A Novel Approach for *k*-Coverage Rate Evaluation and Re-deployment in Wireless Sensor Networks

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Coverage problem is a fundamental issue in wireless sensor networks. In this paper, we consider two sub-problems: *k*-coverage rate evaluation and *k*-coverage rate deployment. The former aims to evaluate the ratio of *k*-covered area relative to the monitored area, while the latter aims to determine the minimum number of sensors required and their locations to guarantee that *k*-coverage rate of the monitored area meets application requirements. For *k*-coverage rate evaluation problem, a non-uniform-grid- based approach for random deployments is proposed. For *k*-coverage rate deployment problem, a greedy-based approach is suggested to meet the requirement of *k*-coverage rate. Simulation results show that both our schemes are more time efficient than previous work.

Index Terms—Coverage problem, coverage rate, grid scan, wireless sensor networks

I. INTRODUCTION

Coverage is one of the most important issues in wireless sensor networks (WSNs), which is concerned with how well a specified area is monitored by sensors [1]-[8]. Degree of coverage is often used as a measurement of the Quality of Service of WSNs. There are two critical sub-problems in coverage issue: coverage determination (or coverage evaluation) and deployment. The former aims to evaluate the degree of coverage, while the latter aims to determine the minimum number of sensors required and their locations to guarantee that the degree of coverage of monitored area meets application requirements.

Coverage level may be the most popular metric of degree of coverage. An area is called to have coverage level *k*, or *k*-covered if every point in the area is within sensing radius' of *k*-distinct sensors. Due to limited lifetime of sensors and infeasible to replace batteries on tens of thousands of sensors, numerous applications require $k > 1$ for reducing the influence of sensor failure [7][8]. Coverage rate is another important metric, which is the ratio of the area achieving the coverage requirement of target application relative to the whole monitored area. If the coverage rate falls below application requirement, WSNs may not function normally.

A large number of studies have considered coverage level. In coverage evaluation, *k*-coverage evaluation problem which aims to evaluate whether the monitored area is *k*-covered has been widely studied [2][7][8]. In deployment problem, *k*-coverage deployment which aims to determine the minimum number of sensors required and their locations to guarantee that monitored area are *k*-covered is also important [1][3][4].

In this paper, we consider both coverage level and coverage rate. We investigate two problems: *k*-coverage rate evaluation and *k*-coverage rate deployment. *k*-coverage rate evaluation and *k*-coverage rate deployment are generalizations of *k*-coverage evaluation and *k*-coverage deployment, respectively. The former aims to determine the ratio of *k*-covered area relative to the whole monitored area, while the latter aims to determine the minimum number of sensors required and their locations to guarantee that *k*-coverage rate of the monitored area meets application requirements. Clearly, *k*-coverage rate of given area provides more certain, more precise information of coverage than *k*-coverage.

In [5], a *k*-coverage rate evaluation scheme, called Grid Scan, is proposed. The main idea is to divide the monitored area into uniform-sized grids. Then *k*-coverage rate of the monitored area can be obtained by evaluating whether grids are *k*-covered. There a grid is evaluated as "*k*-covered" if the grid's center is *k*-covered. Besides, a Grid Scan-based scheme for *k*-coverage rate deployment is also introduced in [5]. In this scheme, sensors are iteratively deployed at centers of grids to maximize the number of "*k*-covered" grids. The main drawback of Grid Scan is its high computation cost. Clearly, the computation cost of Grid Scan is directly proportional to the number of grids. However, in order to minimize the evaluation error, grid size should be sufficiently small, which leads to huge number of grids. To make matters worse, the drawback is propagated to the Grid Scan-based *k*-coverage deployment scheme.

This paper makes two main contributions. For *k*-coverage rate evaluation problem, a non-uniform-grid-based approach for random deployments is proposed. In our scheme, each grid is further divided into sub-grids if the division benefits *k*-coverage rate evaluation. Based on our *k*-coverage rate evaluation scheme, a greedy *k*-coverage rate deployment scheme is suggested. Besides, two approximation algorithms are provided. Notice that our scheme is not only for grid deployments. In fact, there is no additional restriction on sensor locations in our scheme. The computation costs of our *k*-coverage rate deployment scheme and two approximation algorithms are shown to be much less than Grid Scan-based deployment. Simulation results show that our approximation algorithms provide almost the same coverage rate increment and require extremely less time as compared to Grid Scan-based deployment.

