A Deployment Strategy for Mobility-Assisted Wireless Sensor Networks

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Abstract-*Sensor deployment is the fundamental issue in wireless sensor networks (WSNs). This paper proposes a grid-based sensor deployment strategy for the mobility-assisted WSNs, also called hybrid WSNs, which consist of both static and mobile sensors. The proposed algorithms calculate coverage holes for hole healing, select mobile sensors for dispatching, and discover redundant sensors for network lifetime extending. All the computation is completed based on the hexagonal virtual grids into which the sensing field is divided. The performance evaluation shows the proposed algorithms based on the grid-based deployment strategy can achieve the improvement of field coverage in the WSNs.*

Keywords: Deployment, Hybrid Wireless Sensor Network, Hexagonal Virtual Grid, Coverage.

1. Introduction

In a wireless sensor network (WSN), the sensor coverage in the field is always the fundamental requirement for the applications of environmental monitoring. And, sensor deployment becomes the important issue since coverage correlates closely with the deployment [1]. The early proposed works for sensor deployment [2, 3, 4, 5] assumed sensors are all static. In many conditions, manual sensor deployment is not practical. Instead, a random deployment such as sprinkling sensors from the air becomes applicable. However, it often causes both uneven sensor distribution and insufficient field coverage. Many later related works [6, 7, 8, 9, 10] assumed sensors are mobile, and coverage ratio of sensing field can be increased by the sensor movements. For balancing the trade-off between sensor cost and coverage, both static and mobile sensors could be employed in a WSN [11, 12]. This paper proposes a grid-based sensor deployment strategy to improve the sensor coverage for the mobility-assisted WSN, that is, a hybrid WSN which consists of both static and mobile sensors.

2. Background and Assumptions

A sensor device in the WSN may have location finding system and mobilizer as its additional components besides the basic components of processor, memory, micro sensor, RF transceiver, and power [13]. Regarding the location finding system for a WSN, many related researches [14, 15, 16, 17, 18] of the sensor positioning and localization techniques were proposed. By this reason, we assume that the sensors utilized in our works can obtain their location and send the coordinates information to the sink node for further processing. Additionally, due to the related works of sensor devices with mobility techniques had been proposed in [19, 20], we also assume that mobile sensors in the network can move freely, this is not unrealistic in the real world. The other assumptions in this work are that each sensor has the same sensing radius; sensors will be randomly deployed to the sensing field at the initial phase; each sensor will sent location information to the network coordinator (sink node); and, proposed algorithms run as a centralized approach.

3. Proposed Deployment Strategy

3.1. Hexagonal Virtual Grid

Once all sensors have been randomly deployed in the sensing field, the field will be divided into hexagonal virtual grids upon the cellular concept in telecommunication systems that hexagonal cells have the largest coverage area and smallest overlap compared with square and equilateral triangle ones according to their original coverage circles. In this paper, we define the grid radius r_g as

$$r_g = r_s / 2 \tag{1}$$

, where r_s is the sensing radius of a sensor. This definition implies that first, any sensor located within a grid will fully cover the grid, and second, once a sensor is located at the common vertex of three pairwise neighbored grids, it will fully cover the three grids (Shown as Fig. 1). Accordingly, sensors located in the same grid have same coverage contributions to that grid and they may have no need to be all active at the same time for the purpose of saving energy and extending network lifetime, although this will bring a little reduction of coverage contribution to the other grids (details will be described later). On the other hand, for the purpose of increasing coverage contribution, each mobile sensor is expected to move to a common vertex of three pairwise neighbored grids which need to be covered. The preliminary assumption in this paper is that the sensing field is divided into n_g virtual grids denoted as grid set $G=\{g_i \mid i=1, 2, 3, ..., n_g\}$, and $V=\{v_i \mid i=1, 2, 3, \dots, n_v\}$ is the set of all n_v vertexes in the field. It is satisfied that

$$d(v_c,c_a)=d(v_c,c_b)=d(v_c,c_c)=r_g \tag{2}$$

$$d(c_a,c_b)=d(c_b,c_c)=d(c_c,c_a)=2r_g\cos\frac{\pi}{6}=\sqrt{3}r_g \tag{3}$$

, where c_a, c_b, and c_c are the center points of the three pairwise neighbored grids g_a, g_b, and g_c. And v_c is their common vertex.

