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Strengthening Barrier-coverage of Static Sensor Network with Mobile Sensor Nodes

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Abstract A wireless sensor network (WSN) provides a barrier-coverage over an area of interest if no intruder can enter the area without being detected by the WSN. Recently, barrier-coverage model has received lots of attentions. In reality, sensor nodes are subject to fail to detect objects within its sensing range due to many reasons, and thus such a barrier of sensors may have temporal loopholes. In case of the WSN for border surveillance applications, it is reasonable to assume that the intruders are smart enough to identify such loopholes of the barrier to penetrate. Once a loophole is found, the other intruders have a good chance to use it continuously until the known path turns out to be insecure due to the increased security. In this paper, we investigate the potential of mobile sensor nodes such as unmanned aerial vehicles and human patrols to fortify the barrier-coverage quality of a WSN of cheap and static sensor nodes. For this purpose, we first use a single variable first-order

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grey model, GM(1,1), based on the intruder detection history from the sensor nodes to determine which parts of the barrier is more vulnerable. Then, we relocate the available mobile sensor nodes to the identified vulnerable parts of the barrier in a timely manner, and prove this relocation strategy is optimal. Throughout the simulations, we evaluate the effectiveness of our algorithm.

Keywords Wireless sensor network · barrier coverage · mobile sensor node · grey forecasting model GM(1, 1)

1 Introduction

During the recent years, wireless sensor network (WSN) has received lots of attentions [2–6]. In the literature, the coverage of a WSN refers the quality of the sensor network satisfying a certain surveillance requirement. During the recent years, several types of coverage models such as point-coverage, area-coverage [7], and barrier-coverage have been intensively investigated. We say a WSN offers barrier-coverage over an area of interest if the WSN guarantees to detect an object of interest moving into the area. Unlike the point-coverage and area-coverage models in which a WSN is required to concurrently monitor a given whole set of points and a given whole area of interest, respectively, a WSN can provide barrier-coverage over an area by simply forming a seamless chain of sensor nodes surrounding the area [8].

The concept of barrier-coverage is very useful and has a wide range of important real-life applications such as border protection and enemy intrusion detection during a war. However, such a barrier of wireless sensors is subject to suffer from loopholes caused by various temporal failures such as inaccurate readings and environmental changes [9]. One interesting aspect of the applications of barrier-coverage is that the intruders are smart enough to identify such loopholes of the barrier protecting the border. Once an intruder identifies a path to penetrate successfully (possibly detected, but not captured), it is likely that the other intruders will try the similar path in the near future. Therefore, in those applications, it becomes very crucial to identify such a trend and accordingly fortify the border security in a timely manner.

Fig. 1 illustrates a WSN offering barrier-coverage over the area B (the area below the rectangular area L of width l) from intruders coming from the area T over the rectangular area. In our example, to form a flawless barrier over L, we need at least 8 sensor nodes (see Fig. 1(b)). Initially, there are three main routes that the intruders are using for penetration, and the number of intruders using each path is different. Suppose we deploy more number of sensor nodes along one of those routes which are used the most frequently. Then, this path will soon be abandoned due to the increased chance to get caught. Possibly, the intruders will be using the other main paths or will try a new path. Throughout this example, we can learn that if we can predict the trend of intruders on which path they will use, we can protect the border better. At the same time, this should be done in a timely manner since the trend (what is the main route) keeps changing.

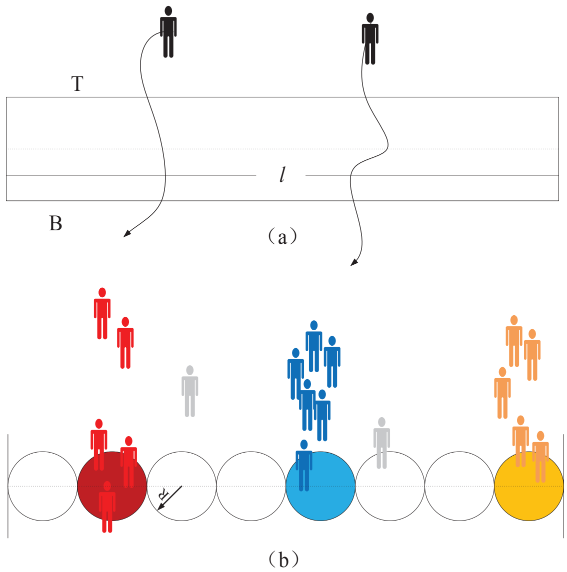


Fig. 1 Frequently, intruders are intelligent enough to identify and penetrate the weakest part of the barrier.

