are needed compared to $N(s_i, s_j)$ when only stationary nodes have location errors. ∎

B. *Progressive Mobile Node Deployment*

For any two known true locations of s_i and s_j within R_i and R_j respectively, $N^u_s(s_i, s_j)$ is enough to connect them with a guarantee. However, the difficulty is that the true locations are unknown in reality, so deploying $N^u_s(s_i, s_j)$ mobile nodes derived from the largest distance of two known true locations may not be able to connect s_i and s_j with a guarantee. To solve this problem, we propose a progressive method to use as few mobile nodes as possible to connect two stationary nodes with a guarantee.

The basic idea of the progressive method is to deploy mobile nodes progressively from the left stationary node to the right stationary node. Given two stationary nodes s_i and s_j and their measured locations $\tilde{l}_i$ and $\tilde{l}_j$, the progressive method is described as follows:

- Step 1: Deploy a mobile node on the line segment $\tilde{l}_i\tilde{l}_j$ to make it overlap with all nodes located within the location region of s_i and the distance between the mobile node and $\tilde{l}_i$ maximized.
- Step 2: Check whether the new deployed mobile node overlap with all nodes located within the location region of s_j or not. If yes, stop; otherwise, go to step 3.
- Step 3: Deploy a new mobile node on the line segment $\tilde{l}_i\tilde{l}_j$ that is $2r_s$ away from the previously deployed mobile node, go to step 2.

Suppose the first deployed mobile node is denoted by m_k and its expected location is $l_k = (x_k, y_k)$. According to Step 1, we have

$$\begin{aligned}\text{Maximize} \quad & d(\tilde{l}_i, l_k) = \sqrt{(\tilde{x}_i - x_k)^2 + (\tilde{y}_i - y_k)^2} \qquad (2)\\ \text{subject to} \quad & \sqrt{(\tilde{x}_i - x_i)^2 + (\tilde{y}_i - y_i)^2} \leq \delta \\ & \sqrt{(x_i - x_k)^2 + (y_i - y_k)^2} \leq 2r_s \\ & (y_k - \tilde{y}_i)(\tilde{x}_j - x_k) = (\tilde{y}_j - y_k)(x_k - \tilde{x}_i)\end{aligned}$$

The objective is to maximize the distance between the $\tilde{l}_i$ and l_k. The first constraint indicates that the location error between the true and measured location is no larger than δ, and the second constraint indicates that m_k should overlap with s_i no matter where the true location of s_i is, and finally the third one restricts m_k on the line segment $\tilde{l}_i\tilde{l}_j$.

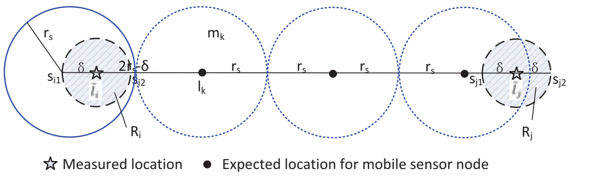


Fig. 4. An illustration of the progressive method. The blue solid circle with radius of r_s denotes the sensing region of s_i located at s_{i1}. The blue dashed circles with radius of r_s denote the sensing regions of mobile nodes.

As shown in Figure 4, s_{i1} and s_{i2} are the two intersections of line $\tilde{l}_i\tilde{l}_j$ and the location region of s_i, R_i. According to geometry, for any point p on line segment $\tilde{l}_i\tilde{l}_j$, the largest distance from the point p to any point within R_i is the distance from the point p to the point s_{i1}. In other words, if the mobile node at point l_k overlaps with a node at point s_{i1}, it overlaps all the nodes located within R_i. As m_k moves along $\tilde{l}_i\tilde{l}_j$, both $d(s_{i1}, l_k)$ and $d(\tilde{l}_i, l_k)$ increase accordingly. When $d(\tilde{l}_i, l_k) = 2r_s - \delta$, m_k cannot move further since any further movement would not guarantee the overlap of m_k and s_i. Therefore, the maximum of $d(\tilde{l}_i, l_k)$ is $2r_s - \delta$. When more mobile nodes are required, they will be added one by one with the interval of $2r_s$ until a mobile node overlaps with all nodes located within R_j.

Theorem 5. *The progressive method is an optimal way that connects s_i and s_j with a guarantee by using $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$ mobile nodes.*

Proof: We first prove that the progressive method uses $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$ mobile nodes to guarantee the connection of s_i and s_j, and then prove that it is optimal.

