LETTER

VAMSD: Voronoi Diagram Based Autonomous Mobile Sensor Deployment for Maximizing Coverage

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SUMMARY This letter proposes a novel mobile sensor deployment scheme for maximizing coverage. The basic idea is to force mobile sensors to move to predetermined target points that are the optimal layout in a distributed manner using Voronoi diagram data structure. A simulation shows that the result of the proposed scheme is quite close to the optimal result and outperforms previous works.

key words: *mobile sensor networks, sensor deployment, distributed algorithm, Voronoi diagam*

1. Introduction

As computer hardware and software technologies have been advanced, Wireless Sensor Networks (WSNs) can have a capability to monitor various physical environments [1]. The deployment of sensors has a dramatic impact on the effectiveness of the WSN. However, in various risky environments such as disaster areas, battle fields, and toxic urban regions, the manual deployment approach cannot be applied. In these cases, it is one of the most practical ways to deploy sensors randomly. Most commonly used random deploy method is to scatter sensors from an airplane on the target field. This approach, however, cannot always lead to effective coverage. Lately, hardware that can support mobility is fortunately getting smaller and cheaper [2]. As a sensor node with mobility can move to provide the required coverage autonomously, it will be able to help enhanced deployment. WSNs that consist of mobile sensor nodes are called Mobile Sensor Networks (MSNs).

Recently, the deployment of sensors in MSNs has been researched very intensely. There have been several research efforts on deploying mobile sensors. However, most of works are based on the centralized or the potential field based approach that is one of the distributed approaches [3]–[5]. In the centralized approach, a single sensor node has full responsibilities for determining target points and unicasting the proper relocated points to all sensor nodes [3]. It can be huge burden for a single sensor node due to communication and computation overhead. Furthermore, it may cause the single point failure because this approach is absolutely dependent upon one sensor node. On the other hand, all sensor nodes have attractive or repulsive forces to each other in the potential field based approach, and the force of all sensor nodes remains in equilibrium after completing this scheme [4], [5]. Especially in ATRI (Adaptive Triangular Deployment Algorithm for Unattended Mobile Sensor Networks) [5], by dividing the transmission range into six sectors, each sensor node adjusts the relative distance to its one-hop neighbors in each sector separately to achieve the ideal node layout. However, to achieve this equilibrium state, each sensor node should move iteratively until reaching the final destination.

The goal of this letter is spreading out all sensor nodes to achieve maximizing coverage with limited energy. The battle field surveillance system can be the one of possible applications. After all sensor nodes are scattered from an airplane at the same time in this environment, they may be deployed densely in the limited area because they are under same external conditions, such as the velocity and the direction of wind. Additionally, there should be no boundary condition in this application. We define the maximizing coverage as the maximum capable sensing area that is achieved with given limited sensor nodes.

This letter aims at designing an energy-efficient and coverage-maximizing sensor deployment scheme for MSNs. We propose Voronoi diagram based Autonomous Mobile Sensor Deployment (VAMSD) scheme that needs only one-time movement for each sensor. Because a movement of sensor is the most energy consuming process in MSNs, it had better move only once through additional communications. In this letter, we present VAMSD algorithm in detail and simulation results in the following sections.

2. Voronoi Diagram Based Autonomous Mobile Sensor Deployment (VAMSD) Scheme

The proposed scheme starts with the random deployment of sensor nodes. Each sensor node is associated with sensing area by a circle with the same radius and the initial energy of sensor nodes is equivalent. In addition, we assume that each sensor node already knows its current position using various localization algorithms. To know its location information is essential in MSNs, because where data is sensed as well as what data is sensed is very important. Lastly, we assume that the communication range of each sensor is equivalent and much longer than its sensing range. Hence, the communication range does not affect our deployment scheme. The proposed scheme is widely divided into two phases: the decision of target points and the movement of sensor nodes.