In this paper, we assume there is a WSN offering barrier-coverage over an area of interest. Then, we study how to relocate a set of available mobile sensor nodes to fortify the sensor barrier against the intruders which may alter their main routes for penetration. Largely, the contribution of this paper has two folds.

(a) Based on the previous history of the arrival time of intruders detected by each sensor nodes, we predict the likelihood of intruders being detected by each sensor node in the near future. In particular, we adopt a mathematical model known as a single variable first-order grey model, GM(1,1), which has been widely used to predict events which are repeatedly occurring and is known to be highly reliable and efficient for this purpose [10–14].

(b) Once we identify static sensor nodes which have higher chance to detect intruders, we relocate the available mobile sensor nodes nearby the static sensors so that the area covered by these nodes can be monitored even more thoroughly. Since this should be done in a timely manner, it is necessary to relocate the mobile nodes in a way that the maximum travel distance among the nodes is minimized. We introduce a new mobile sensor nodes relocation algorithm which tries to satisfy this requirement in a way that a static sensor node with higher chance to detect an intruder will obtain assist from more number of mobile sensor nodes. We also prove our relocation strategy is optimal.

The rest of this paper is organized as follows. Section 2 and Section 3 introduce related work and some preliminaries, respectively. In Section 4, we introduce a new two-phase algorithm to identify the static sensor nodes to be fortified and to relocate the mobile sensor nodes accordingly. We present the simulation results and make discussions in Section 5. Finally, we conclude the paper in Section 6.

2 Related Work

Over years, the traditional coverage models such as point-coverage [15] and area-coverage [16] have been intensively investigated. In the literature, a WS-N is told to provide a barrier-coverage over an area of interest if the WSN guarantees to detect any object crossing over the area. The barrier-coverage model is distinguished from the other traditional coverage models in a sense that barrier-coverage aims to protect an area of interest or points of interest by simply having a chain of sensor nodes surrounding them rather continually monitoring the entire area or all of the points.

Originally, the concept of barrier-coverage has emerged in the context of robotic sensors [8]. In [17], Chen et al. studied how to maintain the quality of barrier-coverage by identifying when the performance of the barrier-coverage becomes lower than a predefined level and where to fix to meet the demanded quality. In [18], Li et al. studied a sensor network scheduling problem whose goal is to maximize the lifetime of sensor network by having a sleep-wakeup schedule of the sensors while continuously satisfying a given intruder detection probability requirement. Chen et al. [19] introduced a localized barrier-coverage protocol to detect all intruders whose movement are confined to a slice of the original strip region (the region that the intruders are allowed to move for intrusion).

In many applications, sensor nodes are subject to fail due to their inherited cheap hardware. Therefore, there have been lots of discussions on fault-tolerant coverage model. For instance, the fault-tolerance of area-coverage model can be improved by having at least k sensors to monitor the area at the same time. Similary, we can improve the fault-tolerance of point-coverage model by making each point to be concurrently covered by at least k sensors. In [20], Kumar et al. introduced the concept of fault-tolerant barrier-coverage for the first time. Then, they propose the k-barrier-coverage model, which is a fortified version of barrier-coverage model in a sense that a WSN with k-barrier-coverage can detect any intruder with at least k-different sensors. Unfortunately, while k-barrier-coverage model with very large k is very helpful to enhance the fault-tolerance of barrier-coverage, it is not easy to implement since there always can be some paths which allows an intruder to trespass the barrier while only confronting sensors which is significantly less than k.