When $d(\tilde{l}_i, \tilde{l}_j) + 2\delta \le 2r_s$, no mobile node is needed. When $d(\tilde{l}_i, \tilde{l}_j) + 2\delta > 2r_s$, mobile nodes should be deployed. In the progressive method, for the first mobile node m_k, $d(\tilde{l}_i, l_k) = 2r_s - \delta$ and therefore $d(s_{i1}, l_k) = 2r_s$. Thus, we deploy the first mobile node $2r_s$ away from s_{i1} on $\tilde{l}_i\tilde{l}_j$, and then deploy other mobile nodes one by one with the interval of $2r_s$ until the distance between a mobile node and s_{j2} is not larger than $2r_s$. Therefore, the number of mobile nodes needed in the progressive method is $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$.

In Lemma 2, we proved that at least $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$ mobile nodes are needed to connect s_i and s_j with a guarantee. Since the progressive method uses exactly $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$ mobile nodes, it is an optimal way of deploying mobile nodes. ■

C. Minimum Number of Mobile Nodes Needed to Form Barrier Coverage

Mobile nodes can be deployed between stationary nodes to fill in gaps to form a barrier. However, there are too many ways to deploy mobile nodes and how to find the optimal way using the minimum number of mobile nodes is challenging. In this subsection, we will model the barrier coverage formation problem with location errors as a fault tolerant weighted barrier graph and use it to find the minimum number of mobile nodes needed to form barrier coverage with a guarantee.

Definition A ***Fault tolerant weighted 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), all the stationary sensors (S) and the right boundary (t) of the belt region, that is, $V = \{v_1, v_2, \cdots, v_{n+2}\} = \{s \cup S \cup t\}$. $E = \{e(v_i, v_j)\}$ is the set of edges between any pair of vertices. $W : E \to \mathbb{R}$ 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 nodes needed to guarantee the connection of v_i and v_j.

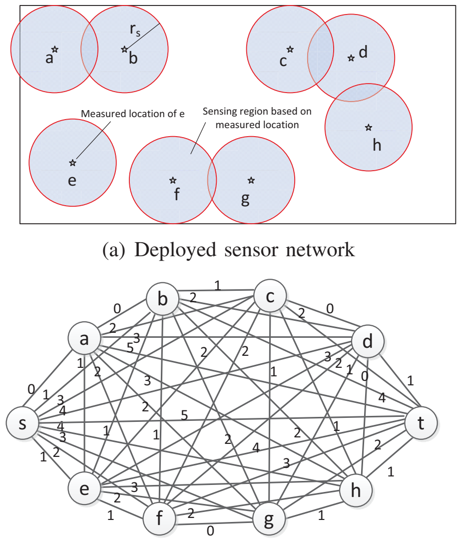
According to Theorem 5, in order to guarantee the connection of s_i and s_j, $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$ mobile nodes should be deployed and therefore $w(s_i, s_j) = \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1$. For a node s_j, the maximum distance between it and the left boundary s is $\tilde{x}_j + \delta$, where $\tilde{x}_j$ is x-coordinate of the measured location of s_j. In order to guarantee the connection of them, $w(s, s_j) = \lceil \frac{\tilde{x}_j+\delta-r_s}{2r_s} \rceil$ mobile nodes are needed. Also, the maximum distance between s_j and the right boundary t is $L - (\tilde{x}_j - \delta)$. In order to guarantee the connection of them, $w(t, s_j) = \lceil \frac{L-(\tilde{x}_j-\delta+r_s)}{2r_s} \rceil$ mobile nodes are needed. We can also deploy mobile nodes directly from the left boundary to the right boundary, and the minimum number of mobile nodes needed to connect s and t is $w(s, t) = \lceil \frac{L}{2r_s} \rceil$. In summary, we have

$$w(v_i, v_j) = \begin{cases} \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)+2\delta}{2r_s} \rceil - 1 & \text{if } v_i = s_i \text{ and } v_j = s_j \\ \lceil \frac{\tilde{x}_j+\delta-r_s}{2r_s} \rceil & \text{if } v_i = s \text{ and } v_j = s_j \\ \lceil \frac{L-(\tilde{x}_j-\delta+r_s)}{2r_s} \rceil & \text{if } v_i = t \text{ and } v_j = s_j \\ \lceil \frac{L}{2r_s} \rceil & \text{if } v_i = s \text{ and } v_j = t \end{cases} \tag{3}$$

Figure 5 shows a deployed sensor network and its corresponding fault tolerant weighted barrier graph. s and t are the virtual vertices corresponding to the left and right boundary of the belt region. The weight of each edge is the minimum number of mobile sensor nodes needed to guarantee the connection of the pair of vertices.

