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Deployment Method for Wireless Sensor Networks on Weighted Fields

Wei-Chei Ko, Ying-Chin Chao, and Ming-Jer Tsai
Department of Computer Science
National Tsing Hua University
Hsing Chu, Taiwan, ROC

Abstract: The deployment of sensors on a given field is an important issue that affects wireless sensor networks. Traditionally, all areas of a sensor field are equivalent, and multiple deployment algorithms are used to maximize the area covered by a given number of sensors or a certain budget. However, in many applications, such as fire control system, battlefield surveillance, detection of nuclear, biological, or chemical (NBC) attack, and other things, the areas must be weighted based on priority of deployment: the more critical the area, the higher the weight and the higher the priority. In this paper, we introduce the problem of the weighted field sensor: and determine the maximum weight of the coverage area by deploying a given number of sensors on a given weighted field. Then an algorithm is proposed to find a near-optimal solution for the weighted field sensor covering problem.

Key-Words: Wireless sensor networks, deployment algorithm, coverage problem, preferential coverage, grid covering.

1 Introduction

A wireless sensor network is composed of a number of wireless sensors, each of which monitors specific environmental attributes, records the sensing data, derive environmental conditions by aggregating the sensing data, and returns these aggregated data back to the base station. The rapid development of wireless communications and embedded micro-sensing technologies has facilitated the use of wireless sensor networks in our daily lives; a wide range of applications exist for wireless sensor networks, including fire control systems, environmental monitoring, battlefield surveillance, health care, nuclear, biological, chemical (NBC) attack detection, intruder detection, and so on. Recently, the studies of wireless sensor networks have received considerable attention [7, 8, 9, 11].

The deployment of sensors on a given field is an important issue that affects wireless sensor networks. A deployment algorithm must guarantee connectivity, ensuring that all sensors can communicate with each other. A deployment algorithm must also provide a predetermined coverage level for a given application. The coverage problem is a fundamental issue with wireless sensor networks [1].

Many deployment algorithms address the full coverage problem, assuming that there are many enough sensors to fully cover the given field or the given targets. Heterogeneous sensors – which have a longer range and are more expensive – may be deployed to get full coverage on a given field at a near-minimum cost [3]. Many researchers believe that the most effective means of prolonging the life of wireless sensor networks is by finding an active subset of sensors which fully covers a given field or targets [2, 10]. Then, only the sensors in the active set are responsible for surveillance, while the others enter sleep mode in order to reduce power consumption.

Sometimes, however, sensor fields are large or wide, or the given budget cannot provide enough sensors for full coverage on the sensor field; for example, those needed to deploy intrusion alert sensors at a military installation, or fire detection sensors in a large building. Another example is a wilderness ecological observation network: it would be impossible – not to mention impractical – to create a wireless sensor network that fully covers the wilderness. In some situations, sensors are constrained by limited sensor ranges, and it is difficult to get full coverage on the sensor field except

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when there are a large number of sensors. For example, bomb detection sensors [13] have very limited sensor ranges, and it would be impossible to deploy as many sensors as would be necessary to protect an entire train station, government office or other location against a bomb attack. In [4, 5, 6, 12], the authors want to maximize the coverage area on the field using a limited number of sensors.

In the literature, the proposed deployment algorithms provide coverage levels in which all areas of a field are seen as equivalent. Because this is so, they cannot adequately distinguish between critical areas and common areas. In some daily applications, areas must be weighted based on priority of deployment: the more critical the area, the higher the weight and the higher the priority. For example, "smart home" sensors, such as fire control systems, may give the kitchen a higher priority than other areas in the house. In a military installation, some places might be more susceptible to intrusion, while others have terrain features that strongly favor defense. One place might be used to store weapons, while another might warehouse articles for daily use. It is smarter to give a higher priority to strategic battlefield locations, and a lower priority to others. For the wilderness ecological observation network, it is possible to emphasize the "hot spots" frequented by animals or birds by giving those areas a higher priority. In this paper, we will discuss the problem of weighted field sensor coverage: what is the maximum weight of the coverage area that can be achieved by deploying a given number of sensors on a given weighted field? Then, we propose two polynomial-time algorithms to find near-optimal solutions for the weighted field sensor coverage problem. Preliminaries will be provided in Section 2 of this paper, and the two deployment algorithms are proposed in Section 3. Section 4 will demonstrate a computer simulation to evaluate performance, and Section 5 contains our conclusions.

