2008 14th IEEE International Conference on Parallel and Distributed Systems

Using Cable-Based Mobile Sensors to Assist Environment Surveillance

Shanshan Li [1] Xiaoping Wang [1] Mo Li [2] Xiangke Liao [1]
1 National University of Defense Technology, China
2 Hong Kong University of Science and Technology, Hong Kong
shanshanli@nudt.edu.cn xiaopingwang@nudt.edu.cn limo@cse.ust.hk xkliao@nudt.edu.cn

Abstract

In wireless sensor networks, mobile sensors are often employed for enhancing the sensing coverage and detection accuracy. Current approaches assume mobile sensors with the capability of arbitrary movement. The usage of such sensors with unlimited mobility, however, requires complicated sensor manufactures and high intelligence of movement which are practically unrealistic in many practical applications. We investigate the usage of cable-based mobile sensors which move along pre-deployed cables to accomplish sensing tasks at different positions. A target area is said to be reachable, if for any point in this area, at least one mobile sensor can move along the cable and achieve coverage to the point within a specified delay bound. We propose to achieve k-reachability for the sensing field with minimum mobile sensors along the cable. Further, during special events, mobile sensors need to move and help surveillance. We need adjust the positions of the rest of mobile sensors accordingly to balance the reachability within the area. We prove the NP-hardness of the targeted problems and give heuristic approaches. Through comprehensive simulations, we evaluate the performance of this design and show its effectiveness.

1. Introduction

Wireless Sensor Networks (WSNs) are emerging as a promising technology for monitoring the physical environment. Traditional sensor networks rely on deploying static sensors over the field for collecting data and sending back to the monitoring center. Achieving high detection accuracy requires equipping each sensor node with identical sensing devices of the desired accuracy, resulting in high costs. A feasible solution is to build a hybrid network consisting of both static and mobile sensor nodes. While the static sensors are manufactured cheap with coarse resolution and deployed over the entire surveillance field, the mobile sensors can be expensive with accurate sensing devices in a limited number. Thus, we are able to capture events by coarse static sensors and then guide the accurate mobile sensors to carefully investigate the event with desired accuracy.

There have been works done by utilizing mobile sensors as supplementary to assist the sensing coverage for the static sensor nodes in possible event happenings [1-4]. Most of them assume that the mobile sensors are equipped with unlimited mobility and thus can move anywhere within the monitored field. However, the assumption of unlimited mobility has its own limitations and is unrealistic in many practical applications. First, the monitored field might have complex landforms so that arbitrarily moving within the field is impractical for mobile nodes. Second, the mobility planning and modeling in a 2D or even 3D field needs be highly intelligent, out of the capability of resource constraint sensors. Third, using arbitrarily moving sensors may bring disturbance to the regular activities carried out on the field.

In this paper, alternatively, we consider to pre-deploy cables within the monitored field so that mobile sensors move along cables to destinations. In this case, we can far more relax the requirements on the mobile sensors and achieve more realistic usage despite of the complex field landforms. Indeed, this is motivated from our early investigation in the coal mine monitoring application [5, 6] where we hope to deploy more accurate mobile sensor nodes in the tunnel to assist static sensor network for monitoring the environment elements such as gas density, oxygen and water osmosis. We find that existing cables deployed in the tunnel are perfect carriers for deploying mobile nodes which help get rid of the complex circumstance in the underground tunnel.

In our application, what we concern the most is the reachability of mobile sensors to certain targets. In case of event happening, static sensors might coarsely

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DOI 10.1109/ICPADS.2008.33

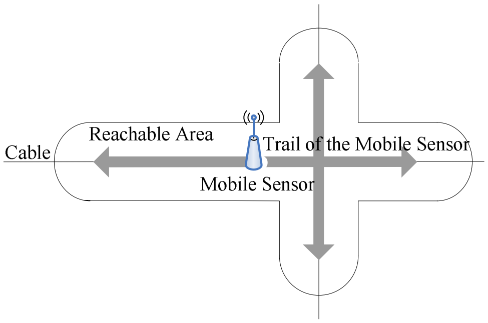

Figure 1. Reachable area of one mobile sensor

detect environment variations and inform adjacent mobile sensors. Then mobile sensors decide to move and catch the event in a predetermined time delay bound. A target area is said to be reachable if for any point in this area, at least one mobile sensor can move along the cable and achieve coverage to the point within a specified delay bound. Figure 1 illustrates the reachable area for one mobile sensor. Reachability extends traditional coverage definition as it indicates the coverage area of a mobile sensor which can be covered under a given delay bound. Accordingly, a target area is said to be k-reachable if any point in this area can be covered by k mobile sensors within the delay bound.