Theorem 6. *The minimum number of mobile nodes needed to form a barrier with a guarantee with stationary nodes is exactly the length of the shortest path from s to t on the fault tolerant weighted barrier graph G and upper bounded by $\lceil \frac{L}{2r_s} \rceil$.*

Proof: According to the definition of the fault tolerant weighted 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 nodes needed on each edge of the path.



(a) Deployed sensor network

(b) Fault tolerant weighted barrier graph

Fig. 5. Sensor network and its corresponding fault tolerant weighted barrier graph when only stationary nodes have location errors ($r_s = 10m$ and $\delta = 1m$)

That is, for a chosen path, the number of mobile nodes required to form a barrier with a guarantee 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 nodes required to form a barrier with a guarantee is the length of the shortest path from s to t on graph G.

The path containing only the edge $e(s,t)$ could either be the shortest or not. If it is not the shortest path, the minimum number of mobile nodes required is smaller than $w(s,t)$; otherwise, the minimum number of mobile nodes required is equal to $w(s,t)$. Therefore, the minimum number of mobile nodes required to form a barrier with a guarantee is always upper bounded by $w(s,t) = \lceil \frac{L}{2r_s} \rceil$. ∎

Theorem 7. *The ROI is guaranteed to be barrier covered after initial deployment of nodes if the length of the shortest path from s to t on the fault tolerant weighted barrier graph G equals zero.*

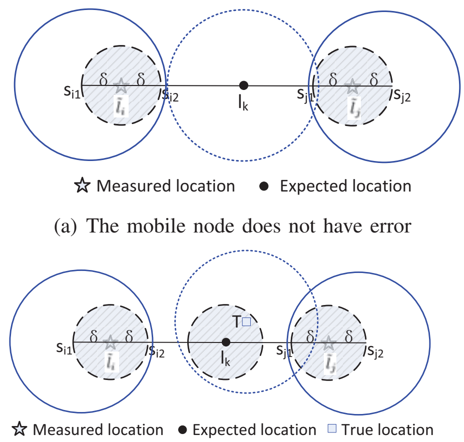
Proof: $\Rightarrow$. If the length of the shortest path from s to t on G equals zero, the shortest path is a barrier that does not need any mobile node. Therefore, the ROI is guaranteed to be barrier covered.

$\Leftarrow$. If the ROI is barrier covered with a guarantee by the sensor network, there exists a barrier (path) on the graph G and no mobile sensor node is needed between any two adjacent vertices on the path. Therefore, the length of the shortest path from s to t on G equals zero. ∎

According to Theorem 6, we can use the classical Dijkstra's algorithm [4] to find the minimum number of mobile nodes needed to form barrier coverage with a guarantee and check whether the ROI is guaranteed to be barrier covered or not after initial deployment. As shown in Figure 5, the shortest path is $s \to a \to b \to c \to d \to t$, the length of which is $0+0+1+0+1=2$. Therefore, the ROI is not guaranteed to be barrier covered after initial random deployment and 2 mobile nodes are needed to deploy between b and c, and d and the right boundary to guarantee the formation of barrier coverage.

V. Barrier Coverage When Both Stationary and Mobile Nodes have Location Errors

In this section, we consider that not only stationary nodes but also mobile nodes have location errors. The location error of mobile node is also assumed to be upper bounded by $\delta < r_s$.



(a) The mobile node does not have error

(b) The mobile node has error

Fig. 6. The effect of location error for mobile sensor nodes

The barrier coverage problem is more complicated when mobile nodes also have location errors. This is because although the measured location of a mobile node shows to be the expected location, due to the location error, the true location of the node may not be the expected location. As shown in Figure 6(a), when the mobile node m_k does not have location error, it can move to the expected location l_k and connect s_i and s_j with a guarantee. However, when the node has a location error, as shown in Figure 6(b), although the measured location is l_k, the true location is actually at point T (denoted by the blue square) which cannot guarantee the connection of s_i and s_j.