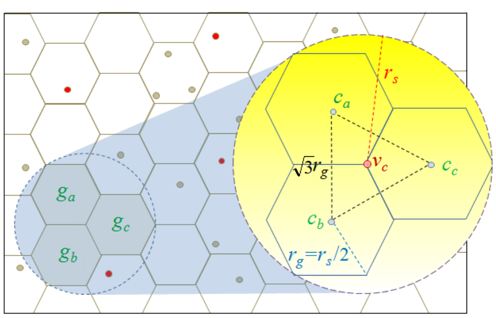


Figure 1. Virtual grids in the sensing field

3.2. Basic Grid-based Deployment

Due to the uneven sensor distribution and insufficient field coverage caused by initial random deployment, some areas, called coverage holes, are not covered by any sensor device, that is, events occur in these holes will not be detected. Therefore, sizes and positions of the coverage holes should be calculated and healed to achieve the coverage requirement. Since a grid will be one hundred percent fully covered if at least one sensor was located in it, our first basic algorithm defines the hole size of grid g_i, denoted as H_i, is

$$\forall\, i=1,2,3,\dots,n_g$$
$$H_i=\begin{cases}0, & \text{if } N_s(g_i)\ge 1\\ 1, & \text{otherwise}\end{cases} \tag{4}$$

, where $N_s(g_i)$ denotes the number of static sensors within the grid g_i. By reason of that mobile sensors would have movements, only static sensors are considered in the function N_s. Besides, since a static sensor could be exactly located at the common edge of two grids or at the common vertex of three grids, it is possible that

$$\sum_{i=1}^{n_g} N_s(g_i)\ge n_s \tag{5}$$

, where n_s is the total number of static sensors in the sensing field. Base on the formula (4), We define G_{vi} as the grid set of three pairwise neighbored grids with the common vertex v_i, and define H_{vi} as the total hole size of these grids or the hole size of vertex v_i.

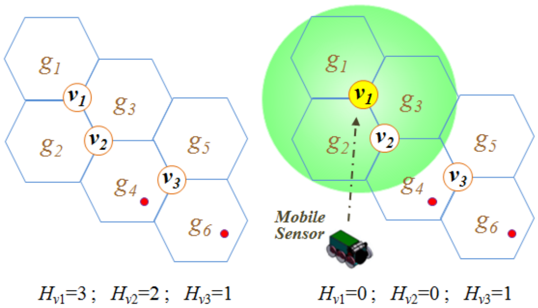
$$\forall\, i=1,2,3,\dots,n_v$$
$$G_{v_i}=\{\,g_j \mid d(c_j,v_i)=r_g,\ \ j\in[1,n_g]\,\} \tag{6}$$
$$H_{v_i}=\sum_{g_k\in G_{v_i}} H_k \tag{7}$$

, where $|G_{vi}|=3$, and $0 \le H_{vi} \le 3$. After calculating the hole size of each vertex, the vertex with largest hole should be healed firstly by dispatching a mobile sensor to cover it. Assume vertex v has the largest hole, and v is shared by the grids g_a, g_b, and g_c with center point $c_a=(x_a, y_a)$, $c_b=(x_b, y_b)$, and $c_c=(x_c, y_c)$ respectively.

