Coverage Improvement Strategy Based on Voronoi for Directional Sensor Networks

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Abstract. Nowadays, directional sensor networks (DSNs) have drawn a lot of attentions, which are made up of a large number of tiny directional sensors that are different from traditional omnidirectional sensors. Directional sensor is characterized by working direction and angle of view (AOV). In this paper we study area coverage of DSNs. We exploit Voronoi theory to divide sensors into polygons, by optimizing the local coverage in each polygon to achieve the overall coverage. We take full use of Voronoi vertexes and edges to judge whether a sensor gets full coverage inside in current polygon, if not, then the sensor calls Move Inside Cell Algorithm (MIC) and Rotate Working Direction Algorithm (RWD) algorithms we have designed. Compared to the similar methods to solve this question our algorithms are relatively simple and moving distance is shorter. Simulation results reveal that our algorithms outperform some existing methods in term of the area coverage.

Keywords: Coverage · Voronoi · DSNs · Sensor network

1 Introduction

With the development of the current technology and wide applications of wireless sensor networks (WSNs), WSNs are playing an increasingly important role in the daily life and have gained wide attentions. Coverage is the fundamental problem in WSNs, previous works most focus on the omnidirectional sensor network that means the working coverage area is a circle. In recent years, attentions have been focused on the DSNs which are different from the general WSNs. Directional sensor is limited to a certain working direction and AOV, such as camera sensor, infrared sensor and so on. In the WSNs, sensing coverage is mainly related to R_s(sensing radius) and the location of sensor. Whereas in the DSNs, sensing coverage is related not only to the location and R_s but also to the working direction and AOV.

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Currently, there are some studies related to the DSNs area coverage. For example, some studies centered on using virtual force between adjacent sensors [4,7], others adopted the Voronoi [9] principle to reduce the complexity of sensor to make decisions [2,3]. In this paper we adopt Voronoi diagram mainly based on the following points: (1) Voronoi can be constructed by the randomly deployed sensors, every sensor lies exactly in the Voronoi cell; (2) by the information of voronoi vertexes, sensor can make a decision to move and rotate; (3) the sensor's moving trajectory is limited to the cell of current sensor. In this paper, we raise coverage enhancement algorithm MIC and RWD. Sensor by adjusting working direction and updating location to get full coverage in each Voronoi polygon. Our algorithm can get the better coverage and RWD needs sensor to move the shorter distance compared to DVSA proposed in [2].

The rest of the paper can be organized as follows. In Sect. 2, we summarize the related work. In Sect. 3, we state the problem clearly and introduce some preliminaries. Then, we analyse the theoretical framework and provide coverage increment algorithms in Sect. 4. Performance evaluation and analysis are presented in Sect. 5. Finally, we conclude conclusions in Sect. 6.

2 Related Work

For the DSNs and WSNs area coverage, some scholars conducted extensive researches in [6]. Wang et al. [1] and Ghosh [8] studied hybrid WSNs. They employed Voronoi diagram to solve coverage problem. Liang et al. [5] presented two distributed self-deployment schemes of mobile sensors, namely Circumcenter-based and Incenter-based. The former constructs Voronoi diagram by the circumcenter of sensor's sensing sector, if sensor does not get the optimal coverage, then sensor moves until the circumcenter coincides with the centroid of current cell. The later also adopts this pattern, difference is that it employs inceneter of sensor's sensing sector to construct Voronoi diagram.

In [4,7], authors put forward coverage enhance algorithms based on virtual force between sensors. Dan et al. [7] presented potential field based coverage-enhancing algorithm (PFCEA). PFCEA mainly takes centroid of sensing sector area as stressed point, sensor adjusts its working direction by resultant force from neighbor sensors. Liang et al. [4] also employed virtual force, the difference is that they added Voronoi diagram on the basis of [7] and proposed a scheme consists of four different forces caused by neighboring sensors and uncovered regions in the field, namely: the Centroid Push Auxiliary point Force (CPAF), the Centroid Push Centroid Force (CPCF), the Voronoi point Pull Centroid Force (VPCF), and the Neighbor Repulsive Force (NRF). Their core idea is to adjust working direction based on resultant force of sensor.