Lemma 8. *Given two stationary nodes s_i and s_j and their measured locations $\tilde{l}_i$ and $\tilde{l}_j$, the minimum number of mobile nodes needed to guarantee the connection of s_i and s_j is $\lceil \frac{d(\tilde{l}_i, \tilde{l}_j)}{2r_s - 2\delta} \rceil - 1$ when both stationary and mobile nodes have location errors.*

Proof: Since both the stationary and mobile nodes have location errors upper bounded by $\delta < r_s$, according to Lemma 1, two nodes (either be stationary or mobile nodes) overlap with each other with a guarantee only if their measured distance is no larger than $2r_s - 2\delta$. Therefore, the distance between two expected locations of two mobile nodes should not be larger than $2r_s - 2\delta$, otherwise they may not overlap with each other. Thus, in order to use as few mobile nodes as possible, the expected locations should be on the line segment $\tilde{l}_i\tilde{l}_j$ with an interval of $2r_s - 2\delta$.

Therefore, the minimum number of mobile nodes needed to guarantee the connection of s_i and s_j is $\lceil \frac{d(\tilde{l}_i,\tilde{l}_j)}{2r_s-2\delta} \rceil - 1$ when both stationary and mobile nodes have location errors. ■

Recall that $N(s_i, s_j)$ is the true minimum number of mobile nodes needed to connect s_i and s_j. Let $N^u_{sm}(s_i, s_j)$ and $N^l_{sm}(s_i, s_j)$ denote the upper and lower bound of $N(s_i, s_j)$ when both stationary and mobile nodes have location errors. According to Lemma 8, $N^u_{sm}(s_i, s_j) = \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)}{2r_s-2\delta} \rceil - 1$. According to Equation (1), the lower bound is $N^l_{sm}(s_i, s_j) = \max(0, \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)-2\delta}{2r_s} \rceil - 1)$. Thus, $\triangle N_{sm}(s_i, s_j) = N^u_{sm}(s_i, s_j) - N^l_{sm}(s_i, s_j)$ represents the influence on $N(s_i, s_j)$ when both stationary and mobile nodes have location errors. When $\triangle N_{sm}(s_i, s_j) = 0$, the location error does not affect the minimum number of mobile nodes needed.

Theorem 9. *Considering a sensor network where both stationary and mobile nodes have location errors upper bounded by* $\delta < r_s$, *at most* $\max(\lceil \frac{4\delta}{2r_s-2\delta} \rceil, \lceil \frac{\delta d(\tilde{l}_i,\tilde{l}_j)+2\delta r_s-2\delta^2}{r_s(2r_s-2\delta)} \rceil)$ *more mobile nodes are needed to connect* s_i *and* s_j *compared to the true minimum number of mobile nodes needed. That is,* $\triangle N_{sm}(s_i, s_j) \le \max(\lceil \frac{4\delta}{2r_s-2\delta} \rceil, \lceil \frac{\delta d(\tilde{l}_i,\tilde{l}_j)+2\delta r_s-2\delta^2}{r_s(2r_s-2\delta)} \rceil)$.

Proof: When $d(\tilde{l}_i,\tilde{l}_j) - 2\delta \le 2r_s$, $\triangle N_{sm}(s_i, s_j) = \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)}{2r_s-2\delta} \rceil - 1 \le \lceil \frac{2r_s+2\delta}{2r_s-2\delta} \rceil - 1 = \lceil \frac{4\delta}{2r_s-2\delta} \rceil$.

When $d(\tilde{l}_i,\tilde{l}_j) - 2\delta > 2r_s$, $\triangle N_{sm}(s_i, s_j) = \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)}{2r_s-2\delta} \rceil - \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)-2\delta}{2r_s} \rceil \le \lceil \frac{\delta d(\tilde{l}_i,\tilde{l}_j)+2\delta r_s-2\delta^2}{r_s(2r_s-2\delta)} \rceil$.

Therefore, at most $\max(\lceil \frac{4\delta}{2r_s-2\delta} \rceil, \lceil \frac{\delta d(\tilde{l}_i,\tilde{l}_j)+2\delta r_s-2\delta^2}{r_s(2r_s-2\delta)} \rceil)$ more mobile nodes are needed when both stationary and mobile nodes have location errors compared to the true minimum number of mobile nodes needed to connect any pair of stationary nodes with a guarantee. ■

According to Theorem 4, at most 2 more mobile nodes are needed when only stationary nodes have location errors. However, according to Theorem 9, $\triangle N_{sm}(s_i, s_j)$ is related with the measured distance and δ when both stationary and mobile nodes have location errors. As δ or the measured distance increases, more mobile nodes will be needed. Therefore, the existence of location error for mobile nodes could significantly influence the minimum number of mobile nodes needed to form barrier coverage.