The rest of this paper is organized as follows. Some necessary and important assumptions and notations are introduced in Section II. A *k*-coverage rate evaluation scheme is proposed in Section III, a greedy *k*-coverage rate deployment scheme is suggested in Section IV, and the simulation results are shown in Section V. Finally, we conclude this paper with some remarks in Section VI.

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II. PRELIMINARIES

In this section, some important assumptions and notations are introduced. Throughout this paper, sensors are assumed to have ideal sensing ranges (i.e., circles) and the same sensing radius (denoted by r) and to be static after deployment. Besides, sensors are aware of their own location and should report their location information to base station. By the aid of location information of sensors, evaluating k-coverage rate of the monitored area and figuring out the location for deploying sensor are performed by base station.

Besides, we have the following definition. An area A' is called to be *fully covered* by a sensor s if each point in A' is covered by s. And A' is called to be *partially covered* by s if some points in A' are covered by s and some are not. If A' is not fully covered or partially covered by any sensor, then A' is *uncovered*. For simplicity, an area fully covered by exactly n distinct sensors is called to be *exactly n-fully covered* (*n-fully covered* for short), and an area partially covered by exactly n distinct sensors is called to be *exactly n-partially covered* (*n-partially covered* for short). An illustrative example is shown in Fig. 1. Three circles denote the sensing ranges of three sensors s_1, s_2 and s_3. Clearly, grid g_5 is fully covered by sensors s_2 and s_3 and partially covered by sensor s_1.

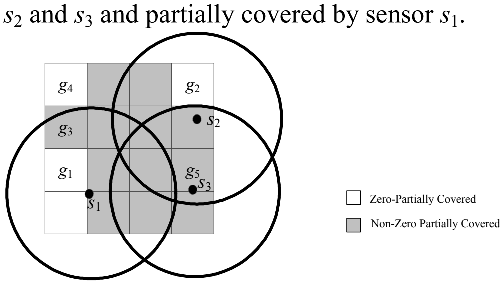

Fig. 1 An example of fully covered, partially covered, and uncovered grids. Each grid has side length $r/2$.

III. K-COVERAGE RATE EVALUATION SCHEME (K-CRE)

This section is devoted to evaluating k-coverage rate of monitored area. Monitored area is divided into non-uniform-sized grids. By coverage information of grids (i.e., grids are fully covered, or partially covered), k-coverage rate of monitored area can be evaluated.

Clearly, when a grid g is fully covered by sensor s, one hundred percent of g is covered by s. However, when g is partially covered by s, evaluating what percentage of g is covered by s requires complex computation. The matter goes worse as grids are partially covered by more than one sensor. In order to obtain more precise coverage rate, grids are further divided into sub-grids. Obviously, dividing those grids which are zero-partially covered does not bring any benefit to coverage rate evaluation. Consider grid g_1 in Fig. 1. Grid g_1 is one-fully covered and zero-partially covered. When g_1 is further divided into four sub-grids a, b, c, and d as shown in Fig. 2, no further information about coverage rate is obtained. In fact, no matter how many sub-grids which g_1 is divided into, the situation cannot be improved. Besides, for k-coverage rate evaluation, grids which are fully covered by at least k sensors do not need any more division. Hence, division is performed on those grids which are partially covered by at least one sensor and fully covered by less than k distinct sensors. Since the coverage situations of these grids are uncertain, they are called *uncertain grids* in the rest of this paper. Refer to Fig. 1 again. Assume 2-coverage rate evaluation problem is considered, i.e., $k = 2$. Only uncertain grids are divided into sub-grids as shown in Fig. 3.

Definition 1: A grid g is called an uncertain grid for k-coverage rate evaluation, if the following two conditions hold.

1. g is partially covered by some sensors.
2. g is fully covered by less than k distinct sensors.

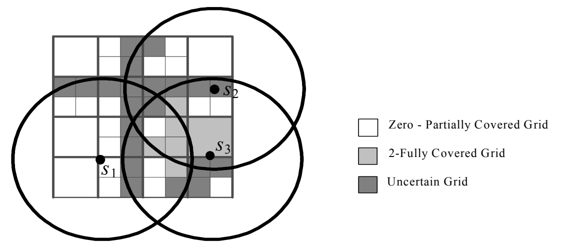

Fig. 2 An example of each grid with side length $r/4$.