2 Preliminaries

In this paper, each area is assumed to have a given weight density of weight per square meter, or $W/_{m^2}$. We do not study how to weight each area in a field; this is determined by the designer or an expert in that domain, such as a civil engineer, architect, safety officer, or security system designer. Fig. 1 shows the weighted field of a mass rapid transport station, where we give the barrier and the stair higher weight densities because they

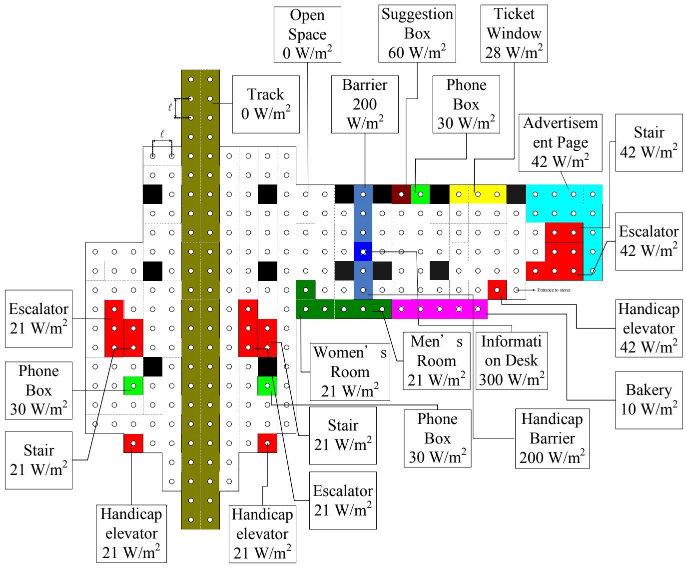

Figure 1. The weighted field of a mass rapid transport station.

are the travel path of a terrorist and the position that a bomb might be placed.

In this paper, the sensors are deployed on regular grid points, with a ℓ by ℓ spacing, as shown in Fig. 1, where there are 282 grid points. Two grid points are *neighbors* if their distance is $\le R_t$, where R_t denotes the sensor's transmission range, so that two sensors located on neighboring grid points can communicate with each other. To achieve connectivity of the wireless sensor network, it is necessary that $\ell \le R_t$. Suppose that there is a 2-dimensional coordinate system for grid points on the sensor field. The k-deployment map, denoted by $M(k)$, is a set of 2-dimensional coordinates for k sensors that has been deployed, while $M(p,k)$ denotes the k-deployment map stored by the sensor on grid point p. $W(p,k)$ denotes the weight of the coverage area by deploying k sensors in deployment map $M(p,k)$. The sensor is said to be in deployment map M only if its coordinate is an element of M.

The weight of the coverage area by deploying a sensor on grid point p in deployment map M, denoted by $W(p,M)$, is evaluated by the weight of the area covered

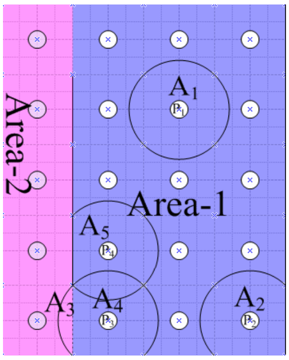

Figure 2. Example of a weighted field for the illustration of $W(p,M)$ for grid point p and deployment map M.