Very recently, several attempts are made to improve the performance of barrier-coverage by employing mobile sensor nodes. In [21], Saipulla et al. studied the problem of relocating mobile sensors with limited mobility to have maximum number of sensor barriers after the random deployment of sensor nodes. Keung et al. [22] studied the problem of providing k-barrier-coverage

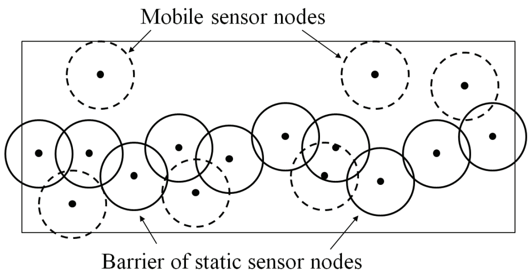


Fig. 2 Barrier of sensors with static sensors assisted by mobile sensor nodes.

with a given set of static sensor nodes by employing the minimum number of mobile sensor nodes. One interesting, but predictable conclusion of this paper is that the performance of barrier-coverage can be improved as we have more number of mobile sensor nodes.

In [23], He et al. considered a sensor network with mobile sensor nodes only. Then, they introduce a patrolling algorithm for multiple mobile sensor nodes to improve the detection probability. The key idea of this algorithm is utilizing the previous intruder arrival information to determine the trajectories of the mobile sensor nodes. In detail, they studied the temporal correlation among events under the assumptions that (a) the inter arrival time of each intruder will obey Weibull distribution and (b) only one intruder arrives at somewhere in each time slot. However, in practice, human mobility is with very high complexity in terms of spatial and temporal domain [24]. For instance, at any given time slot, more than one intruder may move into the sensing area of the same sensor.

To the best of our knowledge, He et al.'s work is the closest to our research. However, ours is different from theirs mainly due to the following two reasons. First, we break the assumption of He et al. that one intruder may arrive at a sensor node within each time slot since this is not always true. Also, to predict the future pattern of the intruders, we use GM(1,1) which relies only on the history of intruders in the past instead of assuming the inter arrival time of the next intruder will follow Weibull distribution. Second, the objective of our research is the fortification of a complete barrier of static sensors rather than forming a barrier using a set of static sensors and a group of mobile sensors, and thus the objectives of theses researches are different.

3 Preliminaries and Problem Statement

3.1 Network Model

This paper considers a WSN of n static sensor nodes within a two-dimensional rectangular area along with m mobile sensor nodes with limited sensing capability. Throughout this paper, we assume the intruders are moving from the top of the area to the bottom to trespass, but never circumvent the area. The static sensor nodes are deployed in the area and already providing barrier-coverage over the bottom region of the area. On the other hand, the mobile sensor nodes are randomly deployed in the area and will relocate themselves to enhance the quality of the coverage. We follow Saipulla et al. [21] and assume the coordinate (x, y) of each sensor node is known in advance, which can be done using either an on-board GPS unit or any existing localization mechanism. We further assume that the mobile sensor nodes have the knowledge of their locations within the area. Each sensor node has a sensing range r and is capable of detecting any intruder within its sensing region, whose shape resembles a disk with radius r centered at the sensor node. The sensing capability of a mobile node is similar to that of the static sensor node, but different from its sensing range, which is d instead of r. We refer an intruder is covered or detected by a static sensor node or a mobile node once the intruder moves over the sensing region of the node [25].

3.2 Single Variable First-order Grey Model, GM(1,1)

This section introduces GM(1,1) which can be used to predict the time that the next intruder will arrive at a sensor node based on the history of intruders collected by the sensor node. Suppose we have an initial intruder arrival time sequence measured by the sensor node,

$$X^{(0)} = \{x^{(0)}(1), x^{(0)}(2), \cdots, x^{(0)}(l)\}, \tag{1}$$

where $x^{(0)}(i)$ is the time series data at time i and l is an integer such that $l \geq 4$. Based on the initial time series, we generate a new time-series

$$X^{(1)} = \{x^{(1)}(1), x^{(1)}(2), \cdots, x^{(1)}(l)\}, \tag{2}$$

where $x^{(1)}(k) = \sum_{i=1}^{k} x^{(0)}(i)$ for $k = 1, 2, \cdots, l$. The reason to accumulate the measures is to (a) provide the middle message of building a model and (b) weaken the variation tendency [10]. Then, we need to solve the following first-order differential equation of grey model GM(1,1):

$$\frac{dx^{(1)}(t)}{dt} + ax^{(1)}(t) = b \tag{3}$$

by determining a and b. Here, the (a, b) pair satisfying the equation can be computed by least squares, i.e.