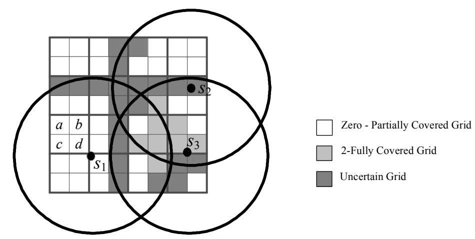

Fig. 3 An example of non-uniform-sized grids.

After an uncertain grid is divided into sub-grids, for the purpose of k-coverage rate evaluation, we try to acquire coverage information of each sub-grid, i.e., how many sensors fully cover or partially cover it. The detail of acquiring coverage information of each grid is depicted below. A grid is fully covered by a sensor if four corners of the grid are covered by the sensor. A grid is uncovered if (1) for each sensor, the distance from each corner of the grid to the sensor is larger than sensing radius of the sensor; and (2) the distance from the center of the grid to the sensor is larger than the summation of sensing radius of sensor and half the side length of the grid. And a grid is partially covered by a sensor if some corners of the grid are covered by the sensor and some are not. That is, there exist two corners, c_1 and c_2, of the grid such that the distance between c_1 (c_2) and sensor is larger (smaller) than the sensing radius of the sensor.

Sometimes grid division is of little worth even if more coverage information is obtained from the new generated sub-grids. In order to acquire more coverage information, a grid is further divided into many sub-grids. However, the contribution of coverage information of these sub-grids is barely on coverage rate evaluation because these sub-grids are so tiny. Here, a criterion for terminating division is introduced. Define *maximum evaluation error* (*MEE*) to be the ratio of uncertainly covered area relative to whole monitored area, i.e., $MEE = \sum_{g \in U} |g| / |A|$, where U denotes the set of uncertain grids, and $|g|$ and $|A|$ denote the area size of g and A, respectively. Also define *maximum tolerable evaluation error*

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(*MTEE*) to be the maximum evaluation error that is permitted for target application.

Our k-coverage rate evaluation (k-CRE) scheme is described below. Initially, the monitored area is divided into equal grids. When coverage information of each grid is obtained, the maximum evaluation error is also available. If maximum evaluation error is higher than maximum tolerable evaluation error, further grid division is needed. Otherwise, return k-coverage rate. The k-coverage rate of monitored area is evaluated as follows:

$$k\text{-coverage rate} \cong \sum_{g\in K} |g| / |A|,$$

where K denotes the set of grids fully covered by at least k distinct sensors.

Consider previous scheme proposed in [5], i.e., Grid Scan. In Grid Scan, all grids are divided into four sub-grids regardless of whether it is an uncertain grid or not. Simulation results show that the number of grids in Grid Scan is at least 10 times the number of grids in k-CRE. And the execution time of Grid Scan is at least 5 times of our protocol for $1 \leqq k \leqq 4$.

IV. *K*-COVERAGE RATE DEPLOYMENT SCHEME (*K*-CRD)

After evaluating k-coverage rate of monitored area, a k-coverage rate deployment scheme is performed to improve the k-coverage rate if the required k-coverage rate is not achieved and there are additional sensors for deployment. The basic idea of our scheme is to increase the total area of k-fully covered grids. Besides, our scheme works iteratively, i.e., one location for deployment is determined at each iteration.

Consider a sensor s is deployed to fully cover a specific grid g. Then, the region that s can be located in to satisfy the criterion is called the *deployment region* with respect to g ($DR(g)$). An example of deployment region with respect to g is shown in Fig. 4. There hollow circles denote the sensing ranges of s when s is deployed at the solid gray circles. The region enclosed by a dashed line denotes $DR(g)$. Obviously, the shape of the deployment region is not a simple geometric shape. For simplicity, in the rest of this paper, $DR(g)$ is simplified to be the maximal circle enclosed by the original deployment region. Since the sensing range of each sensor is assumed to be a circle, it is not difficult to check that $DR(g)$ is the circle of radius $r-\sqrt{2}l/2$ centered at the center of g, where l is the side length of g. An example is shown in Fig. 5.

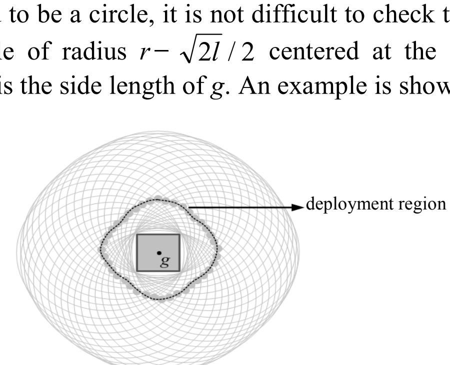

Fig. 4 The original deployment region with respect to grid g.