$$v=\arg\max_{v_i\in V} f(v_i),\quad \text{where } f(v_i)=H_{v_i} \tag{8}$$

$$(x_v,y_v)=\left(\frac{x_a+x_b+x_c}{3},\frac{y_a+y_b+y_c}{3}\right) \tag{9}$$

, where (x_v, y_v) is the coordinates of vertex v, and also the target position a selected mobile sensor will move to. After the healing, the vertex with second largest hole according to previous calculation cannot be the next healing target because of previous healing could contribute coverage for the nearby grids, that is, the hole sizes of some grids and vertexes may change. An illustration shown in Fig. 2(a) indicates that $H_1=H_2=H_3=H_5=1$, $H_4=H_6=0$, and the grids g_1, g_2, g_3, and g_5 need to be coverd by the healing process. $G_{v1}=\{g_1, g_2, g_3\}$, $G_{v2}=\{g_2, g_3, g_4\}$, $G_{v3}=\{g_4, g_5, g_6\}$; and $H_{v1}=3$; $H_{v2}=2$; $H_{v3}=1$; Due to the hole size $H_{v1}>H_{v2}>H_{v3}$, v_1 should be firstly healed. Notice that once a mobile sensor was selected to heal the hole of v_1, the sensor will contribute the full coverage to g_1, g_2, and g_3, and then $Hv_1=0$, $Hv_2=0$, and H_{v3}=1. So, the next healing target should be v_3, not v_2. By this reason, a recalculation of hole sizes should be made after each coverage hole healing.



(a) (b)

Figure 2. An illustration of healing the hole

As shown in Fig. 3, according to the influence of coverage contribution brought by previous hole healing, only the vertexes which is at a distance of less than $2r_g$ from the previous healed one may need to recalculate their hole sizes. Additionally, the vertexes which have a zero hole size have no need to recalculate. Let v_h be previous healed vertex and V' be the set of vertexes need a recalculation, then

$$V' = \{ v_i \mid d(v_i, v_h) \le 2r_g \text{ and } H_{v_i} > 0, i \in [1, n_v] \} \quad (10)$$

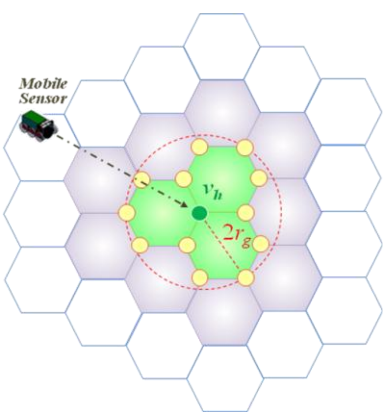


Figure 3. Vertexes may need to recalculate hole

3.3. Extended Grid-based Deployment

In this section we describe our second algorithm which improves the basic algorithm described above. In the basic algorithm, a grid with no sensor in it was treated as one hole. It can be precisely improved to calculate the hole size for a grid, and further, a precise vertex hole size will be obtained for achieving a higher effect of healing process. Fig. 4 shows that a grid has the possibility of being partially covered by the static sensors within its direct and indirect grid neighbors.

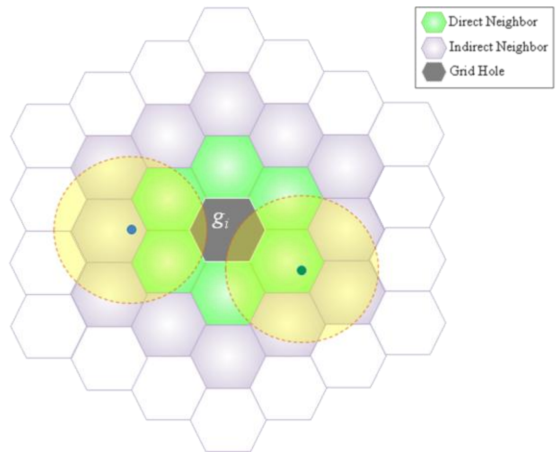


Figure 4. Partially covered by nearby sensors

Accordingly, we redefined the hole size, H_i, of grid g_i as following

$$\forall\, i = 1, 2, 3, \ldots, n_g$$

$$H_i = \begin{cases} 0, & S_i \ne \phi \\ & \text{or } \exists \text{ a set } R \subseteq B_i \text{ that } \bigcup_{s \in R} (C_s \cap g_i) = g_i \\ Area(g_i), & \bigcup_{s \in B_i} (C_s \cap g_i) = \phi \text{ and } S_i = \phi \\ Area(g_i) - Area(\bigcup_{s \in B_i} (C_s \cap g_i)), & S_i = \phi \end{cases} \quad (11)$$

, where S_i denotes the set of static sensors in grid g_i; B_i, the set of static sensors in direct and indirect neighbor grids of g_i; C_s, the region covered by sensor s; and $Area()$ is the function of area size. The obtained value of H_i indicates the precise real size of the hole region in the grid g_i.