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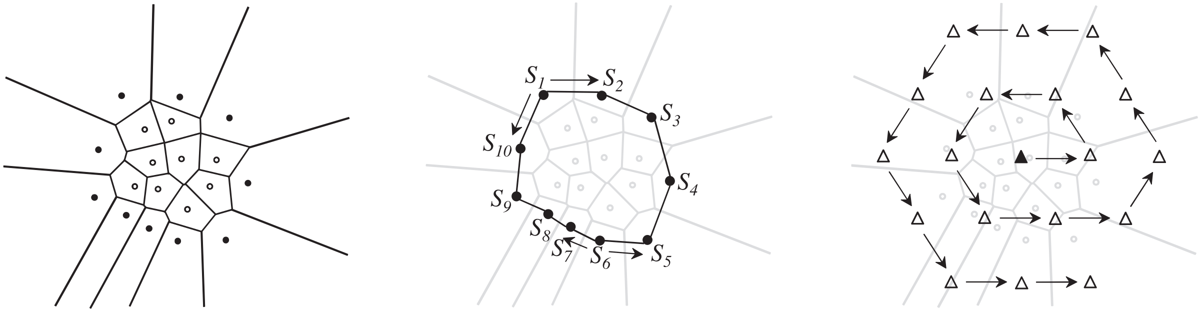


(a) Initial Deployment (b) Estimation of Center Position (c) Decision of Target Points

Fig. 1 The decision of center position and target points.

2.1 The Decision of Target Points

In [5], the author proved that the node layout for maximum coverage is optimal when all Delaunay triangles are equilateral triangles with edge length of $\sqrt{3}r$, where r is sensing range. We define target points as a set of points where sensor nodes will be located optimally in this letter. Figure 1(c) shows one example of target points with 19 sensor nodes that are represented as a triangle shape. After sensor nodes are randomly deployed, the center position that is shown as a black colored triangle in Fig. 1(c) should be determined for deciding target points. When all sensor nodes have the shared common center position, they can eventually determine equivalent target points. The center position can be calculated as follow.

$$Q = \arg\min_{x_c, y_c} \left(\sum_{i=1}^{n} \{(x_i - x_c)^2 + (y_i - y_c)^2\} \right) \tag{1}$$

where n is the total number of sensors, x_i and y_i are current x-axis and y-axis position of i-th sensor, x_c and y_c are the center position among sensors, respectively. The parameter x_c and y_c are, therefore, values that minimize the numerial formula (1). They are easily found by taking partial derivative of (1) with respect to x_c, y_c.

$$\frac{dQ}{dx_c} = -2 \sum_{i=1}^{n} x_i + 2nx_c \tag{2}$$

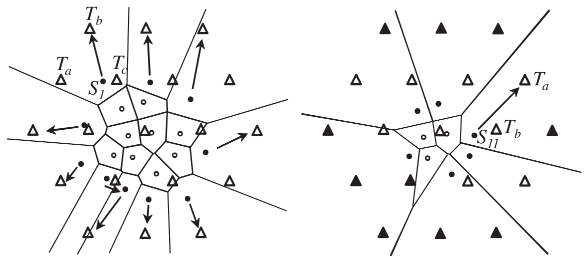
$$\frac{dQ}{dy_c} = -2 \sum_{i=1}^{n} y_i + 2ny_c \tag{3}$$

To set the above resulting expressions equal to 0, we can get the below result.

$$x_c = \frac{\sum_{i=1}^{n} x_i}{n}, y_c = \frac{\sum_{i=1}^{n} y_i}{n} \tag{4}$$

For determining the center position using above method in a distributed manner, each sensor node should know location information of all other sensor nodes. If the number of sensor nodes is n, $O(n^2)$ number of transmissions are required in a flooding method. However, the proposed scheme does not require the exactly correct center position but commonly shared one. Therefore, we propose the new estimation scheme of determining the center position to reduce communication overhead in this letter.