$$(a, b)^T = [\mathbf{X}^T\mathbf{X}]^{-1}[\mathbf{X}^T\mathbf{Y}], \text{ where} \tag{4}$$

$$\mathbf{X} = \begin{pmatrix} -\frac{1}{2}[x^{(1)}(1) + x^{(1)}(2)] & 1 \\ -\frac{1}{2}[x^{(1)}(2) + x^{(1)}(3)] & 1 \\ \vdots & \vdots \\ -\frac{1}{2}[x^{(1)}(n-1) + x^{(1)}(n)] & 1 \end{pmatrix}, \mathbf{Y} = \begin{pmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{pmatrix}.$$

Once we obtain the (a, b) pair, we plug them into the differential equation in Eq. (3) and solve it to obtain a GM(1,1) forecast model as follow:

$$\hat{x}^{(1)}(k+1) = [x^{(0)}(1) - \frac{b}{a}]e^{-ak} + \frac{b}{a}, \quad (5)$$

for $k = 1, 2, \cdots, n$. Here, $\hat{x}^{(1)}(k+1)$ is the predicted value of $x^{(1)}(k+1)$ at the time slot $k+1$. From this equation, we can obtain the *forecast value* of $\hat{x}^{(0)}(k+1)$ at time $k+1$ as a function of $\hat{x}^{(1)}(k+1)$ and $\hat{x}^{(1)}(k)$, which is

$$\hat{x}^{(0)}(k+1) = \hat{x}^{(1)}(k+1) - \hat{x}^{(1)}(k). \quad (6)$$

In the literature, this model is also referred as "Whole Data GM(1,1) Model". Note that as we can see from the equations above, its forecast data series is solely dependent on the historical data collected.

3.3 Problem Statement and Our Approach

In this paper, we study how to fortify the barrier of sensors using mobile sensor nodes. We assume that a sensor node has a higher chance to detect intruder in the near future since the sensor node is vulnerability. Then, we measure the vulnerability of each sensor node using GM(1,1) whose only input is the history of intruders collected by the sensor node. Once a set of vulnerable sensor nodes are identified, we relocate the available mobile sensor nodes to assist the vulnerable static sensor nodes such that the maximum travel distance of the mobile sensor nodes is minimized. As a result, this relocated can be achieved in a timely manner.

4 Predict and Fortify: A New Way to Improve Barrier-coverage using Mobile Sensor Nodes

In this section, we introduce our two-phase algorithm to dispatch available mobile sensor nodes in a timely manner so that the weak part of the barrier of sensors can be effectively fortified. Let X be the random variable of the number of intruders detected by a barrier of sensors during a certain time period. Clearly, this inter arrival time of intruders can be modeled as a renew process. We use Poisson distribution with parameter $\lambda > 0$ as the probability distribution of the number of intruders since this distribution has been widely adopted to model such a real world random event. Note that the expected value of a Poisson random variable X with parameter λ is λ, i.e. $\lambda = E(X)$.

4.1 Predicting Vulnerability of Static Sensors

Let T_i^k be the time of k_{th} intruder detected by a static sensor node s_i. As we introduced, to apply GM(1,1), we assume that T_i^k is available for any $1 \leq k \leq l$

and $1 \leq i \leq n$ pair, where $l \geq 4$ is the number of intruders detected so far and n is the number of static sensor nodes. Then, using GM(1,1), we obtain $\hat{T}_i^{k+1}$, which is the predicted time that $k+1_{th}$ intruder (or the first intruder in the next time slot) will arrive at s_i for each i. Then, compute $\Delta_i = \hat{T}_i^{k+1} - T_i^k$, which is the expected inter arrival time of $k+1_{th}$ intruder. Then, we define we compute the weight of s_i as

$$W_i = \frac{\lambda}{\Delta_i}.$$

This equation implies that with larger expected inter arrival time Δ_i, s_i will detect less number of intruders in the next time slot. Therefore, we can determine that a sensor node s_i with higher W_i value is more vulnerable. Let F_i be the number of mobile sensors needed by sensor node s_i. Clearly, the more W_i is, the higher F_i should be. One good equation that we can use is

