Grid Scan: A Simple and Effective Approach for Coverage Issue in Wireless Sensor Networks

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***Abstract*— This paper describes a basic coverage issue, and proposes a scheme named Grid Scan which is applied to calculate the basic coverage rate with arbitrary sensing radius of each node. Based on Grid Scan, re-deployment approach is suggested to meet any k-covered rate in some region according to application requirements. The objective of our re-deployment is to get equivalent coverage rate using less number of sensor nodes or to achieve higher coverage rate with the same number of sensor nodes. The results of simulation experiments support that Grid Scan based re-deployment is more effective to cover monitored area than random spread.**

I. Introduction

Recent technological advances in low-power micro sensors, actuators, embedded processors, have brought distributed wireless sensor networks (WSNs) to a wide range of applications such as battlefield surveillance and nuclear monitoring etc. The technologies related to WSNs have been one of the dominant research trends and the subject of numerous studies in the last few years. WSNs represent a significant difference from traditional sensors, which impose diverse challenges on researchers and developers due to its wireless nature, high node density, limited resources, low reliability of the nodes, distributed architecture and frequent mobility [1] [2]. With those characteristics, energy consideration, reliability design and application-driven localization or tracking have dominated most of the researches in WSNs, which have been dedicated to sensor networks [3] [4] [5].

Since sensor nodes are often spread in a random manner, coverage issue, which is one of the fundamental problems, should be studied deeply in addition to location calculation, target tracking,and time synchronization in WSNs. The basic coverage issue reflects how well the sensors observe the physical space, and usually is one of the measurements of the Quality of Service of WSNs. Under the assumption that the topology architecture of WSNs does not change, a number of coverage algorithms have been proposed for coverage models and energy consumption according to the initial task assignment and requirements [6] [7] [8].

However, work targeted at k-covered rate calculation and re-deployment based on coverage rate is scarcely done. It is highly necessary to re-deploy nodes to non-coverage area to enable WSNs work effectively. The motivation of the coverage is to guarantee that the monitored area be detected by the networks. For example, when WSNs are applied to fire detection, one may ask how well WSNs can observe the target area and what the chances are that a fire starting in a specific location will be detected in a given time.

In this paper, we consider a more general sensor coverage issue. Given a set of sensor nodes randomly deployed into a two-dimension area, we propose a simple scheme named Grid Scan to calculate k-covered rate for arbitrary sensing radius. The true coverage area can be estimated when grid size is smaller enough. An effective Grid Scan based re-deployment approach is put forward. The basic goal of this approach is to provide a better coverage with less nodes. The sensor nodes will be re-deployed into a maximum blind region of sensing, which can improve overall coverage rate rapidly.

The remainder of this paper is organized as follows. In section 2, related work will be summarized in brief. We will introduce our Grid Scan scheme and Grid Scan based re-deployment approach in detail in section 3. Section 4 gives simulation experiments and evaluation results. Finally, we make some concluding remarks and discuss some future work.

II. Related Work

Coverage issue is one of the key point of WSNs. If the coverage rate falls below some predefined value in some case, WSNs may no longer function normally. Furthermore, coverage schemes should be energy-efficient because of unattended sensor nodes.

The difficulty in this issue is to fully cover the monitored area with the least number of sensor nodes. It can also be stated as developing a sensor distribution algorithm to make the blind area the least or to minimize the overlapped sensing area of sensor nodes. There exists a close relationship between the static coverage and the art gallery problem (AGP), which is about how to determine the minimum number of guards required to cover the interior of an art gallery. Introducing the AGP to the sensor coverage, the algorithm can be solved optimally in two-dimensional area while shown to be NP-hard in the three-dimensional space. However, accurate coverage solutions can only be used in regular small monitoring area. To address this problem, local optimal schemes are presented to solve coverage issue in large irregular areas. A linear programming approach was induced in [9] [10], and a least active node set for full coverage is suggested.

On the exposure-based coverage problem, an optimal polynomial time worst and best case algorithm for coverage calculation is established by combining the Voronoi diagram with the graph search algorithms [7]. An algorithm is proposed to find the shortest exposure path in [11]. Under the assumption that each sensor node have equal distance to its neighbor nodes, Slijepcevic presented a heuristic coverage scheme [12]. Virtual force algorithm (VFA) was also introduced into sensor coverage problem [13]. Each sensor behaves as a source of force for all other sensors. This force can be either positive (attractive) or negative (repulsive) according to the distance between each other. It is found that this method can fully cover the monitored area.