by the sensor but not covered by any sensor in M (see Fig. 2). Suppose that sensors S_1, S_2, S_3, S_4 are deployed on grid points p_1, p_2, p_3, p_4, respectively, in that order. That is, $M(0)=\varnothing$, $M(1)=\{p_1\}$, $M(2)=\{p_1,p_2\}$, $M(3)=\{p_1,p_2,p_3\}$, and $M(4)=\{p_1,p_2,p_3,p_4\}$. Let A_1 and A_2 be the sensing areas of sensors S_1 and S_2, respectively, and let $|A_1|$ and $|A_2|$ be the measurements of A_1 and A_2, respectively. Since A_1 is in Area-1, the weight of the coverage area by deploying sensor S_1 in deployment map $M(0)$, $W(p_1,M(0))$ is $W_{Area-1}\times|A_1|$, where W_{Area-1} denotes the weight density of Area-1. Since there is no intersection between A_1 and A_2, the weight of the coverage area by deploying sensor S_2 in deployment map $M(1)$, $W(p_2,M(1))$ is $W_{Area-1}\times|A_2|$. It is noted that $|A_1|=\pi\times R_s^2$, where R_s denotes the sensor range. It is also noted that $|A_2|\le\pi\times R_s^2$ since some of radiation of sensor S_2 is blocked by the wall. In addition, let A_3 denote the sensing area of sensor S_3 in Area-2, let A_4 denote sensor S_3's sensing area in Area-1, and let A_5 denote sensor S_4's sensing area which cannot be sensed by sensor S_3. Moreover, let $|A_3|$, $|A_4|$, and $|A_5|$ be the measurements of A_3, A_4, and A_5, respectively. The weight of the coverage area by deploying sensor S_3 in deployment map $M(2)$, $W(p_3,M(2))$ is $W_{Area-2}\times|A_3|+W_{Area-1}\times|A_4|$, where W_{Area-2} denotes the weight density of Area-2. The weight of the coverage area by deploying sensor S_4 in deployment map $M(3)$,

Table 1
SUMMARY OF NOTATIONS

W_{Area-1}	The weight density of Area-1.
W_{Area-2}	The weight density of Area-2.
R_s	The sensor range.
R_t	The sensor's transmission range.
$Dist(p,q)$	The distance between two grid points p and q.
$N(M)$	The set of grid points q such that q is not in deployment map M and $Dist(q,p)\le R_t$ for some grid point p in deployment map M.
$M(k)$	The deployment map of k sensors (the k-deployment map).
$M(p,k)$	The k-deployment map stored by the sensor on grid point p.
$W(p,k)$	The weight of the coverage area by deploying k sensors in deployment map $M(p,k)$.
$W(p,M)$	The weight of the coverage area by deploying a sensor on grid point p in deployment map M.
$W(k)$	The weight of the coverage area by deploying k sensors.

$W(p_4,M(3))$ is $W_{Area-1}\times|A_5|$. Let $W(k)$ be the overall weight of the area covered by k sensors. In Fig. 2, $W(4)$ is equal to the sum of $W(p_1,M(0))$, $W(p_2,M(1))$, $W(p_3,M(2))$, and $W(p_4,M(3))$.

Table 1 summarizes the notations used in this paper.

3 The Deployment Algorithm

The DP-like Algorithm, which deploys k sensors on a weighted field such that the weight of the coverage area, $W(k)$, is as great as possible, is introduced in this section. The sensors are deployed on regular grid points, with a ℓ by ℓ spacing, in our methods. In addition, for the sake of convenience, suppose that there exists a 2-dimensional coordinate system for grid points on the sensor field. For example, Fig. 3 shows a weighted field in which a grid point is given a 2-dimensional coordinates (x, y), if the grid point is on the x row from the top and the y column from the left. Moreover, $Dist(p,q)$ denotes the distance between two grid points p and q. For deployment map M, $N(M)$ denotes the set of grid points $q \notin M$ such that $Dist(q,p) \le R_t$ for some grid point $p \in M$. For example, in Fig. 3 $N(\{(1,1),(2,1)\}) = \{(0,1),(1,0),(1,2),(2,0),(2,2),(3,1)\}$, assuming that $\ell \le R_t < \sqrt{2}\ell$.