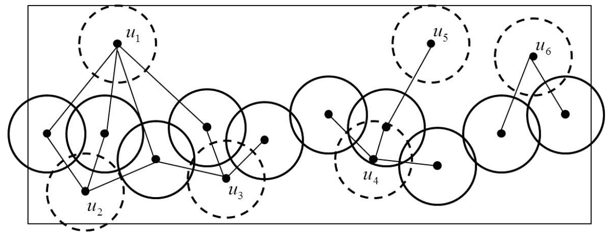
$$F_i = |\lceil \frac{W_i}{\alpha} \rceil - c|,$$

where α is used to normalize W_i so that $\sum_{\forall i} F_i$ cannot exceed m, the total number of available mobile sensor nodes, and c is introduced to distinguish the group of vulnerable sensors from the rest. For the sake of simplicity, we set $\alpha = 1$, $c = 1$, and proceed.

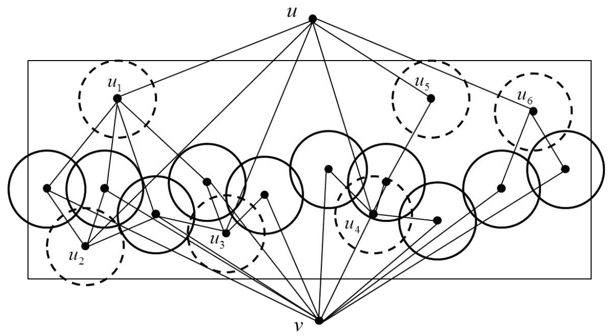
4.2 Strengthening Barrier with Mobile Sensors

Suppose $\mathcal{V}$ is the set of vulnerable sensor nodes, i.e. $\mathcal{V} = \{s_i | F_i \geq 0\}$, identified by the previous phase. Then, for each sensor node s_i, we would like to (ideally) move at most F_i mobile sensor nodes to assist s_i. Note that we normalise $\alpha = 1$ and $c = 1$, and thus $\sum_{\forall i} F_i \geq m$ may happen. However, our strategy for relocating mobile sensor nodes introduced in this section is the one with the best effort, and thus it still works. In this section, we assume each mobile node is allowed to move at most $\mathcal{D}$ unit distance through the three steps introduced below. In the following algorithms containing 3 steps, we introduce how to allocate the mobile nodes to the vulnerable sensor nodes. The goal is to use all the mobile nodes.

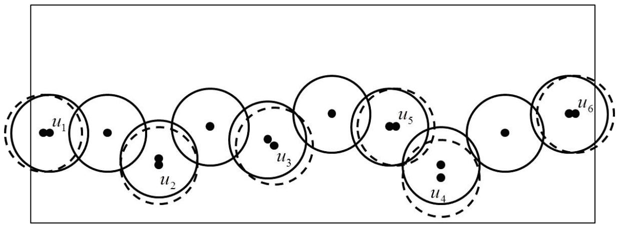
The idea of the following algorithm is like this, since s_i needs F_i nodes at most, we added F_i duplicated nodes. We would like to find out the maximum match between S' and M, the set of mobile nodes, so that we can use as many mobile nodes as possible. To find the maximum match, we add a “source” node u and a “sink” node v, assign each edge weight 1, and try to find out the maximum flow between u and v. Obviously then, the maximum flow is the number of mobile nodes we can use at most. We actually would like to use all the mobile nodes, therefore only when the maximum flow equals to the number of mobile nodes, the design goal has been achieved.



(a) Step 1: there is a line between a mobile node m_i to a static sensor node if their Euclidean distance is no greater than a limitation, say $\mathcal{D}$.



(b) Step 2: two nodes u and v are added, and a bipartite graph is constructed. Then, a max-flow algorithm is applied to find the maximum flow from u to v.