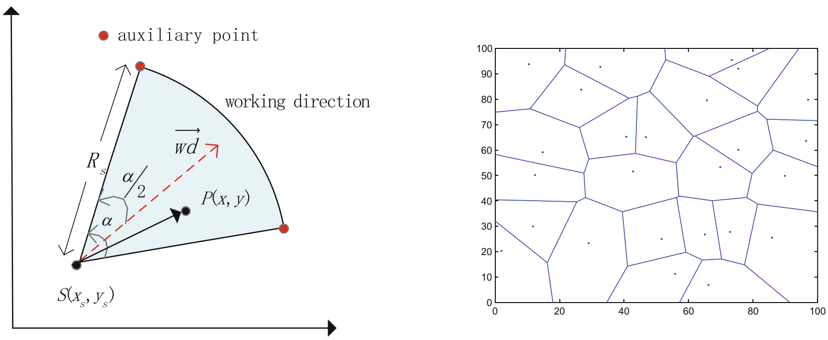
Sung and Yang [2,3] mainly adopted Voronoi theory and Delaunay triangulation to design distributed self-redeployment coverage enhancement algorithm. In DVSA [2], main idea is to calculate corresponding field angle and side length of each vertex in each polygon, and then compare AOV and R_s with field angle and side length. If result is equivalent, then sensor moves to that vertex and take the longer side as one boundary of sensing sector. In [3], they presented several coverage increment algorithms, Vertex-based adjustment with Voronoi diagram(V-VD), Edge-based adjustment with Voronoi diagram(E-VD), Edge-based adjustment with Delaunay triangulation (E-DT) and Angle-based adjustment with Delaunay triangulation (A-DT). In E-VD sensor chooses the midpoint of the farthest edge of its own cell as working direction.

In this paper we study the area coverage of DSNs in the case of random deplyment. Sensor makes a decision on adjusting working direction and updating location by the vertex information of Voronoi diagram. The final goal for the sensor is to get local maximum coverage in current cell.

3 Preliminaries

3.1 DSN Sensing Model

Compared with the traditional WSNs, directional sensor has some differences as shown in Fig. 1(a), which is characterized by directional working direction $\omega(-\pi \leq \omega \leq \pi)$ and AOV α. $\overrightarrow{wd}$ splits angle α and is defined as working direction vector which is unit vector. The effective coverage field of sensor is the sector area $\alpha R_s^2/2$. Two auxiliary points a_l, a_r we introduce are to help make decision later in our algorithm. Given a point $p(x, y)$ which is covered by the sensor $s(x_s, y_s)$, the following two conditions must be met:



(a) Sensing model (b) Voronoi diagram

Fig. 1. Sensing model of DSN and voronoi diagram.

(1) Euclidean distance between p and s must be smaller than sensing radius R_s.

$$d(s, p) = \sqrt{(x - x_s)^2 + (y - y_s)^2} \leq R_s \tag{1}$$

(2) Absolute included angle between $\overrightarrow{wd}$ and $\overrightarrow{sp}$ must be smaller then $\alpha/2$.

$$\phi = \arccos \frac{\overrightarrow{wd}\overrightarrow{sp}}{\|sp\|} \leq \frac{\alpha}{2} \tag{2}$$

3.2 Voronoi Diagram and Some Assumptions

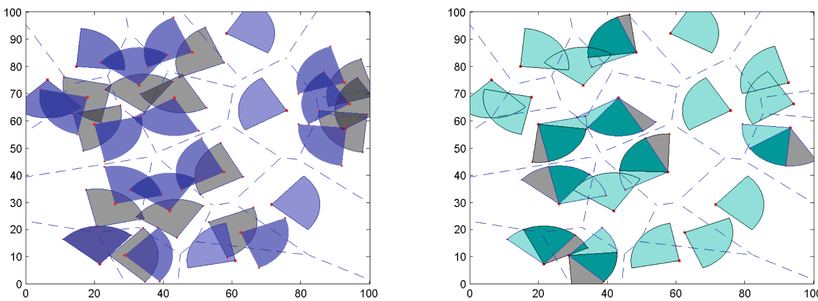
Voronoi diagram is an important data structure in computational geometry which is widely used in many fields. The main properties we need to use in this paper are that (1) each sensor s_i lies exactly in the current cell and any point p within the current cell has the shortest distance between sensor s_i and point p compares to other sensor i.e. $d(s_i, p) \leq d(s_j, p)$; (2) point in a shared edge of two sensors has equivalent distance from two sensors. Here, as a example we choose 25 random nodes to generate Voronoi diagram as Fig. 1(b) shows. In order to refine the question we study and make the key researched point stand out, some assumptions are made as follow:

(1) All of directional sensors are homogeneous, that is to say every sensor has the same sensing radius R_s, viewing angle α, rotation ability and mobility.
(2) For every sensor we can acquire accurate coordinate by GPS or other localization algorithm such as DV-hop, Amorphous and so on.
(3) All sensors have strong transmission ability to ensure the network connected and Voronoi diagram constructed successfully.

3.3 Problem Statement

Our ultimate aim is to reduce overlap and enlarge effective coverage in the target area. By using the rotating ability and mobility of sensor coupled with Voronoi information to make sensor get full coverage in every cell. Mobility and working direction adjustment must meet three principles:

(1) For every sensor, moving range is restricted at the current cell.
(2) To get maximal coverage in current cell and minimum overlap with other cell's sensor.
(3) Although we do not consider energy consuming, we only take the mobile distance as a measure of standards i.e. minimum moving distance meanwhile maximum coverage.



(a) Mobility　　(b) Rotation

Fig. 2. Example of results before and after execution of algorithms.

Here, we give a simple exhibition of mobility and motility as shown in Fig. 2. Figure 2(a) is mobility deployment, Fig. 2(b) is rotation deployment, grey area is the status after mobility and rotation.

4 Theoretical Analysis

4.1 Judge Whether Working Area is Wrapped by Polygon

If the sensor s and auxiliary points a_l, a_r all inside in polygon as Fig. 3(b) and (c) show, then we approximately think that sensor s gets full coverage, which means sensor does not need to move and rotate.

To prove the sensors's coverage field is wrapped in the cell, we can prove points s, a_l and a_r are all in the convex polygon. To prove whether one point (assuming p) is in the convex polygon, we exploit triangle segmentation to compute the convex polygon area S_{V_s} and the area S_{pv_s} constructed by p and V as Fig. 3(a) demonstrates. V_s denotes vertex set of sensor S.

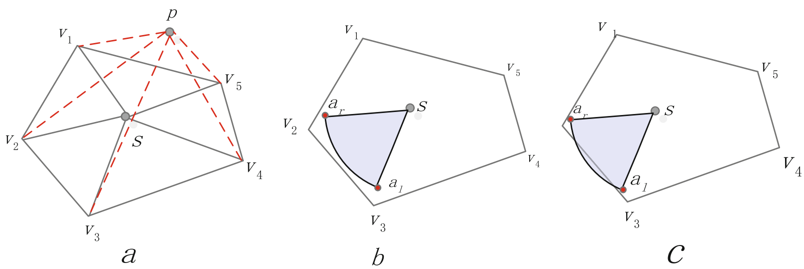


Fig. 3. Proof point in convex polygon and sector wrapped in convex polygon

$$S_{v_s} = \sum_{v_{i=1}}^{V_s-1} S_{\Delta s v_i v_{i+1}} \quad S_{pv_s} = \sum_{v_{i=1}}^{V_s-1} S_{\Delta p v_i v_{i+1}} \tag{3}$$

If $S_{v_s} = S_{pv_s}$, than we can judge that point p is inside in polygon. If two auxiliary points a_l, a_r of sensor s are all in the polygon, we can infer that sensor get relatively full coverage although not completely as shown in Fig. 3(c). If $S_{v_s} \neq S_{pv_s}$, which means sensor does not get full coverage in current polygon, then sensor will move or adjust $\overrightarrow{wd}$.