Suppose that we want to build a wireless sensor network of k $(k \ge 2)$ nodes with one sensor on grid point p such that $W(p,k)$ is maximized. We must first find grid point q among all grid points in $N(\{p\})$ such that $W(q,k-1)+W(p,M(q,k-1))$ has the maximum value, and then let $W(p,k)=W(q,k-1)+W(p,M(q,k-1))$ and $M(p,k)=M(q,k-1)\cup\{p\}$. Thus, we obtain the recurrence (1)

$$W(p,k)=\begin{cases} Max\{W(q,k-1)+W(p,M(q,k-1)) \mid q \in N(\{p\})\} & \text{if } k \ge 2,\\ W(p,\varnothing) & \text{if } k=1. \end{cases}$$

However, the naive recursive method, which is an implementation of Eq. 1, may get poor results on some weighted fields. Take, for example, Fig. 4. Fig. 5a, 5b, 5c, and 5d show $M(p,2)$, $M(p,3)$, $M(p,4)$, and $M(p,5)$ for all grid points p on the weighted field shown in Fig. 4, respectively. Note that the cardinality of $M(p,5)$, $|M(p,5)|$, is equal to 4 for all grid points p, as seen in Fig. 5d. That means the coverage weight evaluated by Eq. 1 is not good enough since at least two sensors are deployed on a grid point. As seen in Fig. 5a, $M((0,0),2)=\{(0,0),(0,1)\}$, $M((1,1),2)=\{(0,1),(1,1)\}$, and $M((0,2),2)=\{(0,1),(0,2)\}$. Thus, we have $M((0,1),3)=\{(0,1),(1,1)\}$ by Eq. 1 as seen in Fig. 5b. We find that $|M((0,1),3)|=2$ since two sensors are deployed on grid point $(0,1)$. The reason for deploying two sensors is that $(0,1)$ is in $M(p,2)$ for all $p \in N(\{0,1\})$. Observe that $M((0,1),2)=\{(0,1),(1,1)\}$.

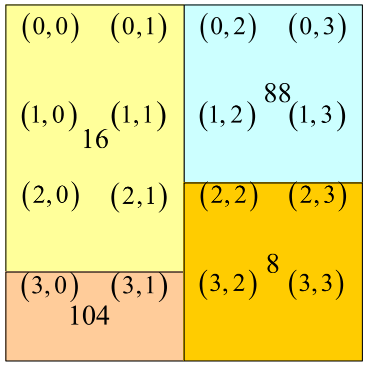

Figure 3. 16 grid points with 2-dimensional coordinates on a weighted field.

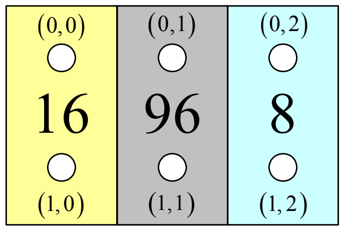

Figure 4. A weighted field with 6 grid points having 2-dimensional coordinates $(0,0)$, $(0,1)$, $(0,2)$, $(1,0)$, $(1,1)$, and $(1,2)$.

Clearly, if we let $M((0,1),3)=M((0,1),2)\cup\{q\}$ for some $q \in N(M((0,1),2))$, we have $|M((0,1),3)|=3$. Thus, we obtain the recurrence (2)

$$W(p,k)=\begin{cases} Max\{Max\{W(p,k-1)+W(q,M(p,k-1)) \mid q \in N(M(p,k-1))\}, & \\ \quad Max\{W(q,k-1)+W(p,M(q,k-1)) \mid q \in N(\{p\}), p \notin M(q,k-1)\}\} & \text{if } k \ge 2,\\ W(p,\varnothing) & \text{if } k=1. \end{cases}$$