In order to find the minimum number of mobile nodes needed to form barrier coverage with a guarantee, we can also build a corresponding fault tolerant barrier graph for the sensor network. Similar to the graph in Section IV-C, the left and right boundary are considered as virtual vertices s and t, respectively. Each stationary node is modeled as a vertex. There is an edge between any pair of vertices and a weight is assigned for each edge which represents the minimum number of mobile nodes needed to connect any pair of vertices with a guarantee.

Since mobile nodes also have location errors, the weight of each edge is not the same as that in Equation (3). Similar to the derivation for Equation (3), we have

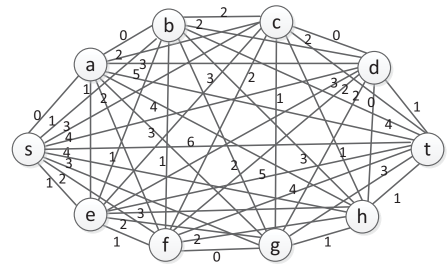


Fig. 7. The fault tolerant weighted barrier graph corresponding to Figure 5(a) when both stationary and mobile nodes have location errors

$$w(v_i, v_j) = \begin{cases} \lceil \frac{d(\tilde{l}_i,\tilde{l}_j)}{2r_s-2\delta} \rceil - 1 & \text{if } v_i = s_i \text{ and } v_j = s_j \\ \lceil \frac{\tilde{x}_j-(r_s-\delta)}{2r_s-2\delta} \rceil & \text{if } v_i = s \text{ and } v_j = s_j \\ \lceil \frac{L-\tilde{x}_j-(r_s-\delta)}{2r_s-2\delta} \rceil & \text{if } v_i = t \text{ and } v_j = s_j \\ \lceil \frac{L}{2r_s-2\delta} \rceil & \text{if } v_i = s \text{ and } v_j = t \end{cases} \quad (4)$$

Theorem 10. *The minimum number of mobile nodes needed to form a barrier with a guarantee with stationary nodes when both stationary and mobile nodes have location errors is upper bounded by* $\lceil \frac{L}{2r_s-2\delta} \rceil$.

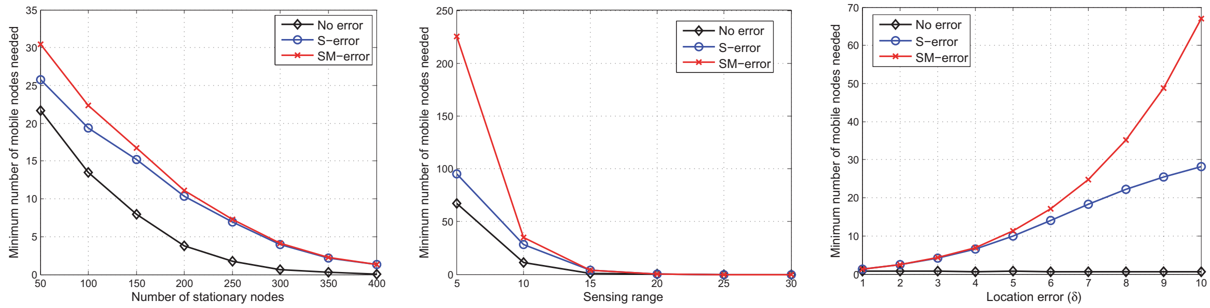
Proof: The proof is omitted because it is similar to the proof of Theorem 6. ■

Figure 7 shows the fault tolerant weighted barrier graph when both stationary and mobile nodes have location errors. Note that the only difference between this figure and Figure 5(b) is the weight of each edge representing the minimum number of mobile nodes needed to connect any pair of vertices with a guarantee. As shown in Figure 7, the shortest path is $s \to a \to b \to d \to t$, the length of which is $0 + 0 + 2 + 1 = 3$. Therefore, the ROI is not guaranteed to be barrier covered after initial random deployment and 3 mobile nodes are needed to guarantee the formation of barrier coverage.