4.2 Move and Rotate Based on Vertex

If auxiliary points a_l, a_r are not all inside in current polygon, location and working direction will adjust. We choose the farthest vertex (assume v_1) of polygon as the $s's$ initial working direction mainly consider that original coverage may be relatively full, which can help to move by the shorter moving distance or make

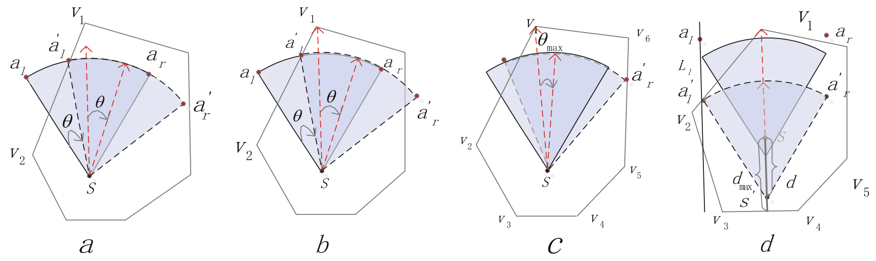


Fig. 4. Move and rotate inside cell

the smaller adjustment of working direction. Let we see Fig. 4(a), select v_1 as working direction $\overrightarrow{sv_1}$, there are two situations here:

Case 1: Rotate Working Direction Algorithm (RWD). $R_s \leq d(s, v_1)$ and auxiliary point a_r is inside of polygon the other auxiliary point a_l is not.

For this situation we can rotate the working direction by θ to get the aim of letting the $a_l^{\prime}s$ position update to $a_l^{\prime}$. While rotating θ may lead $a_r^{\prime}$ to be out of polygon as Fig. 4(b) shows, therefore we should primarily figure out θ_{max} (see in Fig. 4(c)) which is maximal rotation angle. If $\theta \leq \theta_{max}$, rotate working direction by θ, if not, rotate by θ_{max}. To compute θ and θ_{max}, as follow elaboration:

According to $s(x_s, y_s)$ and corresponding angle ω of $\overrightarrow{wd}$, we can get the included angle β of $L_{sa_l^{\prime}}$ relative to coordinate axis and coordinate of $a_l^{\prime}$.

$$\psi = \arctan(\frac{y_{v_1} - y_s}{x_{v_1} - x_s}) \tag{4}$$

if $\psi \leq 0$.

$$\begin{cases} \omega = \psi & x_{v_1} \geq x_s, y_{v_1} \leq y_s \\ \omega = \psi + \pi & x_{v_1} \leq x_s, y_{v_1} \geq y_s \end{cases} \tag{5}$$

if $\psi \geq 0$.

$$\begin{cases} \omega = \psi & x_{v_1} \geq x_s, y_{v_1} \geq y_s \\ \omega = \psi + \pi & x_{v_1} \leq x_s, y_{v_1} \leq y_s \end{cases} \tag{6}$$

if rotate to right

$$\begin{cases} \beta = \omega + \frac{\alpha}{2} - \theta \ \omega \geq 0. \\ \beta = \omega - \frac{\alpha}{2} + \theta \ \omega \leq 0. \end{cases} \tag{7}$$

if rotate to left

$$\begin{cases} \beta = \omega - \frac{\alpha}{2} + \theta \ \omega \geq 0. \\ \beta = \omega + \frac{\alpha}{2} - \theta \ \omega \leq 0. \end{cases} \tag{8}$$

We can get the θ for point $a_l^{\prime}(x_{a_1^{\prime}}, y_{a_1^{\prime}})$ is at line $L_{v_1 v_2}$.

$$\begin{cases} x_{a_1^{\prime}} = x_s + R_s \cos(\beta) \\ y_{a_1^{\prime}} = y_s + R_s \sin(\beta) \\ L_{v_1 v_2} = \arctan(\frac{y_{v_1} - y_{v_2}}{x_{v_1} - x_{v_2}})(x - x_{v_1}) + y_{y_1} \end{cases} \tag{9}$$

In a similar way see in Fig. 4(c), we can solve the θ_{max} according to the above method, the only difference is that we combine a_r' with line $L_{v_5v_6}$.

Case 2: Move Inside Cell Algorithm (MIC). Two auxiliary points of sensor s are all outside of polygon, Fig. 4(d).