A polynomial-time algorithm is presented in terms of the number of sensors to determine whether every point in the service area of sensor networks is covered by at least k sensors, where k is a predefined value [6]. With this algorithm, WSNs work well in situations that require stronger environmental monitoring and impose more stringent fault-tolerant capability.

III. Grid Scan Scheme

A. Problem Statement

In our scheme, a set of sensor nodes $S = \{s_1, s_2, \ldots, s_n\}$ are given to spread into a two-dimensional rectangle area $\mathcal{A}$ with two sides lL,lR. It is static that once the senor nodes are deployed and each sensor node can be self-located or located in the area $\mathcal{A}$ with a coordinate (x, y). The sensing range of a node s_i is defined as a circle with the center of node s_i and the radius r_i.

Define $\mathcal{A}_{s_i}$ as the area covered by s_i. The area $\mathcal{A}$ is divided into $L \times R$ same square grids with side l. Center point of grid $g_{(a,b)}$ has coordinate (a_g, b_g).

Definition 1 A grid $g_{(a,b)}$ in $\mathcal{A}$ is said to be covered by sensor s_i, if the distance d_{ig} between s_i and the center point of this square grid is less than or equal to r_i.

$$g_{(a,b)} \in \mathcal{A}_{s_i} \Leftrightarrow d_{ig} = \sqrt{(x_i - a_g)^2 + (x_j - b_g)^2} \leq r_i \quad (1)$$

A n-sequence $\mu_{g_{(a,b)}}$=$(\mu^1_{g_{(a,b)}}, \mu^2_{g_{(a,b)}}, \ldots, \mu^n_{g_{(a,b)}})$ takes records if the grid $g_{(a,b)}$ is covered by sensors in set S. $\mu^1_{g(a,b)} = 1$ means grid $g_{(a,b)}$ is covered by sensor node s_1. $\mu^k_{g_{(a,b)}} = 0$ means grid $g_{(a,b)}$ is out of sensing range of sensor node s_k.

Definition 2 A grid $g_{(a,b)}$ in $\mathcal{A}$ is said to be k-covered, if the distance between the center point of square grid and any k sensor nodes in S is less than or equal to corresponding radius.

$$\begin{gathered} g_{(a,b)} \in \cap\{\mathcal{A}_{s_i}\} \\ \Leftrightarrow d_{ig} \leq r_i, i \in \{j|\mu^j_{g_{(a,b)}} = 1, 1 \leq j \leq n\} \\ s.t \sum_{j=1}^{n} \mu^j_{g_{(a,b)}} = k \end{gathered} \quad (2)$$

Definition 3 Coverage rate is defined as the percentage of coverage, i.e., the ratio of the covered area to the total monitored area.

$$C = \frac{\mathrm{U}\{\mathcal{A}_{s_i}\}}{\mathcal{A}}, i = 1 \ldots n \quad (3)$$

B. Grid Scan Scheme

1) Basic coverage rate calculation: Our scheme named Grid Scan is inspired by APIT which has been proposed for range-free localization [14]. The monitored two-dimension area is divided into small square grids. Sensor nodes are spread randomly into the given area $\mathcal{A}$. Grid Scan scheme scans each grid in the area and easily judges if the grid is in the sensing range of one sensor node according to **Definition 1**. So, k-covered rate can be calculated by Grid Scan scheme quickly .

$$\begin{gathered} C_k = \frac{\sum_{a=1}^{L}\sum_{b=1}^{R} \alpha_{g_{(a,b)}}(k)}{L \times R} \\ s.t. \quad \alpha_{g_{(a,b)}}(k) = \begin{cases} 1 & if \quad \sum_{i=1}^{n} \mu^i_{g_{(a,b)}} = k \\ 0 & otherwise \end{cases} \end{gathered} \quad (4)$$

The total coverage C can be obtained according to Equation.4.

$$C = \sum_{k=1}^{s} C_k \quad (5)$$

There, C_k is obtained from Equation4. Theoretically, Grid Scan scheme can compute k-covered rate with arbitrary sensing radiuses of sensor nodes because the scheme goes through each grid in the given area $\mathcal{A}$. Without loss of generality, each sensor node has the same sensing radius r. Additionally, the transmission range of sensor nodes is assumed to be at least twice as long as the sensing range, so coverage can imply connectivity [15].

The error in Grid Scan scheme is mainly caused by the granularity of grid size because we only consider center point coverage of grid instead of whole grid area. If grid is smaller enough or $(L \times R)$ larger enough, C_k will get a value, which approaches the actual k-covered rate.

Grid Scan can dynamically obtain the coverage of the whole monitoring are degree distribution, but has a cost of $O(n \times L \times R)$.