The k-reachability for the entire surveillance field is often required to facilitate accurate and reliable event monitoring. In this study, we aim to deploy a minimum number of mobile sensors under the given cable deployment, such that the entire monitored area is k-reachable. Further, when events happen, some mobile sensors move from their original positions for targets, so we need adjust the positions of the rest of mobile sensors accordingly to balance the reachability within the area.

Several challenges exist for this design. First, the cable deployment as a predetermined constraint factor restricts the possible movement of mobile sensors and thus limits our optimization on achieving the k-reachability. Second, as the cable deployment is a free input from external, the reachable area of the mobile sensor at different positions along the cables vary so much that the deployment of mobile sensors can hardly be modeled as what traditional coverage problems did. Third, it is in nature difficult for the mobile sensors to obtain a global view of the cable deployment and the event distribution as preknowledge, so the position adjustment for the mobile sensors is challenging especially in a distributed manner.

We explore a set of heuristics and accordingly propose our algorithms to address above challenges. The main contributions of this work are as follows:

(1) We formally investigate the KRMMS (k-reachability with Minimum Mobile Sensors) problem and prove it to be NP-hard, then discretize this problem and propose a heuristic greedy algorithm to solve it approximately. We further analyze the lower bound of its performance for the grid cable deployment.

(2) We propose a utility based Distributed Repositioning Algorithm (DRA) to adjust the positions of mobile sensors in case of event happenings. In DRA, each mobile sensor decides its direction and distance of movement locally based only on the movement of its neighbors.

(3) We conduct large scale simulations to evaluate the performance of the proposed approaches. The results show that our heuristic greedy algorithm outperforms random algorithm by a factor of 2, and DRA is able to achieve the desired reachability in over 80% of the target area with varied factors.

The rest of this paper is organized as follows. We briefly review related work in Section II. In section III, we present the network model including the network architecture and the cable modeling. In section IV, we investigate the KRMMS problem. We propose our approaches to discretize this problem and approximately solve it. In section V, we describe the distributed reposition algorithm. In section VI we discuss our simulation methodologies and present the results on evaluating our approaches. We conclude the work in Section VII.

2. Related work

There has been much work done to exploit controlled mobility to enhance the network performance. Wang et al. aim to compensate the coverage of the original sensor deployment by strategically repositioning the mobile sensors [1]. They further design a distributed self-deployment protocols for mobile sensors [2]. They use voronoi diagrams to discover the coverage holes and propose three heuristic algorithms to guide sensor movement to heal the coverage holes. They are vector-based, voronoi-based and minimax-based respectively. Zou and Chakrabarty [3] propose a virtual force algorithm (VFA) to coordinate the mobile sensors for achieving maximum coverage after original random placement of sensors. The combination of attractive and repulsive forces is utilized to determine the motion paths of sensors and the velocity of the movement. All of above proposed algorithms focus on spreading sensors over the field to enhance the coverage after an initial random placement of sensors, and achieve a stationary deployment such that the sensing coverage is maximized. They all focus on a strategy of one-time repositioning.

Wang et al. further exploit the drawback in the one-time repositioning scheme that the coverage can still be unbalanced if the number of mobile sensors is not enough [4]. They discuss the potential benefit from the continuous movement of mobile sensors and propose a markov-based scheme to schedule the sensors. Liu et al. also study the coverage problem of a mobile sensor network from the similar perspective [7]. Instead of trying to achieve an optimized network configuration as a result of sensor movement, they focus on the coverage capacity from the continuous movement of the sensors. Wu and Yang propose SMART that uses scan and dimension exchange to achieve a load balanced state from an initial unbalanced network [8]. Bisnik et al. consider enhancing the event capture by using mobile sensors [9]. An event is said to be captured if it's sensed by one of the mobile sensors before it fades away. This paper analyzes how the quality of coverage scales with the velocity, path and number of mobile sensors.