For this situation, sensor should move, moving direction and moving distance are primarily under consideration. We choose the reverse direction of $\overrightarrow{sv_1}$ as moving direction and take a_l which is far from polygon as reference point for reason that if a_1 is moved into polygon then a_r is also in polygon. Sensor moves until a_1 is exactly in the edge of polygon, so moving distance $d = d(a_l, a_l') = d(s, s')$. If $d \leq d_{max}$, moving distance by d, if not move distance by d_{max}. a_l' is intersection of line L_1 and $L_{v_1V_2}$, then if we can find out L_1 and $L_{v_1V_2}$, problem will be solved. Constructed calculation of d and d_{max} is as below:

$$\begin{cases} x_{a_1} = x_s + R_s cos(\omega + \frac{\alpha}{2}) \\ y_{a_1} = y_s + R_s sin(\omega + \frac{\alpha}{2}) \\ L_1 = \psi(x - x_{a_1}) + y_{a_1} \\ L_{v_1v_2} = \frac{y_{v_1} - y_{v_2}}{x_{v_1} - x_{v_2}}(x - x_{v_1}) + y_{v_1} \end{cases} \tag{10}$$

we can get the coordinate of a_1' by combining L_1 with $L_{v_1v_2}$. Similarly d_{max} can be worked out by combining $L_{ss'}$ with $L_{v_3v_4}$. Updated sensor location (x_s', y_s'):

$$x_s' = \begin{cases} x_s - d_{max} * cos(\omega) & d_{max} \leq d \\ x_s - d * cos(\omega) & d_{max} > d \end{cases} \tag{11}$$

$$y_s' = \begin{cases} y_s - d_{max} * sin(\omega) & d_{max} \leq d \\ y_s - d * sin(\omega) & d_{max} > d \end{cases} \tag{12}$$

5 Performance Evaluation

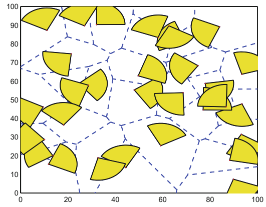
In this section, we conduct corresponding simulations about the algorithms we have designed. In order to make a remarkable contrast, we compare RWD and MIC with random deployment and DVSA [2]. Some essential parameters in the simulation are listed at following Table 1.

Table 1. Main notations.

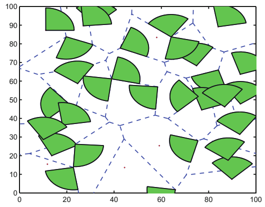
The number of sensors N	N = 30, 60, 90, 120, 150, 180, 210, 240, 270, 300
Sensing radius	$R_s = 6\,\text{m}, 8\,\text{m}, 10\,\text{m}, 12\,\text{m}$
Angle of view AOV	$\alpha = \frac{\pi}{2}$
Size of monitoring area	$Area = 100\,\text{m} \times 100\,\text{m}$

5.1 Sensing Coverage

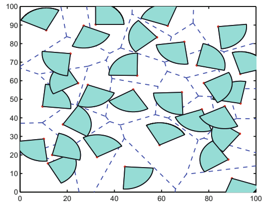
We chose $R_s = 12\,\text{m}$, AOV is $\frac{\pi}{2}$ and the number of sensor is 30 as the initial conditions. We compare our algorithm with Random Deployment and DVSA [2]. Figure 5(a) is the random deployment and Fig. 5(b) is the DVSA deployment, Fig. 5(c) is the RWD deployment, Fig. 5(d) is MIC deplyment, the last one Fig. 5(e) is RWD coupled with MIC.



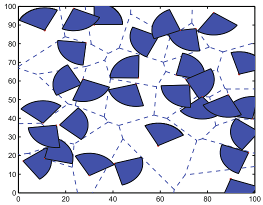
(a) Random



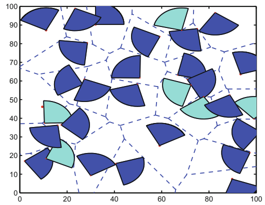
(b) DVSV



(c) RWD



(d) MIC



(e) MIC coupled with RWD

Fig. 5. Coverage.

5.2 Coverage Ratio

Coverage ratio is basic measure of DSNs. Figure 6 shows five kinds of coverage ratio. From the simulation results we can see that MIC coupled with RWD get the optimal result. when the number of sensors N is less, coverage increment ratio is not so remarkable and when N is relatively big, coverage increment ratio is obvious, if N is big enough, then advantage disappears. However, this situation is foreseeable and understandable.