(c) Step 3: the mobile nodes are relocated onto the static sensor nodes. This happens only if the max-flow value is equal to the number of mobile nodes. Otherwise, Steps 1 and 2 are repeated after $\mathcal{D}$ is adjusted properly.

Fig. 3 This figure illustrates how mobiles nodes are assigned.

- Step 1: Suppose $S = \{s_1, \cdots, s_q\}$ is the set of sensor nodes identified to be vulnerable in the previous phase. From S, we first induce S' such that for each $s_i \in S$, we add F_i sensors $s_{(i,1)}, s_{(i,2)}, \cdots, s_{(i,F_i)}$ (all of which locate at the position of s_i) to S'. Let $M = \{u_1, u_2, \cdots, u_m\}$ be the set of mobile sensor nodes available. Next, we construct the bipartite graph $\mathcal{B} = \{S', M, E\}$, where E will contain an edge between $s_{(a,b)} \in S$ and $u_j \in M$ only if s_a is reachable from u_j, i.e., their Euclidean distance is at most $\mathcal{D}$.

- Step 2: From $\mathcal{B} = \{S', M, E\}$, we construct a new graph $\mathcal{G} = (V_G, E_G)$ such that
$$V_G = S' \bigcup M \bigcup \{u\} \bigcup \{v\}$$
and
$$E_G = E \bigcup \{(u, s_{(i,j)}| \text{ for all } s_{(i,j)} \in S'\} \bigcup \{(v, u_i)| \text{ for all } u_i \in M\}.$$
Here we assume the capacity of each edge is 1. Then, we apply a maximum flow algorithm such as Ford-Fulkerson[26]) over $\mathcal{G}$.
- Step 3: Finally, the mobile sensor nodes are assigned in a way that if the maximum flow includes an edge from $s_{(i,j)} \in S'$ to $y \in M$, we assign the mobile sensor node y to s_i.

Fig. 3 illustrates how the three steps work.

4.3 Computation of Optimal $\mathcal{D}$

To find the optimal $\mathcal{D}$, we utilize binary search. We first compute the distance between every static sensor node and mobile node pair. Suppose $\{\mathcal{D}_1, \mathcal{D}_2, \cdots, \mathcal{D}_q\}$ be the list of distinct distances sorted by non-decreasing order. Then, we initially set $\mathcal{D} \leftarrow \mathcal{D}_{\lceil q/2 \rceil}$ and apply our two-phase algorithm introduced in the previous two steps. If there exists a mobile node m which is not assigned, then we increase $\mathcal{D}$ by setting $\mathcal{D} \leftarrow \mathcal{D}_{\lceil (q+q/2)/2 \rceil}$. Otherwise, we decrease $\mathcal{D}$ by setting $\mathcal{D} \leftarrow \mathcal{D}_{\lceil (1+q/2)/2 \rceil}$. We keep repeat this until we cannot proceed any further. Then, we will find minimum $\mathcal{B}$ which allows all of the mobile sensor nodes to be assigned. We now prove this strategy results in an optimal solution for this relocation problem.

Theorem 1 *The proposed relocation algorithm with binary search results in an optimal solution.*

Proof Let $\mathcal{D}_{opt}$ be an optimal distance, and $D = \{\mathcal{D}_1, \mathcal{D}_2, \cdots, \mathcal{D}_q\}$ be the list of distinct distances sorted by non-decreasing order. Clearly, we have
$$\min_{\mathcal{D}_i \in D} \mathcal{D}_i \leq \mathcal{D}_{opt} \leq \max_{\mathcal{D}_j \in D} \mathcal{D}_j.$$
This is because (a) if we only allow all of mobile sensor nodes to move at most $\min_{\mathcal{D}_i \in D} \mathcal{D}_i$, none of them can move onto any existing static sensor node, and (b) $\max_{\mathcal{D}_j \in D} \mathcal{D}_j$ is always enough to move all of the mobiles sensor nodes to move whichever static sensor nodes we want to relocate onto. Then, we have two cases: either $\mathcal{D}_i < \mathcal{D}_{opt} < \mathcal{D}_{i+1}$ for some i or $\mathcal{D}_{opt} = \mathcal{D}_j$ for some j. Clearly, for any optimal solution $\mathcal{D}_{opt}$ satisfying the first condition, $\mathcal{D}_i$ is always sufficient for the same relocation arrangement of the mobile sensor nodes. Therefore, the second case is always true. Finally, since we are using a binary search strategy, the proposed algorithm will find a minimum $\mathcal{D}_{opt} = \mathcal{D}_i$ for some i. Therefore, this theorem is true.