2) Grid Scan based re-deployment: After initial random sensor nodes deployment, some regions in the network maybe are not covered by any sensor node, which may cause WSNs to perform abnormally with low application performance such as temporary tracking failure in target tracking applications. In these cases, in addition to the basic coverage rate calculation, an incremental re-deployment scheme based on Grid Scan is proposed to get a predefined coverage rate over the whole area.

The proposed scheme is a multi-steps scheme where each step is a greedy exploration process running over all potential re-deployment points. Only one potential point with maximum number (Z) of neighboring non-covered grids in the sensing range of radius r is chosen as the point at which the new-added sensor node will be re-deployed. For simplicity, in our implementation, only the center point of each grid is considered as the potential point. Then, the coverage rate with the new-added sensor node is re-calculated using the basic coverage rate calculating scheme mentioned above. This re-deployment will not stop until coverage rate exceeds a certain expected value or the value of Z falls below a predefined value.

For example, if an incremental re-deployed sensor node s_j has coordinate (x_j, y_j). In region that meets $\sqrt{(x_j - g_a)^2 + (y_j - g_b)^2} \leq r$, we can get Equation.6.

$$Z = \max_{1 \leq x_j \leq L, 1 \leq y_j \leq R} \{ \sum_{d_{jg} \leq r} \alpha_{g_{(a,b)}}(0) \} \quad (6)$$

The coordinate (x_j, y_j) corresponding to Z is the point, onto which we would like to put the sensor node into the area $\mathcal{A}$.

This Grid Scan based re-deployment scheme can be easily extended to the case in which the whole area should be k-covered. The metric we use to choose a re-deployment point can be the sum of the difference between k and current coverage degree of the grids in the sensing range of this point.

Proposed re-deployment scheme is simple and effective and always deploys a new-added sensor node to the biggest blind region based on current coverage distribution. The computing complexity of proposed re-deployment scheme is O($L \times R \times r^2$).

IV. Experiment Evaluation

A. Simulation Environment

In order to evaluate our proposed scheme, we consider the effect of grid size on the performance of Grid Scan and compare Grid Scan based re-deployment scheme with random spread in our simulation experiments.

The simulation is performed based on MATLAB. The issue we address here is sensing coverage, so some other issues such as MAC protocol, routing protocol and location discovery are all ignored in our simulation. Our simulation scenario are set up in a 50×50m^2 area $\mathcal{A}$. Sensor nodes are randomly distributed in the field initially and kept stationary once deployed. In order to simplify the simulation experiment and make this model reasonable, all sensing range of nodes has the same radius r. We only concentrate on the coverage and re-deployment issues in the simulation. The main performance metric is the percentage of coverage.

B. K-Covered Rate Calculation

In this experiment, r=8, grid size is $1 \times 1m^2$. Figure1 shows the coverage rate of random spread in area $\mathcal{A}$. The number of nodes is increased from 10 to 40. The plots in Figure1 are average results with twenty running. It is obvious that total coverage rate is improved with an increase in number of nodes. More and more grids are multi-covered, so 1-covered rate is decreased and ≥ 4-covered rate is increased as the number of nodes is increased. Figure 2 exhibits one case of coverage with random deployment.