Eq. 2 tells us $W(p,k)$ is equal to the larger value of *(v1)* $Max\{W(p,k-1)+W(q,M(p,k-1)) \mid q \in N(M(p,k-1))\}$ and *(v2)* $Max\{W(q,k-1)+W(p,M(q,k-1)) \mid q \in N(\{p\}), p \notin M(q,k-1)\}$ if $k \ge 2$. It is noted that the grid point q having *v1* is not in $M(p,k-1)$, implying $|M(p,k-1)\cup\{q\}|=|M(p,k-1)|+1$. It is also noted that the grid point q having *v2* has the property $p \notin M(q,k-1)$, implying $|M(q,k-1)\cup\{p\}|=|M(q,k-1)|+1$. The DP-like Algorithm is an implementation of Eq. 2. In the DP-like

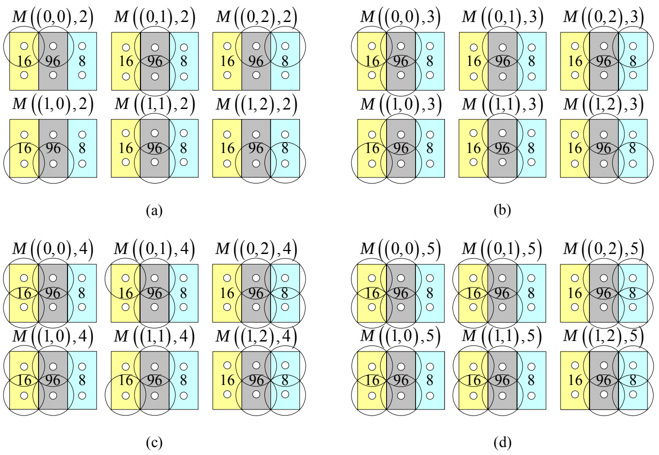

Figure 5. $M(p,k)$ for all grid points p on the weighted field shown in Fig. 4. (a) $k=2$. (b) $k=3$. (c) $k=4$. (d) $k=5$.

Algorithm, $M(p,k)=M(p,k-1)\cup\{q\}$ if $v1>v2$; otherwise, $M(p,k)=M(q,k-1)\cup\{p\}$. This guarantees that $|M(p,k)|=k$.

The DP-like Algorithm

```
begin
    for all grid points p do
    begin
      W(p,1) ← W(p,∅)
      M(p,1) ← {p}
    end
    for i ← 2 to k do
    begin
      for all grid points p do
    begin
      W(p,i) ← 0
      M(p,i) ← ∅
      for all grid points q ∈ N({p}) do
        if p ∉ M(q,i−1) then
          if W(q,i−1)+W(p,M(q,i−1)) > W(p,i) then
          begin
            W(p,i) ← W(q,i−1)+W(p,M(q,i−1))
            M(p,i) ← M(q,i−1) ∪ {p}
          end
      for all grid points q ∈ N(M(p,i−1)) do
        if W(p,i−1)+W(q,M(p,i−1)) > W(p,i) then
        begin
          W(p,i) ← W(p,i−1)+W(q,M(p,i−1))
          M(p,i) ← M(p,i−1) ∪ {q}
        end
    end
  end
end
```