The calculation of vertex hole size H_{vi} of the extended grid-based deployment is same as the formulas (6) and (7) shown in section 3.2, but it will get a precise result for hole healing process since the hole calculation of individual grid is more precise than the one in formula (4). Once a mobile sensor was selected to heal the hole of a vertex v_i, the sensor will contribute the full coverage to the all grids in G_{vi} and partial coverage to some of the others not belong to G_{vi}. Therefore, some vertexes may need a hole size recalculation for next vertex selection of healing process. Also, vertexes with a zero hole size have no need to do so. Fig. 5 shows the possible vertexes need to recalculate hole zise, and formula (12) indicates the necessary vertexes, denotes as V', need to recalculate. It is a little different from the one described in section 3.2.

$$V' = \{ v_i \mid d(v_i, v_h) < 4r_g \text{ and } H_{v_i} > 0, i \in [1, n_v] \} \quad (12)$$

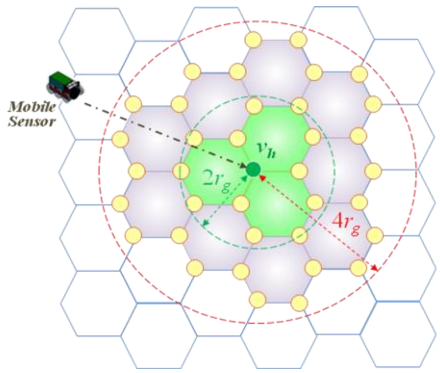


Figure 5. Vertexes may need to recalculate hole

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assume sensing radius of each sensor is r_s
divide the sensor area into hexagonal virtual grids with radius r_g=r_s/2
g_i denotes the i-th grid where i=1, 2, 3,..., n_g; n_g is the number of grids
B_i denotes the set of static sensors in direct and indirect neighbor grids of g_i
S_i denotes the set of static sensors in g_i
C_s means the covered region by sensor s
for each grid g_i where i ∈ [1, n_g]
    if S_i ≠ ϕ or there is a set R ⊆ B_i such that ∪_{s∈R} C_s ∩ g_i = g_i
        set the coverage hole size of g_i, that is H_i, to 0
    else if S_i = ϕ and ∪_{s∈S_i} C_s ∩ g_i = ϕ
            set H_i to Area(g_i), that is, area size of g_i
        else if S_i = ϕ
                set H_i to Area(g_i) − Area( ∪_{s∈S_i} C_s ∩ g_i )
            end if
        end if
    end if
end for
set V to the set of all grid vertexes {v_1, v_2, v_3,..., v_nv}
for each grid vertex v_i ∈ V
    set Gv_i to the set {g_k | distance(center(g_k), v_i)=r_g}, k∈[1, n_g]
    set Hv_i to the sum of hole sizes of grids in Gv_i, that is, Σ_{g_j∈Gv_i} H_j
end for
set U to V — {v_i | Hv_i = 0}
while U ≠ ϕ
    sort the elements in U by their corresponding hole sizes
    select the first element u in U
    set Status to the return value of calling SelectMobileSensor(u)
    if Status = FAILURE
        exit while
    end if
    U = U − { u }
    set U' = {v_i | distance(v_i, u) < 4r_g, v_i ∈ U } where U' ⊆ U
    for each v_i in U'
        recalculate H_j of each g_j in Gv_i
        recalculate Hv_i = Σ_{g_j∈Gv_i} H_j
    end for
end while
```

Figure 6. Extended grid-based algorithm

3.4. Mobile Sensor Selection

The mobile sensors in the sensing field will be selected to heal the holes one by one. Each time the vertex with largest hole will be chosen as the moving target for a mobile sensor. Regarding the mobile sensor selection, since the shorter moving distance will save more energy for the sensor, our first rule is that the sensor which is closest to the target vertex will be chosen firstly.

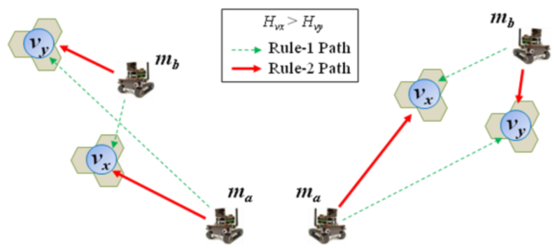
$$\begin{aligned}&\text{select } m_a \in M - M' \text{ such that}\\&\forall m_i \in M - M' - \{m_a\},\ d(m_a, v_h) \le d(m_i, v_h)\end{aligned} \qquad (13)$$

, where M denotes the set of all mobile sensors; M' is the set of previous selected sensors; and v_h is the target vertex.

However, the selection strategy can be improved by the second rule for the cases in following Fig. 7. The hole of v_x is larger than the one of v_y, and the green line is the path result determined by rule-1. The rule-2 will make an exchange of targets, if

$$d(m_a, v_x) + d(m_b, v_y) < d(m_b, v_x) + d(m_a, v_y) \qquad (14)$$

, where the average moving distance of sensors will be reduced further. Notice that actual movements of all the mobile sensors will happen after all dispatch selection are finished since the algorithms are centralized.



(a) (b)

Figure 7. Examples of moving target exchange

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SelectMobileSensor(u)
// u is the grid vertex which needs a mobile sensor to cover

// assume M is the set of all mobile sensors, M={m_1, m_2, m_3,..., m_n}
//   and M' is the set of all selected mobile sensor by previous
//   dispatch request. M' ⊆ M.
if M' = M
    return FAILURE
end if
select a mobile sensor m_a ∈ M-M'
    ,where ∀ m_i ∈ M-M'-{m_a}, d(m_a, u) ≤ d(m_i, u)
set m_T to m_a
set distance d_T to ∞
for each element m_j in M'
    set v_T to the grid vertex to which m_j was dispatched to move
    if d(m_a, v_T) + d(m_j, u) < d(m_a, u) + d(m_j, v_T)
        if d(m_a, v_T) + d(m_j, u) < d_T
            set m_T to m_j
            set d_T to d(m_a, v_T) + d(m_j, u)
        end if
    end if
end for
if d_T = ∞
    set cover target of m_a to u
else
    set cover target of m_a to Target(m_T)
    change cover target of m_T to the vertex u
end if
M = M - {m_a}
M' = M' ∪ {m_a}
return SUCCESS
```
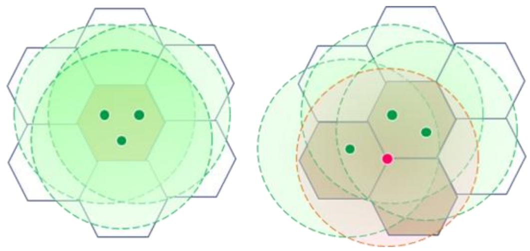