All these work assume that mobile sensors can move anywhere within the field as planned. They do not consider the complexity and overhead brought by this unlimited mobility of sensor nodes.

Batalin et al. [10, 11] report their NIMS system deployed at the James San Jacinto Mountain Reserve. They exploit advanced mobile nodes to ensure adequate coverage, keep high fidelity and minimize resource consumption. In their work, mobile sensors move along fixed cables. However, their work assumes enough number of mobile sensors and those mobile sensors can be scheduled to sense whenever and wherever new event happens. They neither consider the overhead of the deployment of mobile sensors nor the system efficiency of using those mobile sensors.

3. Network model

The sensor network in our work includes two types of sensors: the static sensors, cheap and with coarse resolutions are densely deployed over the field; the mobile sensors, expensive but with much more accurate sensing capabilities, are transported along the cables for detailed investigation on target events. In this work we assume that mobile sensors are location-aware and they are informed through the underlying static network where the target event happens.

We assume cables have been pre-deployed and thus this is an input to our problem. We only study how to deploy and reposition the mobile sensors under given cable deployments. The cables are modeled as a set of cable segments whose endpoints are either border points or branch points. A border point refers to an end connected to only one cable segment. A branch point refers to a position in cable, with the number of cable segments connected to it larger than 2. The cable segments can be expressed as a set of continuous location dependent functions f_i, $i = 1, 2, \ldots, m$. We use S_f to denote the set of f_i. Figure 2 illustrates a basic example, cable segment *AS, BS, CS, DS* are expressed as f_1, f_2, f_3, f_4 respectively. Each f_i has its effective range of x, y and z. As shown in Figure 2, although *AB* is a connected segment, it is divided into two cable segments *AS* and *BS* by the branch point *S*. All cable segments connected by branch points compose the motion trajectory of mobile sensors.

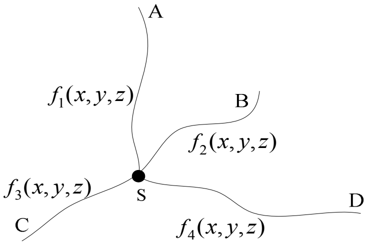

Figure 2. Cable modeling

4. Mobile sensor deployment

In this section, we study the deployment problem of mobile sensors under the given cable deployment. We first formally define the KRMMS problem which is proved to be NP-hard even after transformed into discrete space. Then we propose a discretization method to discretize KRMMS. We analyze the correctness and bound of this method. Based on the potential positions obtained from discretization, we propose a heuristic greedy algorithm to approximate the solution of the KRMMS problem.

4.1. KRMMS problem definition

Given the cable deployment, the size of the covered area of one mobile sensor is highly correlated to its position on the cables and the delay bound specified by the application. Since the mobile sensor is much more expensive, our goal is to find the minimum number of mobile sensors to achieve *k*-reachability for the whole monitored field and the locations for these mobile sensors on the cables. The KRMMS problem is defined as follows:

Given: Area *R* to be monitored, a set of cable segments $f_i(x, y, z)$, $i = 1, 2, \ldots, m$, a constant moving velocity *v* of mobile sensors and the delay bound *t* specified by the application.

Objective: To find the minimum number of mobile sensors and their positions on the cable segments which satisfies *k*-reachability for *R*.

The original KRMMS problem is defined in the continuous space assuming deploying mobile nodes along the continuous segments of cables, which is hard to tackle. We first transform it into discrete space. Actually, KRMMS problem can be proved to be NP-hard even after transformed into discrete space.

4.2. Cable discretization

We select a set of potential positions along the cable to represent the original continuous segments of cables. After cable discretization, KRMMS problem is reduced to selecting the minimum mobile sensors from these positions to achieve *k*-reachability for *R*. A good discretization scheme is extremely important which guarantees the final solution on the discrete space is bounded close to the optimal one in the continuous space. Using traditional discretization schemes we need partition cable segments into small pieces with ε distance. The smaller the ε is, the more fidelity the solution might be, however, a short ε results in a large searching space.