5.3 Moving Track

Although in this paper we do not consider energy consuming, we only take moving distance as the measure of energy consumption. In DVSA, sensor moves to the vertex with side length and field angle similar to R_s and AOV, while in MIC sensor makes a decision to move based on whether the auxiliary points

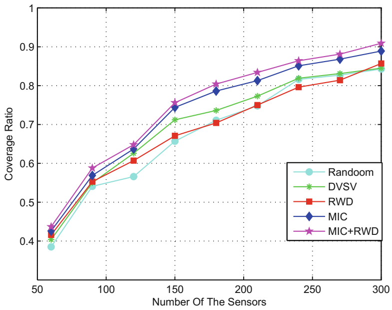
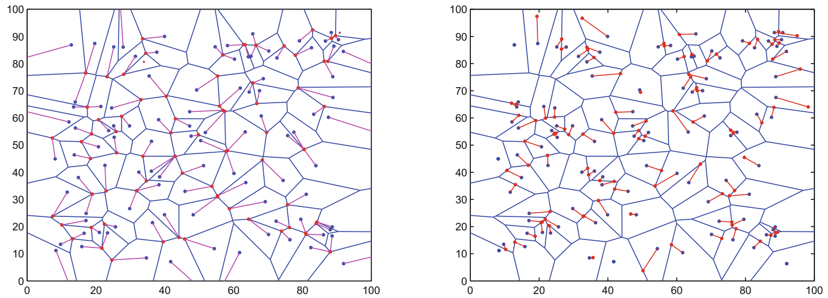


Fig. 6. Coverage ratio.

are in current polygon. Obviously, the former needs all sensors to move to the vertex, the latter does not. Figure 7(a) is the DVSA moving track and Fig. 7(b) is the MIC moving track, blue point is initial position and red point is updated position. Clearly, we can see MIC moving distance is the shorter than DVSA, besides, not all sensors in MIC need to move.



(a) Random (b) DVSA

Fig. 7. Moving track. (Color figure online)

6 Conclusions and Future Work

In this paper, we study area coverage problem in DSNs and propose MIC and RWD coverage increment algorithms based on Voronoi. In order to have a measure for mobility and rotation, we introduce two auxiliary points a_l and a_r. By comparing the simulation results of MIC and RWD with DVSA and random deployment in sensing coverage, coverage ratio and moving track aspects, our algorithms outperform others. As to our future work, we are prepared to embark on researching energy consumption and networks life-time problems.

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References

1. Wang, G., Cao, G., Berman, P., Porta, T.F.L.: Bidding protocols for deploying mobile sensors. IEEE Trans. Mob. Comput. **6**(5), 515–528 (2007)
2. Sung, T.-W., Yang, C.-S.: Distributed Voronoi-based self-redeployment for coverage enhancement in a mobile directional sensor network. Int. J. Distrib. Sens. Netw. **2013**, 1456–1459 (2013)
3. Sungn, T.-W., Yang, C.-S.: Localised sensor direction adjustments with geometric structures of voronoi diagram and delaunay triangulation for directional sensor networks. Int. J. Ad Hoc Ubiquit. Comput. Arch. **20**(2), 91–106 (2015)
4. Liang, C.-K., Chung, C.-Y., Li, C.-F.: A virtual force based movement scheme for area coverage in directional sensor networks. In: 2014 Tenth International Conference on Intelligent Information Hiding and Multimedia Signal Processing, pp. 718–722 (2014)
5. Liang, C.-K., He, M.-C., Tsai, C.-H.: Movement assisted sensor deployment in directional sensor networks. In: 2010 Sixth International Conference on Mobile Ad-hoc Sensor Networks, pp. 226–230 (2010)
6. Guvensan, M.A., Yavuz, A.G.: On coverage issues in directional sensor networks: a survey. Ad Hoc Netw. **9**(7), 1238–1255 (2011)
7. Tao, D., Ma, H.-D., Liu, L.: A virtual potential field based coverage-enhancing algorithm for directional sensor networks. J. Softw. **18**(5), 1152–1163 (2007)
8. Ghosh, A.: Estimating coverage holes and enhancing coverage in mixed sensor networks. In: IEEE International Conference on Local Computer Networks, pp. 68–76 (2004)
9. Aurenhammer, F.: Voronoi diagrams - a survey of a fundamental geometric data structure. ACM Comput. Surv. **23**(3), 345–405 (1991)