After all sensor nodes are randomly deployed in the beginning, they can construct Voronoi diagram data structure with communicating with one-hop neighbors shown as Fig. 1(a). When Voronoi diagram is completed to construct, each sensor node can decide for itself whether it is located in the outmost polygon or not, since the outmost polygon should contain a Voronoi vertex at infinity. We define a boundary node as a sensor node where it is located in the outmost polygon in this letter. In Fig. 1(a), a black colored circle represents a boundary node. These boundary nodes are able to form the convex-ring topology shown as Fig. 1(b). Each boundary node has randomly given backoff value when it is scattered initially. For example, if backoff time of S_1 is expired for the first time, S_1 triggers to send its location data to neighbor nodes. After receiving this data, S_2 and S_{10} cancels its own backoff timer, and then these two nodes individually calculate an average location based on received data from S_1 and their own location. S_2 and S_{10} separately send a calculated average location data to S_3 and S_9 with setting initial triggering node as S_1. Finally, when S_6 receives this data which is triggered by S_1 from S_5 and S_7, it stops sending location data to a neighbor node and floods a calculated average location data, black colored triangle in Fig. 1(c), as the center position to all over network. However, backoff time of one or more sensor nodes could be expired before receiving location data from S_1 due to the property of random backoff time. In Fig. 1(b), when S_6 is expired, S_6 attempts to do same procedure like S_1 did in the above example because it cannot be notified that S_1 already was expired. Any boundary sensor node located between S_1 and S_6 possibly receives two location data that are triggered by different nodes. If S_4 receives duplicated location data from S_1 and S_6, this node can decide which data is to be discarded based on the initial trigger node field in location data header. In this case, after S_4 calculates the average location based on data from S_1, this node sends calculated location data to S_5, and location data from S_6 is discarded. Using this estimation scheme, we can reduce communication and computation overhead to find and share a center position among all sensor nodes. We carried out the simulation to



(a) First Iteration (b) Second Iteration

Fig. 2 The movement of sensor nodes.

compare the proposed scheme with former method. In conclusion, there is not much difference between two methods. Therefore, we adopt latter method as the center position determination.

As all sensor nodes share an equivalent center position, they can determine target points with starting from center position to counterclockwised direction until reaching the number of total sensor nodes shown as triangles in Fig. 1(c). Since each sensor node has same target points determining rule, target points that were made by each sensor node with distributed manners are equivalent.

2.2 The Movement of Sensor Nodes

In this phase, each sensor node should decide where it moves to minimize the total energy consumption of sensor nodes by distributed manner. It is the most important part of the proposed scheme. This problem is eventually equal to the minimizing bipartite matching problem. For solving this problem optimally, Hungarian Algorithm is proposed [6]. This algorithm can find minimum matching in $O(n^3)$, where n is the number of nodes. However, this algorithm is not suitable for MSNs because it only works in centralized manner. Therefore, we propose a distributed greedy heuristic algorithm.

As we mentioned in the previous section, each sensor node is able to achieve whole target points following the optimal node layout in a distributed manner due to knowing the center position. All sensor nodes already have their own Voronoi polygon that is total and exclusive. It means that every target point in a given polygon is closer to the node in this polygon than to any other node. Each sensor node can make a list that includes target points located in its polygon. The only boundary node chooses one target point that is the farthest from its current position in its list. For example, sensor node S_1 is a boundary node and it has three candidate target points, T_a, T_b and T_c, in its polygon as shown Fig. 2(a). S_1 should move to T_b because T_b is the farthest point from S_1. If S_1 selects T_a or T_c instead of T_b as a target point, T_b is never picked as target point among other boundary nodes at the same iteration, because T_b is not included in the polygon of other boundary node. In other words, a sensor node that is located in the inner polygon should move to T_b. Consequently, this sensor node should move relatively longer distance than S_1, and it tends to break balance of energy spent among all sensor nodes. Therefore, the energy consumption of each sensor node can be balanced when only the boundary node moves to the farthest target point. All boundary nodes represented as black colored circles select their target points at first iteration shown as Fig. 2(a). After setting the flag that denotes already moved node, the algorithm will iterate with unsetting sensor nodes just like Fig. 2(b), and selected target point is expressed as black colored triangle. This algorithm will be terminated when there is no more sensor node to move. Our proposed scheme is described in Algorithm 1.

Algorithm 1 VAMSD Algorithm

```
/* the main loop*/
/* each sensor node follows this algorithm */
while not complete do
    construct Voronoi diagram with unsetting neighbor nodes;
    if in outmost polygon then
        if include any target position then
            move to the farthest target position;
            set the flag;
            break; /* Condition of Termination */
        end if
    end if
end while
```

In this algorithm, we sacrifice communication costs[†] for the one-time movement. However, this additional cost can be neglected because the movement of a sensor spends much more energy than communication with each other [2].

3. Simulation Results

To verify the effectiveness of the proposed scheme, we need to compare with an alternative scheme. In this letter, therefore, we choose the Hungarian algorithm as the optimal approach and ATRI for comparing. We can use the result of the optimal as a lower bound and the result of ATRI for comparing with the proposed scheme.