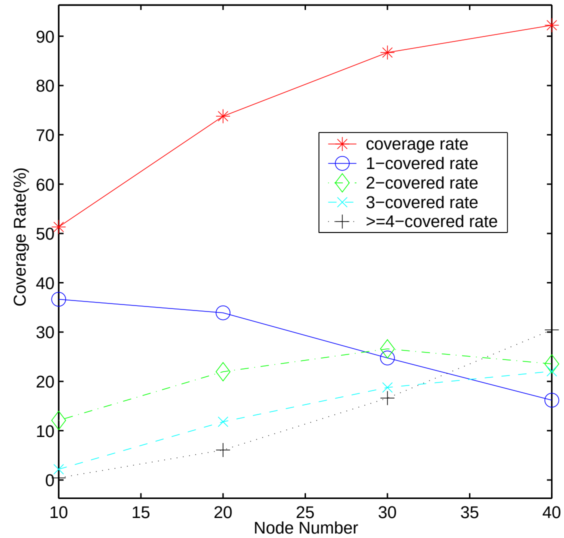

Fig. 1. Basic Coverage Rate Calculation for Random Deployment

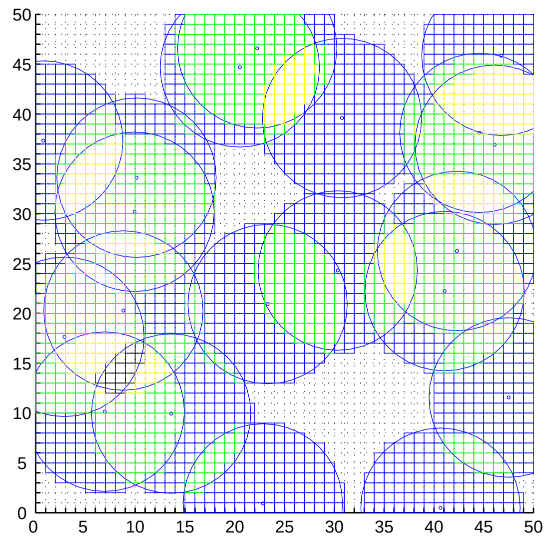

Fig. 2. One Case of Basic Coverage for Random Deployment

C. Effect of Grid Size on Coverage Rate

In Grid Scan scheme, the grid is covered or not related with radius r and distance d between center point of the grid and the senor node. In fact, there are some situations that the center point of grid locates in the sensor ranging but the grid is not fully covered by sensing range, which will cause coverage error according to Grid Scan scheme. If the grid size is small enough, the coverage rate will approach the true result.

So in this subsection, we do some simulation experiments to evaluate the effect of grid size on coverage rate. In the area $\mathcal{A}$, grid side is set $10m$, $5m$, $\frac{5}{2}m$, $\frac{5}{4}m$, $\frac{5}{8}m$, $\frac{5}{16}m$, $\frac{5}{32}m$, $\frac{5}{64}m$ respectively, which means number of grids in $\mathcal{A}$ is 25, 100, 400, 1600, 6400, 25600, 102400, 409600 correspondingly. The number of sensor nodes is 10, experiment repeating times are 50. Define $C(l)$ as the coverage rate function with l. There, the coverage rate error when grid side is $\frac{5}{64}m$ is small enough, so we can take C($\frac{5}{64}$) as an estimate of the true value. Error_square_sum $E = \sum(C(l) - C(\frac{5}{64}))^2$ is a metric of effect.

In Figure3, x-axes is the log of number of grids. In Figure4, the coordinate is the log function of E and the number of nodes respectively. These two figures indicate that E is in inverse proportion to grid size (number of grids) into the area $\mathcal{A}$. It is also explained in these two figures that larger grid size causes more calculate error. In Figure3, it can also be found that when the number of grids exceeds 1600, E decreases significantly while the value is stable when number of grids is larger than 1600.

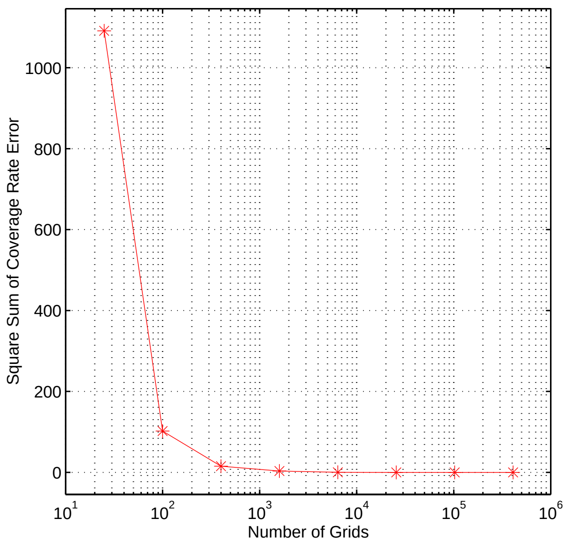

Fig. 3. Log(Number of Grids) *vs.* Error

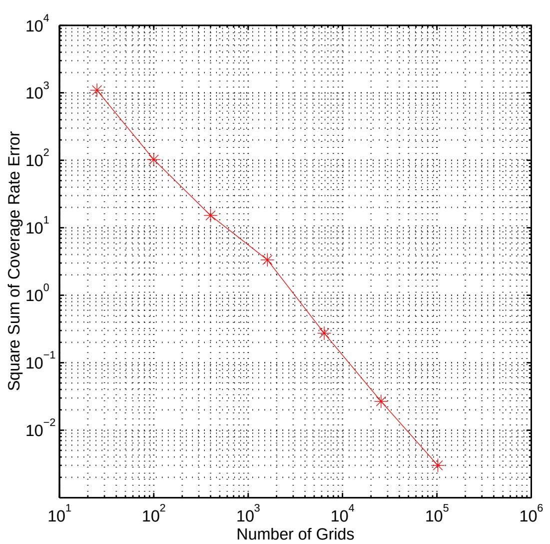

Fig. 4. Log(Number of Grids) *vs.* Log(Error)

D. Re-Deployment Scheme with Grid Scan vs. Random Deployment

Based on the data in Figure2 of above simulation experiment, our re-deployment is effective and quick to find the point to deploy new-added nodes, which is shown as in Figure5.