4 Performance Studies

The human brain usually deploys the first sensor on the gird point so that the maximum coverage weight is obtained, then deploys the next sensor on the gird point so that the maximum additional coverage weight is obtained till all sensors have been deployed, which uses the Greedy Algorithm. Therefore, we compared the DP-like Algorithm with the Greedy Algorithm as well as the Naive Recursive Algorithm. Fig. 6 shows the result under different numbers of deployed sensors (k), where $R_s=\ell/\sqrt{2}$ and $R_t=\ell$. The DP-like Algorithm clearly outperforms the Greedy Algorithm, which is reasonable, while the Naive Recursive Algorithm often obtains the lowest coverage weight among these methods. This is because it may deploy multiple sensors on a grid point. Moreover, we observe that when deploying 47 ($=282/6$) sensors, the DP-like Algorithm and the Greedy Algorithm have much difference on $W(k)$. This is because there are many large areas on the weighted field of the mass transport station. Since an area has a weight density, there is a high probability that all neighboring grid points have the same coverage weight in a large area. Thus, the Greedy Algorithm has difficulty in obtaining a better deployment due to the flaw of its shortsighted view. Furthermore, when deploying large enough sensors, there is little difference on $W(k)$ between the Greedy Algorithm and the DP-like Algorithm because most areas with higher weight densities are covered by sensors. Nevertheless, we observe the distribution of the deployed nodes on the weighted field of the mass rapid transport station. There are 1, 5, 1, and 19 grid points in the areas with weight densities 300, 200, 60, and 42 w/m^2,

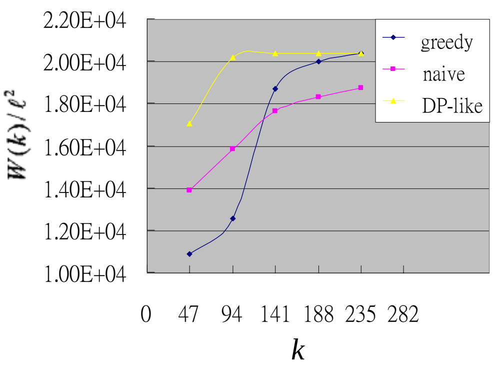

Figure 6. Comparison of the coverage weights under different numbers of deployed sensors.

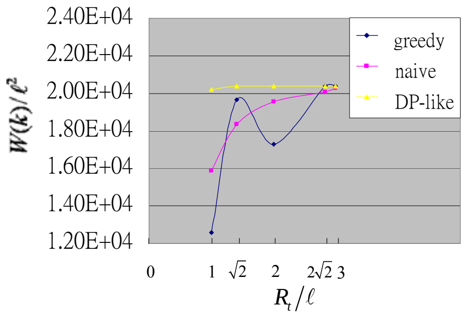

Figure 7. Comparison of the coverage weights by deploying 94 sensors under different values of sensor's transmission ranges $\ell, \sqrt{2}\ell, 2\ell, 2\sqrt{2}\ell, 3\ell$.

respectively, on this field. When we deploy 94 ($=282/3$) sensors with $R_t = \ell$ by the DP-like Algorithm, there are 1, 5, 1, and 18 sensors deployed in the areas with weight densities 300, 200, 60, and 42 w/m^2, respectively. As we might expect, the areas with larger weight densities are almost fully covered by sensors. We think that the DP-like Algorithm finds a near-optimal solution.

To get further insight into the performance of the DP-like Algorithm, we vary the sensor's transmission range, and show the results in Fig. 7. We expected that the larger R_t, the larger $W(k)$, because the wireless sensor network can be built by deploying sensors on two or more far apart areas with large weight densities when R_t is larger. However, the coverage weight obtained by the Greedy Algorithm when $R_t = \sqrt{2}\ell$ is larger than that obtained when $R_t = 2\ell$. The Greedy Algorithm has to randomly select a gird point to locate the next sensor among all the neighboring grid points with the maximum additional coverage weight. Since the Greedy Algorithm can obtain a better solution by chance, it is possible the Greedy Algorithm will obtain a smaller coverage weight when R_t becomes larger.

5 Conclusion

In this paper, we have introduced the problem of weighted field sensor coverage, which wants to find the maximum weight of the coverage area by deploying a given number of sensors on a given weighted field. Then we have proposed the DP-like Algorithm to find a near-optimal solution for the weighted field sensor covering problem. Because the human's brain usually uses the Greedy Algorithm to deploy sensors, we have compared the DP-like Algorithm with the Greedy Algorithm. Experimental results show that the DP-like Algorithm outperforms the Greedy Algorithm in almost all cases.

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