VI. Performance Evaluation

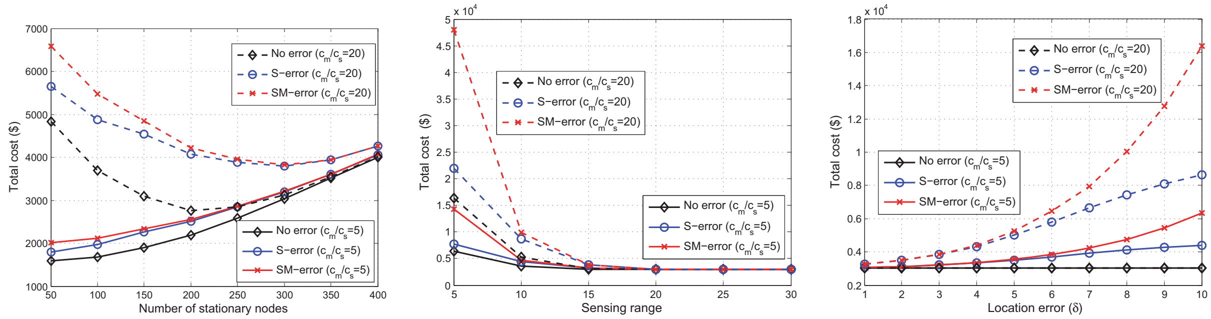
In this section, we conduct simulations to evaluate the effects of location errors on barrier coverage. The ROI is a belt region of length $L = 1000m$ and width $W = 100m$. Initially, stationary nodes are randomly deployed in the ROI. After the minimum number of mobile nodes is calculated, mobile nodes are deployed to form barrier coverage. The evaluation mainly focuses on three metrics: the minimum number of mobile nodes needed to form barrier coverage, the total cost needed to form barrier coverage, and the influence of location error on the minimum number of mobile nodes to connect any pair of stationary nodes.

We evaluate the number of stationary nodes, the sensing range and δ for these metrics. For all the simulation results in Figure 8 and 9, each data point is an average of 100 experiments. For all the simulation results in Figure 10, each data point is the maximum value of 100 experiments.



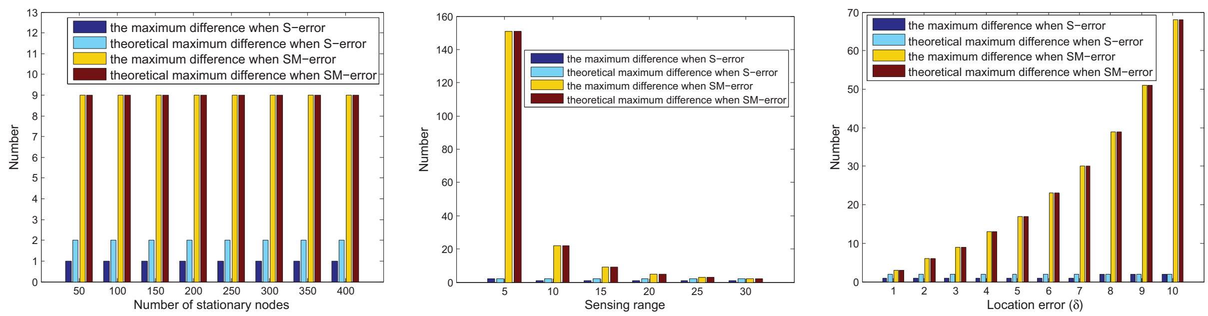
(a) $r_s = 15m$ and $\delta = 3m$ (b) $n = 300$ and $\delta = 3m$ (c) $n = 300$ and $r_s = 15m$

Fig. 8. The effects of different parameters on the minimum number of mobile nodes needed. “No error” means that nodes do not have location error, “S-error” means that only stationary nodes have location error, and “SM-error” means that both stationary and mobile nodes have location error



(a) $r_s = 15m$ and $\delta = 3m$ (b) $n = 300$ and $\delta = 3m$ (c) $n = 300$ and $r_s = 15m$

Fig. 9. The effects of different parameters on the total cost to form a barrier



(a) $r_s = 15m$ and $\delta = 3m$ (b) $n = 300$ and $\delta = 3m$ (c) $n = 300$ and $r_s = 15m$

Fig. 10. The influence of location errors on the minimum number of mobile nodes needed