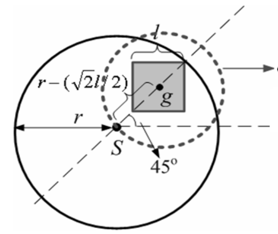

Fig. 5 The dashed circle is a simplified deployment region with respect to grid g.

Notice that points on the periphery of $DR(g)$ also belong to $DR(g)$. That is, if s is deployed at a point on the periphery of $DR(g)$, then s can fully cover g, also. For example, in Fig. 6, if s is located at points a or d, s can fully cover both g_2 and g_3.

Suppose that $m^* = \max\{m \mid$ there exists some grid g is m-fully covered and $m < k\}$. Obviously, deploying sensors to fully cover those m^*-fully covered grids improves k-coverage rate efficiently. Define a *candidate grid* to be an m^*-fully covered grid. On the other hand, deploying sensors to fully cover grids with large area is also an efficient way. Define *grid-weight* of grid g ($GW(g)$) to be $|g|$ if g is a candidate grid and 0 otherwise. And let the *coverage-weight* of each point p ($CW(p)$) located in the intersection of DR(g_i)s be the summation of GW(g_i)s. Refer to Fig. 6, coverage-weight of points b, c, and e are the same, i.e., GW(g_1)+GW(g_3)+GW(g_4), and coverage-weight of points a or d is GW(g_2)+GW(g_3). Intuitively, s should be deployed at a point with highest coverage-weight.

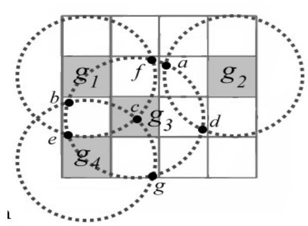

Fig. 6 Intersection of deployment regions.

For a candidate grid g, define *Fit with respect to g* (*Fit*(g)) to be a specific point in DR(g) having highest coverage-weight among all points in DR(g). If there is no other candidate grid whose deployment region intersects with DR(g), then an arbitrary point in DR(g) can be chosen as Fit(g). Otherwise, Fit(g) can be chosen from those intersection points of peripheries of deployment regions. Consider grid g_1 in Fig. 6. Points b, c, e and f are intersection points of peripheries of deployment regions. Since each of points b, c, and e has highest coverage-weight among the four intersection points, it is not difficult to see that one of b, c, and e can be chosen as Fit(g_1). Also define a *best_fit* to be a Fit with highest coverage-weight among all Fits with respect to candidate grids. Clearly, deploying s at a best_fit is an efficient solution. So, the main idea of our k-coverage rate deployment scheme, named k-CRD1, is to deploy ($k-m^*$) sensors at a best_fit and repeat the process until the k-coverage rate requirement is achieved.

A. ***k-CRD1***

Recall that a best_fit is a Fit with highest coverage-weight among all Fits. Obviously, determining such a Fit results in high computation cost in the above scheme. In order

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to reduce computation cost, in k-CRD1, Fits with respect to lower-grid-weight grids are not determined. The main idea is based on the observation that there is a high possibility that a best-fit is a Fit with respect to a higher-grid-weight grid. Let C_α denote the set of first α candidate grids, sorted by grid-weight, where α is a constant. In k-CRD1, a Fit whose coverage-weight is highest among those Fits with respect to grids in C_α is chosen as an approximate best_fit. An example of k-CRD1 with k = 4 and α = 3 is illustrated in Fig. 7. Dotted circles denote deployment regions with respect to candidate grids (i.e., 3-fully covered grids). The first α candidate grids (and their deployment regions) are at the left-up, right-up, and left-down corner, respectively. Clearly, Fits with respect to grids at left-up, right-up, and left-down corner are in I_1, I_2, I_3, respectively. And the Fit with respect to the grid at left-down corner has the highest weight. So, we deploy a sensor in Fit with respect to grid at left-down corner.

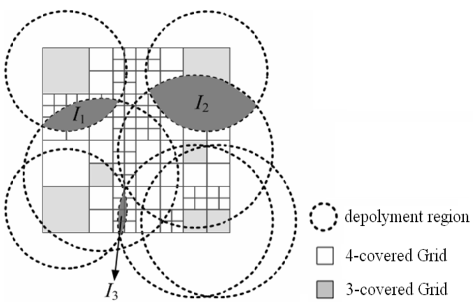


Fig. 7 The first three candidate grids are at left-up, right-up, and left-down corner.