4.4 Further Extension with Time Slots

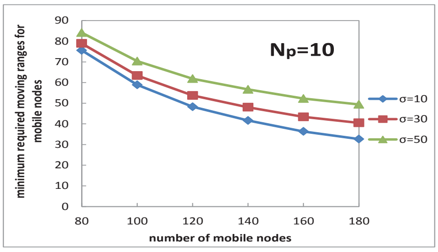
The algorithm described above can be easily implemented in a time slot based system as done by He et al. [23]. That is, we first consider the continuous time domain into a series of time slots with the same length. Then, we assume the time series shown in Eq. (1) are from current time slot. Then, using the first phase of our approach described in this section, we determine the vulnerability of each sensor node in the next time slot. Once decided, we deploy the mobile sensor nodes using the second phase of our approach. At the end of each time slot, we reanalyze the vulnerability of each sensor node and redistribute the sensor node. One benefit of this time slot based approach against the case without it is that we use relatively new history of intruders only rather than using all of the accumulated history to analyze the vulnerability of each node. Depending on the applications, this can improve the accuracy of the prediction achieved by grey model GM(1,1).

5 Simulation Results and Analysis

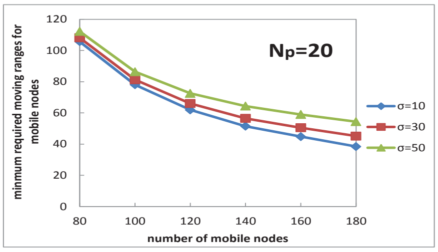
5.1 Performance Evaluation of Mobile Node Relocation Algorithm

In this section, we evaluate the performance of the second phase of our algorithm. We set the number of vulnerable sensor nodes N_p to be 10, 20, 30, and 40. In this simulation, we consider a barrier formed by 100 sensors deployed over a 2000×200 rectangle space. Then, we randomly deploy m mobile sensor nodes along the barriers based on three different random offset variances σ=10, 30, and 50. Note that with larger variance used, the mobile sensors have a better chance to be located further from the barrier. Under the same parameter setting, we apply our algorithm for 100 instances and compute the averaged value.

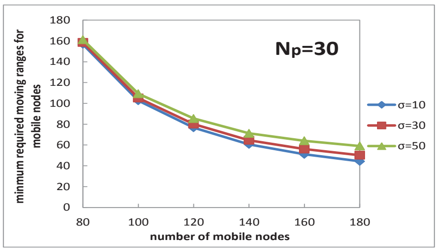
Fig. 4 shows the relationship among the number of mobile nodes, the minimum required moving distance of the nodes, and N_p. In Fig. 4(a), N_p is set to 10 and the number of mobile nodes is increased. As we can observe, with more mobile nodes, the mobile node can be completely relocated within less time. We can also observe that with smaller σ value, the travel distance becomes smaller. We can observe the similar trend from Fig. 4(b), Fig. 4(c), and Fig. 4(d). By comparing Fig. 4(a), Fig. 4(b), Fig. 4(c), and Fig. 4(d), we also can learn the effect of σ is constant regardless from the N_p value, which seems natural. On the other hand, with large N_p value, the maximum travel length of mobile sensor nodes for relocation is greater. From this result, to cover all of the vulnerable nodes, a mobile node may need to travel further as the number of vulnerable nodes increase. We believe this is because to assign all of the mobiles nodes, some nodes may need to travel very far, and this happens more often if we have more number of vulnerable nodes.