Figure 8. Mobile sensor dispatching algorithm

3.5. Redundant Sensors

Regarding the situation shown in the Fig. 9(a), all the sensors in the same grid contribute full coverage of that grid and they have a great overlap in coverage. Accordingly, besides the reserved one, the others can be treated as the redundant sensors which can be scheduled into sleep mode and be waked up as active sensors on demand. Similarly, Fig. 9(b) shows the mobile sensor will contribute full coverage to the three pairwise neighbored grids with the common vertex healed. Therefore, all the static sensors in these three grids can be treated as redundant sensors, too. Scheduling the redundant sensors into sleep mode will make a little reduction of coverage, nevertheless, they can help to extend the lifetime of the sensor network. This is a tradeoff situation. The influence of redundant sensors on coverage will be shown in the next section which describes the results of network simulation.



(a) (b)

Figure 9. Redundant sensors

4. Performance Evaluation

The performance was evaluated by network simulation of proposed algorithms. BGD means basic grid-based deployment while EGD means extended one. Furthermore, BGD-A and EGD-A represent all sensors are active while BGD-S and EGD-S represent redundant sensors are in sleep. The environment parameters of simulation are as

Sensing field: 490m x 360m
Sensing radius: 40m
Grid radius: 20m
Number of sensors: 60/80/100 (three cases)
Mobile sensors: 0% ~ 50% (10% Interval)
Simulation runs: each case has 150 runs

Fig. 10 shows the curves of coverage ratio of 60, 80, and 100 total sensors with 0%~50% mobile sensors. The cyan curve in each figure indicates the initial coverage, and naturally, the more sensors bring the higher ratio. The BGD and EGD algorithms have the significant improvements of the coverage ratio, especially the EGD algorithms obtained higher ratio than the BGD ones because of precise calculation of coverage holes. The evaluation results also show the EGD-S and BGD-S has a little decrease than EGD-A and BGD-A respectively. The decreases are caused by the slept redundant static sensors due to the lack of their coverage contribution. The coverage ratio is even a little less than the initial one where 0% mobile sensor was employed. Nevertheless, the redundant sensors have the contribution to extend the network lifetime. We can see the trade-off between the coverage and the number of redundant sensors from the views of Fig. 10 and Fig. 12.