In this work, we propose a delay-bound based scheme for discretizing cable segments which largely decreases the searching space for finding the solution. In this scheme, some potential points are selected according to the size of the reachable area and the moving distance of mobile sensors under the delay bound. Discretization will result in the loss of optimality. Therefore, the selection process should be considered comprehensively. In the following, we will investigate the discretization scheme and analyze the correctness and bound of this scheme.

Since each mobile sensor can only move along the cable segments, its position on the cable directly determines the size of its reachable area. the mobile sensor at the branch point can reach more area since it has more choices to move. Therefore, we choose to occupy the branch points in preference.

After the branch points, we choose other positions as the following. Starts from each branch point, positions are selected along its connected cable segment every $v \cdot t / k$ in length, and this process stops at the position within $v \cdot t / k$ to the other end of this cable segment. If both ends of a cable segment are branch points, this cable segment is divided from each endpoint respectively. If there is no branch point, positions are selected from the end of each cable. $v \cdot t / k$ corresponds to the delay bound and *k*-reachability specified in the application. The reason for selecting this interval is due to a greedy heuristic, since the reachable area of one mobile sensor is within the area it can move to within the delay bound *t* from its current position. For the ease of expression, later we use *l* to represent this fixed interval $v \cdot t / k$.

Sometimes there are no branch points on the cable segment, such as a circle or just a curve. For the case of a circle, we can start from any position *x* on this circle and stop in the same position. For the case of a curve, the start position is one endpoint of curve and stop in the other endpoint. In the extreme case, there might be isolated cables composed of a set of connected cable segments.

Above discretization, the number of positions selected from this set might be less than *k*. In such a case, more positions are inserted to satisfy *k*-reachability. These positions could be selected in random from the cable segments.

At this stage, all the cables are discretized into a set of positions, denoted by S_p . We will analyze the correctness and lower bound of this discretization.

4.3. Approximating the KRMMS problem

We first analyze the hardness of the KRMMS problem. We divide *R* into multiple fields based on the field concept defined in [12]. Assuming there is one mobile sensor at each position of S_p, each field is reachable by the same set of mobile sensors, so all points in each field can be regarded equivalent. The KRMMS problem can be reduced to selecting the minimum positions from S_p to *k*-reach all the fields of *R*. This can be proved to be NP-hard by a polynomial time reduction to *k*-minimum dominating set problem.

Theorem 1: The KRMMS problem is NP-hard.

Proof: For simplicity, we denote the set of the potential cable points Set *A*, the set of the fields Set *B*. Then KRMMS problem is to select the minimum number of points from Set *A* to reach all fields in Set *B*. We construct a special instance of KRMMS problem. In this instance, the whole area consists of multiple subregions closed to all points in Set *A*. The number of subregions is equal to the number of points in Set *A*, the size of each subregion is very small and nearly overlapped with these points. In this case, these subregions compose Set *B* and can be regarded as overlapped with points in Set *A*, the KRMMS is then problem[13]. Thus the KRMMS problem is NP-hard. transformed to the *k*-minimum dominating set

We propose a greedy heuristic based algorithm CGD (algorithm 1) for approximately solving the discretized KRMMS problem in polynomial-time. The basic idea is, we carry out the algorithm in k iterations. In each loop, the point which heals the largest unreachable area is selected to be included in the final set. If there are any ties in the selection process, they are broken by randomly selecting a choice. The overlapped area produced in the *i-th* round can be added to the reachable area of the $(i+1)$*th* round. If the selection of points in the *i-th* round is enough to reach the target area, the *i-th* round stops and i-reachability is achieved.

In algorithm 1, S is the collection of points selected from S_p to place mobile sensors, $OA(i)$ is the overlapped area in the *ith* round. S returns the selected positions to place mobile sensors. With these mobile sensors, k-reachability can be achieved on the monitored region R.