We carried out the simulation 50 times with varying the number of sensor nodes from 10 to 100 in case of the optimal, ATRI, and the proposed scheme, respectively, and then we achieve the average value for each condition. The sensing range of each sensor is 3 meters, and the communication range is 50 meters. Major metrics are the total moving distance and the standard deviation of a moving distance for each sensor. We can presume the total spending energy through the total moving distance and the energy balance through the standard deviation when the deployment of sensors is completed.

Figure 3 shows the total moving distance which can

[†] Each sensor node is required to transmit data to its one-hop neighbors when it constructs Voronoi diagram, it estimates the center position if it is the boundary node, it relays the center position information, and it advertises where it is going before the movement.

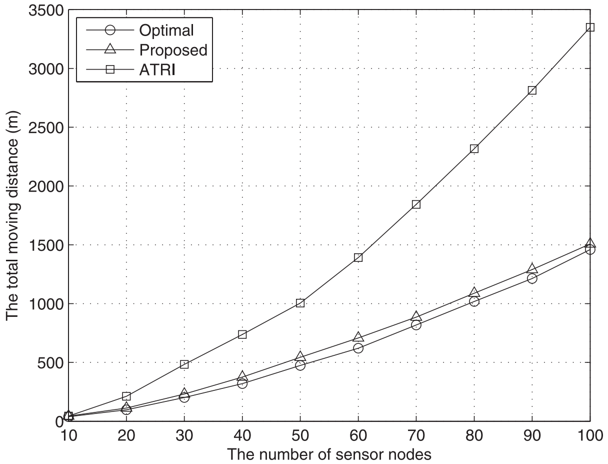


Fig. 3 A comparision of the total moving distance.

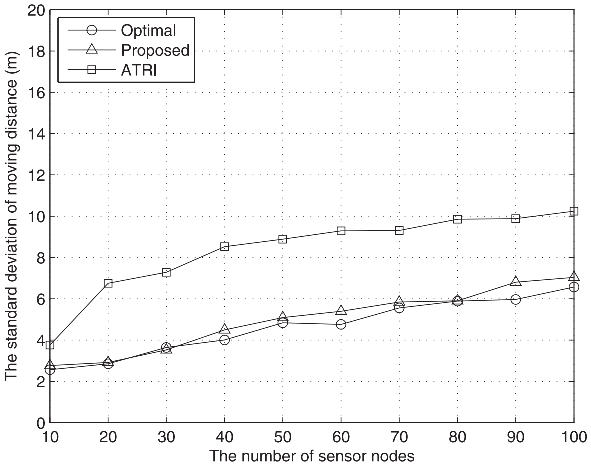


Fig. 4 A comparison of the standard deviation of moving distance.

be measured in the energy consumption versus the number of sensor nodes for the optimal, ATRI and the proposed scheme, respectively. This result shows that the proposed scheme expends slightly more energy than the optimal scheme for deployment. As the number of sensor nodes increases, the energy spending is increased linearly, but the energy consumption rate between two schemes keeps almost always same. In addition, we can see that the proposed scheme reduces more than 50 percent of the total moving distance compared to ATRI, because each sensor node should move iteratively to reach the desired target point in ATRI.

Figure 4 shows the standard deviation of the moving distance. As the number of sensor nodes increases, the standard deviation of moving distance is getting increased. However, it is nothing strange that the standard deviation is increased because the target field is growing larger as more and more sensor nodes are involved for the mission and sensor nodes should be spreading out to fill up the larger target points. The difference of the standard deviation between the optimal scheme and the proposed scheme is relatively very small compared to the total average moving distance. Moreover, we can see that the standard deviation of ATRI is larger than that of the proposed and the optimal scheme, because sensor nodes heading to relatively distant target points are required to move much longer distance due to the iterative movement. As the proposed scheme helps avoiding any node in inner polygon move very long distance, we can achieve the balance of energy for each sensor node. These two results show that our proposed scheme outperforms ATRI and closely follows the optimal scheme that is centralized.

4. Conclusions

In this letter, we have proposed the deployment scheme of mobile sensor for maximizing coverage in MSNs. The basic idea is that we force mobile sensors to move to predetermined target points that are the optimal layout in a distributed manner using Voronoi data structure. Its key difference from alternative schemes is that network topology can be controlled by an operator because our approach determines target points first of all and then runs the matching algorithm. And all sensor nodes need to move only one-time for saving energy. A simulation results show that the result of the proposed scheme is quite close to the optimal result and outperforms previous works.

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