A. Minimum Number of Mobile Nodes Needed

Figure 8 shows the effects of different parameters on the minimum number of mobile nodes needed to form barrier coverage with a guarantee. As shown in Figure 8(a) and (b), we can see that the minimum number of mobile nodes needed decreases as the number or the sensing range of nodes increases. This is because more number of stationary nodes deployed or larger sensing range can reduce the number of gaps between stationary nodes as well as the sizes of gaps. From Figure 8(c), we also observe that the minimum number of mobile nodes needed increases when the location error increases. This is because larger location error results in larger instability of a location and therefore requires more mobile nodes. We can also observe that the required number of mobile nodes when both stationary and mobile nodes have location errors is usually larger than that when only stationary node have location errors.

B. Total Cost Needed

The total cost needed to form a barrier is the sum of the cost of deployed stationary nodes and the cost of mobile nodes needed. Let c_s and c_m denote the cost of a stationary node and a mobile node, respectively. For simplicity, we assume $c_s = 10\$$ for a stationary node.

As shown in Figure 9(a), when mobile nodes are not very expensive (e.g., $c_m/c_s = 5$), the total cost mainly depends on the number of deployed stationary nodes. Therefore, the total cost increases as the number of deployed stationary nodes increase when $c_m/c_s = 5$. However, when mobile nodes are much more expensive than stationary nodes (e.g., $c_m/c_s = 20$), the number of mobile nodes needed can significantly affect the total cost needed. For example, the total cost for $n = 50$ is much larger than that for $n = 200$ because the former one needs much more mobile nodes to form a barrier. For the simulated belt region, the total cost reaches the minimum when 200 stationary nodes are deployed. Therefore, we can conclude that, given an ROI, the number of stationary nodes to be deployed highly depends on c_m/c_s.

We can see from Figure 9(b) that the total cost needed decreases when the sensing range of nodes increases, which is because the number of mobile nodes needed decreases. As shown in Figure 9(c), the total cost needed increases when the location error increases, which is because more mobile nodes are needed for a larger location error.

C. $\triangle N_s(s_i, s_j)$ and $\triangle N_{sm}(s_i, s_j)$

$\triangle N_s(s_i, s_j)$ and $\triangle N_{sm}(s_i, s_j)$ represents the influence of location errors on the minimum number of mobile nodes needed when only stationary nodes have location errors and when both stationary and mobile nodes have location errors, respectively. Figure 10 shows the effects of different parameters on $\triangle N_s(s_i, s_j)$ and $\triangle N_{sm}(s_i, s_j)$ and also their theoretical upper bound. First we can observe that the maximum of $\triangle N_s(s_i, s_j)$ when only stationary nodes have location errors is always no larger than 2, which validates the correctness of Theorem 4. We then observe that the maximum of $\triangle N_{sm}(s_i, s_j)$ when both stationary and mobile nodes have location errors is always no larger than its theoretical upper bound, which validates the correctness of Theorem 9.

As shown in Figure 10(a), the maximum of $\triangle N_{sm}(s_i, s_j)$ does not change when the number of stationary nodes increases. This is because the largest distance of two stationary nodes is almost always the length of the area. Figure 10(b) shows that the maximum of $\triangle N_{sm}(s_i, s_j)$ decreases when the sensing range increases, which implies that the influence of location error is smaller for larger sensing range. Figure 10(c) shows that the maximum $\triangle N_{sm}(s_i, s_j)$ increases as the location error increases, which implies that the influence of location error is more and more serious when the location error become larger and larger.

VII. Conclusions

In this paper, we studied the barrier coverage problem when nodes have location errors. When only stationary nodes have location errors, we proved that at most 2 more mobile nodes are needed compared to the true minimum number of nodes needed to connect any pair of stationary nodes with a guarantee. When both stationary and mobile nodes have location errors, the difference between the minimum number of mobile nodes needed and the true minimum number of mobile nodes needed is related with the length of the belt region and the location error.

We proposed a progressive method that uses exactly the same minimum number of mobile nodes derived in theory to connect any pair of nodes with a guarantee. Furthermore, we proposed a fault tolerant weighted barrier graph and proved that the minimum number of mobile nodes needed to form barrier coverage with a guarantee is the length of the shortest path on the graph. Extensive simulation results validated the correctness of our analysis.