In fact, KRMMS problem belongs to set cover problem, the approximation ratio of our CGD algorithm on the minimum number of sensors is $1+ln(R_{max})$, where R_{max} is the maximum sensing area of position in S_p. We further examine the approximation ratio of CGD to the optimal solution of KRMMS problem for a general gird cable deployment.

Theorem 2 (bound): The number of mobile sensors selected by CGD algorithm is bounded by four times the optimal solution for the KRMMS problem in the gird cable deployment.

Proof: The basis idea of this bound analysis is similar to theorem 2. Suppose there is an optimal solution S' in continuous space, a solution S produced by CGD. For any position $x \in S'$ but $x \notin S$, if x is a branch point, we replace it with its four direct neighbors along the grid cable connected to x in S, else replace it with its two direct neighbors in S. By this replacement we guarantee that no coverage hole is generated. In the extreme case, the number of mobile sensors in S is at most 4 of optimal solution.

Actually, CGD selects branch points with large sensing area with preference, so the size of S produced by CGD is much less than 4 of the optimal number as shown in simulations.

Algorithm 1. CGD Algorithm

```
$S \leftarrow \phi$;
For $i = 1:k$
    While the collection of points in the $ith$ round hasn't reached the target area $R$
        Select point $x$ from $S_p$ which maximize the unreachable area;
        Add the overlapping area produced by $x$ to $OA(i)$;
        $S_p \leftarrow S_p \setminus x$;
    Add these points to $S$;
    Add $OA(i)$ to the reachable area of the $(i+1)th$ round;
```

6. Reposition of mobile sensor

In ordinary status, mobile sensors do not move and preserve k-reachability for the entire area. Once static sensors detect anything unusual in the environment, they inform adjacent mobile sensors instantly, and then the mobile sensors decide whether and where to move based on its distance from the event area so that it can catch the event within the given delay bound. After these mobile sensors move away, the reachability on the rest of the monitored area becomes unbalanced. In order to rebalance the reachability among the rest of the area, we need adjust the positions of other mobile sensors. The event area and those mobile sensors scheduled to the event area will not be included in our consideration. Normally, the area near the event has a much lower degree of reachability as mobile sensors are scheduled towards events. Figure 3 illustrates an example, where nodes B, C, D move to help balance the reachability caused by the movement of node A. Then, the problem is how each sensor judges whether and where it should move. We propose a utility based Distributed Repositioning Algorithm (DRA) for repositioning the mobile sensors.

To keep connection, two closest mobile sensors along the cable should be in the communication range of each other. When k is 1 and the cable segment is in beeline shape, the distance between two neighboring mobile sensors should be at most $2l$ to avoid empty area unreachable. Therefore, for simplicity, we assume the communication radius r of mobile sensors is larger than $2l$. Before we describe the detail of DRA, we give some denotations and definitions here.

DNeighbor(x) is the set of direct neighbors of node x which are next to node x along the cables;

RDeg(R) is the average degree of the reachability of area R;

NR(x) is the current reachable area of x after its movement;

UR(x) is the area originally reachable by node x but un-reachable after its movement.

HSet(x) is the help set of x which we define as the set of its direct neighbors which will move to balance the degree of the reachability imbalanced by the movement of x.

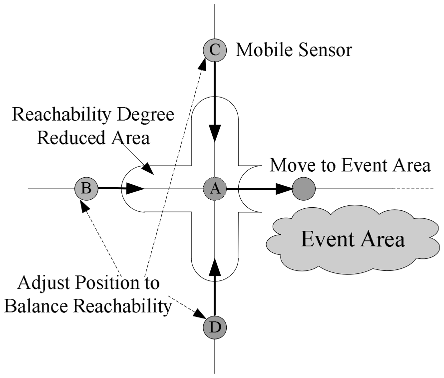

Figure 3. Reposition to balance reachability

6.1. DRA principle

Due to lack of global information, such as cable deployment and the position information of other mobile sensors, each mobile sensor plans its movement only based on the movement of its direct neighbors. The goal of DRA is to balance the degree of the reachability among the whole network through only the local decision of each mobile sensor. To achieve this, we define a utility function $U(x)$ to evaluate the contribution of a movement. The physical meaning of $U(x)$ is the potential gain in the degree of reachability if x moves a segment of distance.

$$U(x) = NR(x) - UR(x) \qquad (1)$$

The main idea of DRA can be described as follows: once a mobile sensor x moves away, it informs all its direct neighbors about its movement and the related event information. For each node $v \in DNeighbor(x)$, it decides whether it should move by checking its utility function $U(v)$. If $U(v) > 1$, the reachability gain between the originally reachable area and the newly reachable one is large and then node v move to balance this gap. The same process is repeated until the balance of the reachability is achieved among the network. We call this a movement test.