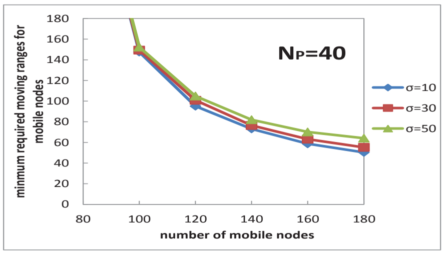
(a) Minimum required moving range for $N_p = 10$



(b) Minimum required moving range for $N_p = 20$



(c) Minimum required moving range for $N_p = 30$

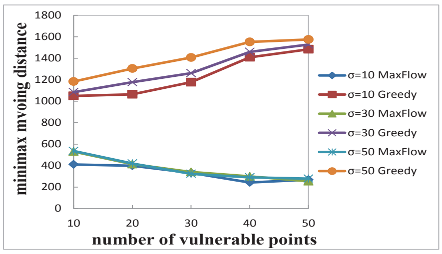


(d) Minimum required moving range for $N_p = 40$

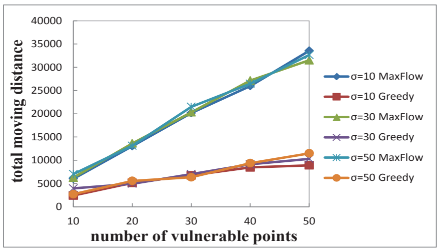
Fig. 4 Performance evaluation of the second phase of the proposed algorithm.

5.2 Performance Comparison of Mobile Node Relocation Algorithm Against He et al.'s Strategy [8] for Our Purpose

In [8], He et al. introduced a multiple mobile sensor node relocation algorithm called CSP whose goal is to relocate a group of mobile sensor nodes into a



(a) Minimum moving range to monitor all vulnerable points



(b) Total moving range to monitor all vulnerable points

Fig. 5 Performance evaluation of mobile node relocation algorithm compare with He et al.'s strategy.

subset of regions based on some probability model to maximize the chance to detect intruders. Therefore, their algorithm also can be used to relocate mobile sensor nodes to solve our problem by replacing our max-flow based algorithm after Step 2 of Phase 2 described in Section 4.2. Note that our algorithm also can be used for their problem. In detail, the CSP algorithm is a greedy algorithm which tries to assign each available mobile sensor to the closest vulnerable point. It assumes that all mobile sensors and vulnerable points are on a straight line, and each vulnerable point is monitored by one mobile sensor. In our scenario, our mobile sensors and vulnerable points are not necessarily on a straight line. However, we can still use the main idea of CSP algorithm. This can be done by iteratively selecting a vulnerable point that has not been assigned any mobile sensor yet, and assign it to the closest available mobile sensor. This process is repeated until all vulnerable points are occupied. Since CSP algorithm assumes the number of avail mobile sensor nodes is equal to the number of vulnerable points, so we keep this assumption for a fair comparison.

Fig. 5 show our simulation results. From the figures, we can learn that the min-max distance of the outputs of our algorithm is better than that of He et al's greedy algorithm (greedy). On the other hand, the total distance that the mobile sensor nodes are moving around is larger than that of greedy's.This is due to the difference in the objectives of the algorithms. That is, the goal of our algorithm is to minimize the min-max distance achieved by the mobile sensor nodes while the goal of He et al's greedy algorithm is to minimize the total (average) distance achieved by the mobile sensor nodes. Therefore, our algorithm outperforms He et al's greedy algorithm for our problem.

6 Conclusion

In this paper, we introduce a new paradigm to use mobile sensor nodes to fortify the strengthen of the barrier of static wireless sensors. Our approach is based on GM(1,1) which helps us to predict which sensor node has a better chance to detect intruders based on the past record of the intruders detected. We assume that a sensor node has a higher chance to detect an intruder because the intruder consider the area covered by the sensor node is easier to penetrate. Therefore, we deploy available mobile sensor nodes to strengthen the coverage of those sensors. The algorithm that we proposed in this paper also utilizes a binary search approach to minimize the maximum travel length of the mobile sensor nodes, and thus make the relocated done in a timely manner. Our simulation results suggest some interesting properties of our algorithm, especially about the second phase which concern about the relocation. As a future work, we plan to use real data set to validate the practicalness of the first phase as well as investigate an algorithm for the second phase with better performance.

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