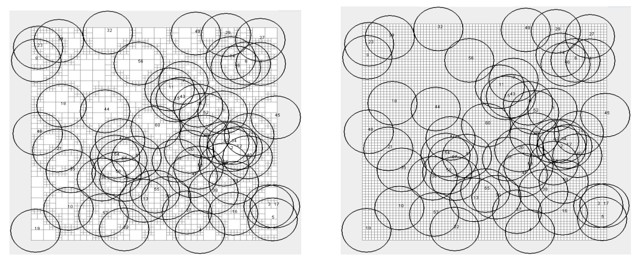
V. SIMULATION RESULT

A simulator is implemented in Java language to evaluate the performance of our schemes. All simulations are executed on personal computer with Intel Core 2 Duo E6400 2.13G/2M, 1 GB RAM, and WindowsXP operation system. There are two major experiments: the first concerns k-coverage rate evaluation and the second concerns k-coverage rate deployment. The assumptions for these two experiments are summarized as follows. Pre-deployed sensors are randomly and uniformly deployed in a 100 m×100 m monitored area. The sensing radius of each sensor is 10 m. For simplicity, network channel is assumed to be error-free and collision-free. All algorithms are executed in base station, so some other issues such as MAC layer protocol and routing overhead are all ignored in our simulator. Each experiment is repeated 20 times with distinct sensor pre-deployments. Besides, the experiment results of our scheme are compared with Grid Scan scheme [5].

A. *Simulation result of k-coverage rate evaluation*

Clearly, in k-coverage rate evaluation experiment, the number of grids is a basic metric for computation cost estimation. The number of grids by our scheme is compared with Grid Scan for different number of pre-deployed sensors (n), maximum tolerable evaluation error (MTEE), and values of k.

According to the experiment results, much less grids are needed in k-CRE scheme than Grid Scan under the same number of pre-deployed sensors, maximum tolerable evaluation error, and value of k. A typical example is shown in Fig. 8. Fig. 8(a) and Fig. 8(b) show grid division for our scheme and Grid Scan, respectively, under MTTE = 0.1, k = 4, and n=60.



(a) (b)

Fig. 8 Grid division for k = 4. (a) k-CRE Scheme, (b) Grid Scan.

Effect of maximum tolerable evaluation error on number of grids. Fig. 9 shows that the difference in the number of grids between k-CRE and Grid Scan increases with maximum tolerable evaluation error decreasing for k = 1. The bars represent the means of experiment results and the red blocks on the tops of bars represent the 95% confidence intervals on the mean surrounding them. Notice that the numbers of grids for n = 90 is the smallest no matter which scheme is considered and which value MTEE is. This is because most part of area are 1-fully covered when n = 90. That is, few grid divisions are required. Besides, in Grid Scan, both the number of grids for n = 30 and n = 60 are the same no matter which value MTEE is. This is because the smallest grid sizes in these cases are the same.

Effect of *k* on number of grids. Fig. 10, Fig. 11 and Fig. 12 show the number of grids of k-CRE and Grid Scan for k = 2, 3 and 4, respectively. According to experiment results, the numbers of grids of these two schemes increase with k increasing. And no matter which value k is, the number of grids in Grid Scan is at least 10 times the number of grids in k-CRE.

According to our simulations, we found that the number of grids is largest when k-coverage rate is between 50% and 65%. This is because there are less uncertain grids when k-coverage rate is higher than 65% or lower than 50%. In Fig. 10, the number of grids of k-CRE scheme for n = 60 is greater than n = 90. This is because 2-coverage rate is about 70% for n = 90 but 60% for n = 60. In Fig. 11 and Fig. 12, the number of grids of k-CRE scheme for n = 60 is smaller than n = 90 because the 3-coverage rate and 4-coverage rate are less than 50% for n = 60.

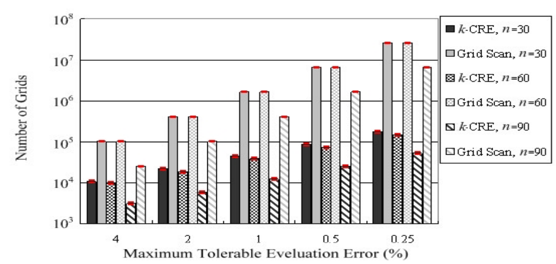


Fig. 9 Number of grids versus MTEE for k = 1.