6.2. DRA protocol

Algorithm 2 gives the detail of the DRA algorithm. On receiving the moving away message from direct neighbor, mobile node will do the movement test to decide whether it should move or not. If it has multiple directions, the one with the largest $U(x)$ is selected. On receiving position update message from other nodes belong to the same *HSet* (v'), mobile node will coordinate with them about the strategy of their movement. We need define two types of message, $MM(x)$ and $UM(x)$, which is the moving away message and the position update message from node x respectively.

Algorithm 2. DRA

```
For each mobile node $x$
On receiving $MM(v)$, $v \in DNeighbor(x)$ (maybe multiple $v$)
1.  For each above $v \in DNeighbor(x)$
2.    Checks whether $x$ can pass the movement test
        if moving $n*\Delta$ towards $v$;
3.  Select the direction with the largest $U(x)$ if there
      are multiple direct neighbors pass the movement test,
      suppose it is $v$, moving $n*\Delta$ towards $v'$;
On receiving $UM(y)$ and $x$ is moving towards $v'$ (maybe multiple $y$)
1.  Select the one with largest $RDeg$ in $HSet(v')$ to
      move first, suppose it's $y'$;
2.  If $y'$ pass the movement test
3.    Do
4.      Stop and wait;
5.    Until $y'$ stops or goes out of communication
        range
6.  For all nodes left in $HSet(v')$
7.    Repeat the process from 1-5;
On moving
1.  While passing the movement test and hasn't heard
      from other nodes
2.    If encountering a branch point
3.      Select the direction with the largest $U(x)$,
          suppose it is $v$, moving $n*\Delta$ towards $v'$;
4.    Else
5.      Moving ahead $n*\Delta$;
```

7. Performance evaluation

In this section, we do extensive simulations in a *C*-based simulator to evaluate the performance of our solution for cable based mobile sensor deployment and reposition algorithm. We deploy the cables into grids in the target area. The size of the target area is varied from 500m*550m to 1400m*1550m in different simulations to test the scalability of our approach. Cables are deployed to fully cover the target area. Simulations are configured according to the setting in Table 1. The moving distance l of mobile sensor can be computed by multiplying the delay bound with the moving rate. In our simulation, l is 150m. We examine the performance of CGD and DRA algorithm respectively in the following. The unit for length is meter by default.

Table 1. Simulation configuration

grid size	(150 ± 25)m *(150 ± 25) m
block size	10m *10m
sensing range of a mobile sensor	100m
delay bound	30s
moving velocity of mobile sensors	5m
communication range	300m

7.1. Node deployment

Figure 4 compares the number of mobile nodes needed by CGD with the number needed by the random algorithm. In the random algorithm, positions for sensor deployment are randomly selected from candidate set after discretization until the desired reachability is satisfied. We calculate the ratio between the two algorithms under different sizes of target areas and reachability degrees. The desired reachability is ranged from 1 to 4. Both of them run 100 times. With the increase of target area, the number of nodes needed by both CGD and random algorithm increase linearly. However, it is shown apparently in the figure that the random algorithm needs about twice of what CGD needed. CGD selects positions with large sensing area with preference. However, it is shown apparently in the figure that the random algorithm needs about twice of what CGD needed Figure 5 illustrates the nodes needed in each round (totally 100 times) on a 1400*1400 area with desired reachability degree of 2. The curve of random algorithm fluctuates intensively, with the max value as much as 3 times of the min value. But the curve of CGD has consistent value around 11 with small fluctuation.

7.2. Reposition

In the repositioning phase, mobile sensors adjust their positions according to DRA to balance the reachability of the area.