Acknowledgement

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References

[1] P. Bahl and V. N. Padmanabhan. Radar: An in-building rf-based user location and tracking system. In *Proc. of IEEE INFOCOM.*, volume 2, pages 775–784, 2000.
[2] D. Ban, W. Yang, J. Jiang, J. Wen, and W. Dou. Energy-Efficient Algorithms for k-Barrier Coverage in Mobile Sensor Networks. *International Journal of Computers, Communication & Control*, V(5):616–624, 2010.
[3] A. Chen, S. Kumar, and T. H. Lai. Designing Localized Algorithms for Barrier Coverage. In *Proc. of ACM MobiCom*, pages 63–74, 2007.
[4] T. H. Cormen, C. E. Leiserson, R. L. Rivest, and Clifford Stein. *Introduction to Algorithms*. 2009.
[5] K. Dantu, M. H. Rahimi, H. Shah, S. Babel, A. Dhariwal, and G. S. Sukhatme. Robomote: Enabling Mobility in Sensor Networks. In *Proc. of IEEE IPSN*, pages 404–409, 2005.
[6] D. W. Gage. Command Control for Many-Robot Systems, 1992.
[7] S. He, J. Chen, X. Li, X. Shen, and Y. Sun. Cost-effective barrier coverage by mobile sensor networks. In *Proc. of IEEE INFOCOM*, pages 819–827, 2012.
[8] T. He, C. Huang, B. M. Blum, J. A. Stankovic, and T. Abdelzaher. Range-free localization schemes for large scale sensor networks. In *Proc. of ACM MobiCom*, pages 81–95, 2003.
[9] B. Hofmann-Wellenhof, H. Lichtenegger, and J. Collins. Global positioning system. theory and practice. *Global Positioning System. Theory and practice.*, 1, 1993.
[10] Y. Keung, B. Li, and Q. Zhang. The Intrusion Detection in Mobile Sensor Network. In *Proc. of ACM MobiHoc*, pages 11–20, 2010.
[11] S. Kumar, T. H. Lai, and A. Arora. Barrier Coverage with Wireless Sensors. In *Proc. of ACM MobiCom*, pages 284–298, 2005.
[12] J. Li, J. Chen, and T. H. Lai. Energy-efficient intrusion detection with a barrier of probabilistic sensors. In *Proc. of IEEE INFOCOM*, pages 118–126, 2012.
[13] B. Liu, O. Dousse, J. Wang, and A. Saipulla. Strong Barrier Coverage of Wireless Sensor Networks. In *Proc. of ACM MobiHoc*, pages 411–420, 2008.
[14] H. Ma, M. Yang, D. Li, Y. Hong, and W. Chen. Minimum Camera Barrier Coverage in Wireless Camera Sensor Networks. In *Proc. of IEEE INFOCOM*, pages 217–225, 2012.
[15] D. Niculescu and B. Nath. Dv based positioning in ad hoc networks. *Telecommunication Systems*, 22(1-4):267–280, 2003.
[16] H. Pirzadeh. Computational Geometry with the Rotating Calipers. *Master Thesis*, 1999.
[17] A. Saipulla, B. Liu, G. Xing, X. Fu, and J. Wang. Barrier Coverage with Sensors of Limited Mobility. In *Proc. of ACM MobiHoc*, pages 201–210, 2010.
[18] A. Saipulla, C. Westphal, B. Liu, and J. Wang. Barrier Coverage of Line-Based Deployed Wireless Sensor Networks. In *Proc. of IEEE INFOCOM*, pages 127–135, Apr. 2009.
[19] C. Shen, W. Cheng, X. Liao, and S. Peng. Barrier Coverage with Mobile Sensors. In *Proc. of I-SPAN*, number 2006, pages 99–104, May 2008.
[20] A. A. Somasundara and A. Ramamoorthy. Mobile Element Scheduling with Dynamic Deadlines. *IEEE Transactions on Mobile Computing*, 6(4):1142–1157, 2007.
[21] D. Tao, S. Tang, H. Zhang, X. Mao, and H. Ma. Strong Barrier Coverage in Directional Sensor Networks. *Computer Communications*, 35(8):895–905, 2012.
[22] Y. Wang and G. Cao. Barrier Coverage in Camera Sensor Networks. In *Proc. of ACM MobiHoc*, 2011.
[23] Y. Wang and G. Cao. On Full-View Coverage in Camera Sensor Networks. In *Proc. of IEEE INFOCOM*, 2011.