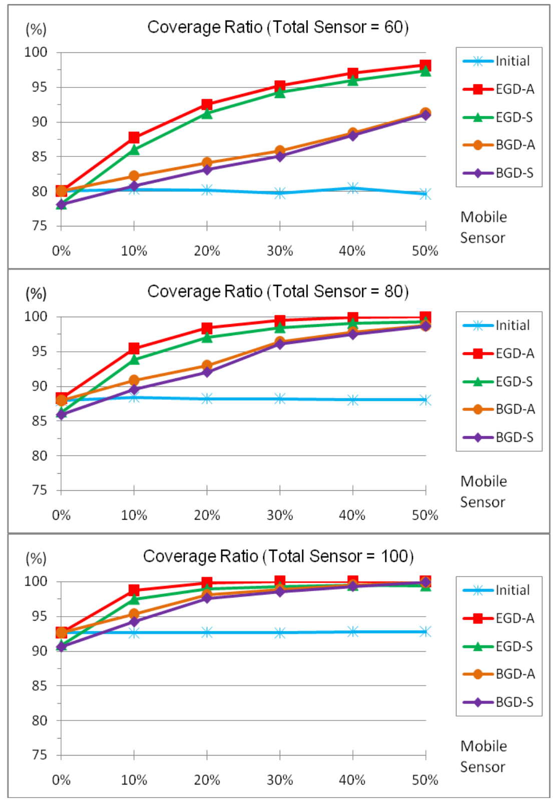


Figure 10. Coverage ratio

In Fig. 11, it shows that the strategy of mobile sensor selection for healing coverage holes can help decrease the average moving distance of selected mobile sensors by performing selection rule 1&2 described in section 3.4. And therefore, it can aid the power saving for the sensors.

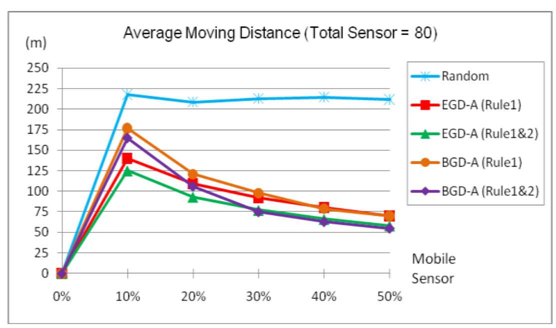


Figure 11. Average moving distance

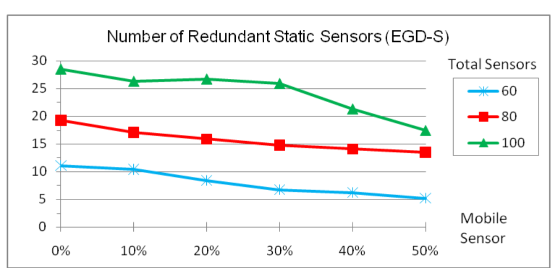


Figure 12. Number of redundant static sensors

Fig. 12 shows the number of redundant static sensors appear in EGD-S deployment algorithm. Although a little coverage will be influenced, these sensors can help to extend the network lifetime by utilizing active/sleep scheduling. Since the increase of mobile sensors leads to the decrease in static sensors, the curve has a downward tendency. And naturally, more sensors in the sensing field will bring more redundant sensors due to the density.

5. Conclusion

This paper utilized hexagonal virtual grids and proposed the grid-based sensor deployment algorithms for the hybrid wireless sensor networks, which consist of both static and mobile sensors. It makes the improvements of coverage ratio, considers the reduction of sensor moving distance, and introduces the influence of redundant sensors. Evaluation shows proposed deployment strategy obtained the significant effect of performance.

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