Figure 6 shows the CDF of obtained reachability degree under different settings of the step length when degree in most of the area is 2, which indicates that the performance of DRA has little dependence on the step length. Figure 7 illustrates the CDF of the obtained reachability degree under different numbers of events. As the number of events increases, the area with the ideal reachability degree is set to be 2. The unit of the step length is the times of the side of each block. From this figure we find there is small difference for different step lengths, and the obtained reachability reachability degree of 1 is increased and that of larger than 2 is decreased since more mobile nodes move to catch event. However, this reduction is small due to the balance introduced by DRA. Figure 8 shows the CDF of attained reachability degree of various event sizes. The unit of the event size is the multiples of the block size. Similar to Figure 6 and 7, the attained reachability degree of most area is 2. As illustrated in these figures, only about 10% of the target area gets reachability degree lower than the desired one.

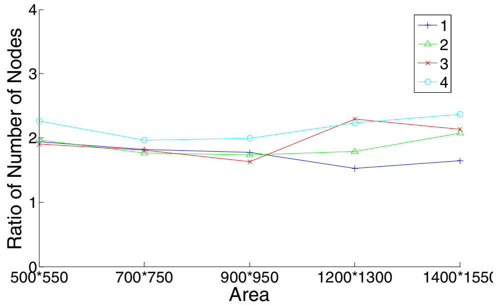

Figure 4. Ratio of mobile nodes needed by CGD compared with random algorithm

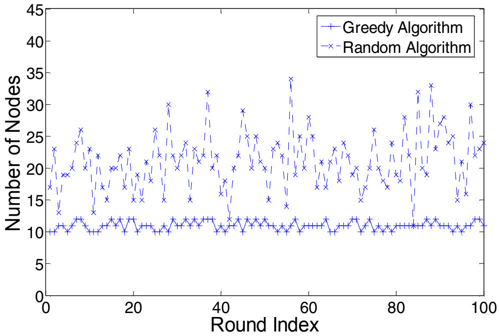

Figure 5. The required number of nodes in 100 round

8. Conclusion

In this paper, we consider deploying mobile sensors along the cables to assist the coverage of environment surveillance. Under the given delay bound, we propose to achieve *k*-reachability for the sensing field with minimum number of mobile sensors. As shown in this paper that this KRMMS problem is NP-hard. Accordingly we propose a heuristic greedy algorithm for sensor deployment and further a repositioning algorithm to balance the reachability over the area. Our simulation shows that the proposed CGD and DRA algorithms outperform the randomized algorithms and

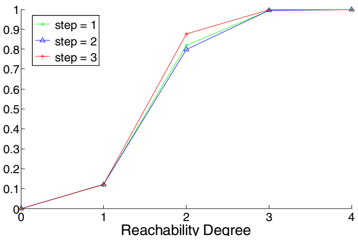

Figure 6. CDF of attained reachability with varying step length

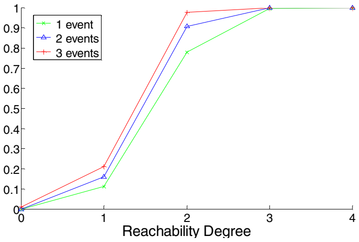

Figure 7. CDF of attained reachability with varying event number

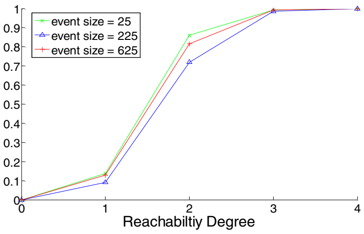

Figure 8. CDF of attained reachability with varying event

achieve high efficiency in terms of the required number of sensors and the balance of the reachability.

A possible future research is to consider the complexity of the monitored events which diffuse spatially and temporally. Under the event diffusion, the information entropy over the monitored area might become uneven. In order to get the accurate information of event, we might need schedule mobile sensors such that their distribution is consistent with the information entropy distribution of events instead of simply the reachability of the field. The problem will become yet more challenging especially when the number of mobile sensors is not adequate.

9. Ackownledgement

This work is supported by the National Basic Research Program of China (Grant No.2006CB303000) and China 863 project (Grant No. 2007AA01Z408)

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