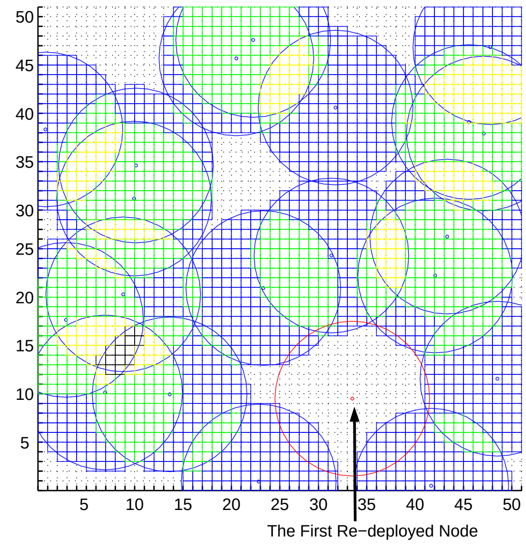

Fig. 5. A Case of Re-Deployment Based on Grid Scan

In order to bear out validity of our scheme, we design an experiment with parameters r=8, n=5,10,15,20. Random distributed manner is used to spread $\lfloor \frac{n}{2} \rfloor$ nodes firstly in our design, then uses grid scan based re-deployment scheme. Figure6 and Figure7 adopt n and coverage-rate as the stop condition of re-deployment respectively. When the number of deployed node is up to n or coverage rate exceeds the value that got by random spread, re-deployment will be stopped.

In Figure6, our re-deployment improves the maximum percentage 26.276% at n=15 to achieve an effective coverage. In Figure7, around sixteen sensor nodes can be saved by Grid San based re-deployment when coverage rate arrives at 93.296%. Therefore, we can draw a conclusion that Grid Scan based re-deployment scheme is more effective than random deployment.

V. Conclusion

In this paper, we proposed Grid Scan scheme to calculate a basic k-covered rate and a Grid Scan based re-deployment scheme. The simulation results show that Grid Scan is a simple and effective approach to calculate any k-covered rate with arbitrary radius of sensing range. Grid Scan based re-deployment is more effective to cover monitored area using less number of sensor nodes compared with random spread.

In the future, we plan to develop a distributed Grid Scan scheme and investigate deeply the energy-efficient issue and robustness to irregular radio model of our scheme.

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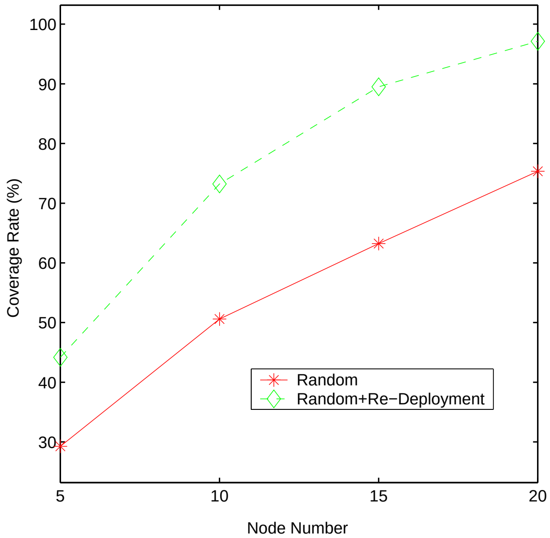

Fig. 6. Coverage Rate Compare with Same Node Number

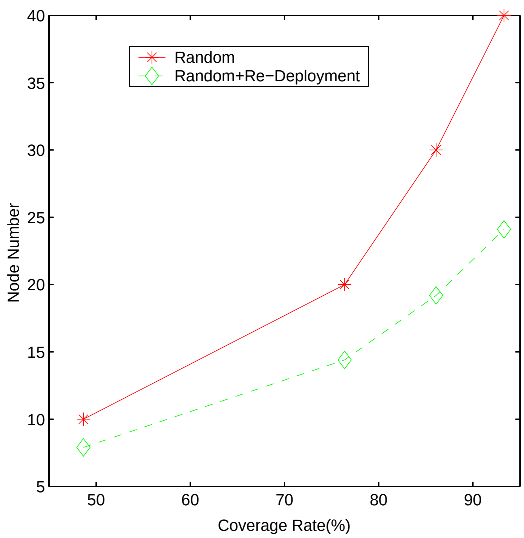

Fig. 7. Node Number Compare Under Coverage Rate Threshold

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