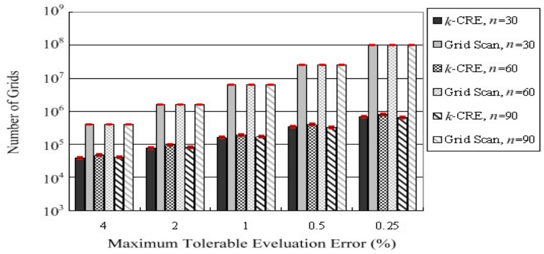


Fig. 10 Number of grids versus MTEE for k = 2.

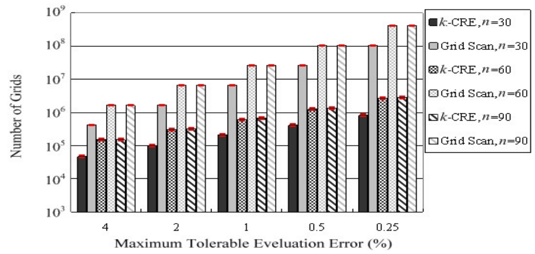


Fig. 11 Number of grids versus MTEE for k = 3.

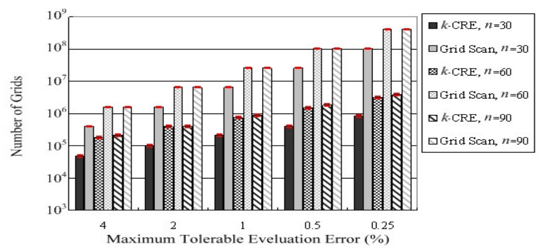


Fig. 12 Number of grids versus MTEE for k = 4.

B. *Simulation result of k-coverage rate deployment*

In k-coverage rate deployment experiments, coverage rate increment and execution time are two metrics for judging performance. Similarly, experiments are performed with 60 pre-deployed sensors, k = 1, and several values of maximum tolerable evaluation error. First, we consider the case that there is only one sensor for deployment. Table I shows that k-CRD1 provides almost the same coverage rate increment and take much less execution time as compared to Grid Scan-based deployment. This is because only probable deployment regions are considered in k-CRD scheme instead of checking all grids in the monitored area. It is also observed that when MTEE is small, Grid Scan-based deployment takes too much time to figure out the location for deploying sensors. For example, when MTEE = 0.5%, Grid Scan-based deployment takes more than 100 days, k-CRD1 takes about one hour.

TABLE I
MAXIMUM TOLERABLE EVALUATION ERROR, COVERAGE RATE INCREMENT, AND EXECUTION TIME

MTEE (%)	Coverage Rate Increment (%)		Execution Time (sec.)	
	k-CRD1	Grid Scan	*k*-CRD1	Grid Scan
4	2.56	2.68	13.6	2985
2	2.69	2.79	92	36519
1	2.74	2.83	598	589407
0.5	2.78	< 2.87	3698	>100 days

Execution time of *k*-CRE and Grid Scan. Fig. 13 shows the execution time of k-CRE and Grid Scan for MTEE = 0.25% and n = 90. The execution time of Grid Scan is at least 5 times of our protocol for $1 \leqq k \leqq 4$.

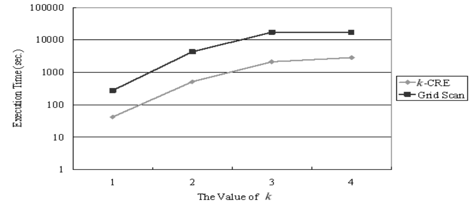


Fig. 13 Execution time versus value of k for n = 90 and MTEE = 0.25%.

VI. CONCLUSION

In this paper, a k-coverage rate evaluation scheme and a k-coverage rate deployment scheme are proposed. In our k-coverage rate evaluation scheme, the monitored area is divided into non-uniformed grids. Each grid is further divided into sub-grids if more coverage information can be obtained from these sub-grids. By the aid of coverage information of grids, an evaluation of k-coverage rate of the monitored area is available. On the other hand, in order to avoid dividing many grids for acquiring little coverage information, another criterion, called maximum tolerable evaluation error, for terminating grid division is also introduced. Based on our k-coverage rate evaluation scheme, a deployment-region-based k-coverage rate deployment scheme is suggested. Besides, two approximation algorithms achieving efficient computational time are also provided. From the simulation results, computation time of both our k-coverage rate evaluation scheme and k-coverage rate deployment scheme are efficiently reduced.

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