Triangle Area Segmentation for Coverage Measurement in Wireless Sensor Networks

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Abstract—Sensing coverage is one of the principal trade-off factors in Wireless Sensor Network design. It is necessary to have a minimum bound of sensing coverage in a sensor network in various aspects like scheduling, target tracking or redeployment phases. There are several methods to determine the sensing coverage. However, a system to provide detailed information about the coverage is still missing. In this paper, we propose a new coverage measurement method using Delaunay Triangulation (DT) that it can provide the coverage value and density distribution of sensors including the number of sensors in dense areas, scattered areas and as well as the number of sensors on the borders among those areas. The simulation results show that the proposed DT method can obtain accurate knowledge of the sensing coverage.

Keywords—ireless Sensor Network, Sensing Coverage, Delaunay Triangulationireless Sensor Network, Sensing Coverage, Delaunay TriangulationW

1 Introduction

Wireless Sensor Network (WSN) has caught the attention of many researches in ad-hoc networks. There are many challenges recognized in this field regarding to have a successful WSN implementation such as sensor scheduling, routing, redeployment or sensor movement. Since the WSN goal is to sense a phenomenon, in all those challenges, using a suitable tool to evaluate sensing coverage can be a promising key to success.

Sensing coverage is defined as a ratio of the sensible area to the entire desired area [1]. While in the ideal environment, this sensible field must be equal to the desired (Deterministic Coverage), [2] showed that by scarifying a small amount of coverage (Stochastic Coverage), the network lifetime can be increased by 3 to 7 times longer. Gaining the network lifetime is particularly influential in WSN where usually changing or charging the sensors batteries are not practical and deploying new sensors in the field may be extremely costly.

The sensing coverage can be classified as a Quality of Service (QoS) characteristic. Nevertheless, the question is how to determine the sensible area in stochastic coverage. In many optimization applications for WSN, the trade off factor is the sensing coverage. Therefore, having an appropriate method to calculate the coverage can alter the optimization quality.

In this paper, we propose a new method to determine the sensing coverage which can provide more detailed information about the coverage characteristics than its priors. This approach is based on Delaunay Triangulation criterion and is useful in many different challenges of WSN.

The rest of this paper is as follows: Section II contains the research background and earlier methods for calculating sensing coverage. In Section III, the coverage measurement model is explained. Two different approaches are proposed subsequently in Sections 4 and 5. This paper is concluded in Section VI.

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2 Research Background

There are several methods to determine the sensing coverage in the WSN field. Each method has its own advantages and disadvantages. In the rest of this section, different approaches for calculating the sensing coverage are discussed.

The simplest method to calculate the sensing coverage is the grid based model [3], [4]. In this method, the mission field is divided to several small square grids. Each grid indicates one sensible area where at least one sensor must be placed inside. The exact location of sensors inside the grid does not influence on the sensing coverage. To determine the coverage percentage, number of grids that have at least one active sensor inside, must be divided to all grids.

The most favorite method for finding sensing coverage is the circular model [2], [5], [6], [7], [8]. In this model, all the sensors have a sensing range (R_s) as a circle shape around themselves. The value of R_s could be a constant like $R_s = 20m$ [5] or related to communication range (R_t) such as $R_s >= R_t/\sqrt{3}$ [2] or $2R_s = R_t$ [8].

Circular models with shadowing effect are similar to ordinary circular model except that they have added an feature called R_u to R_s [1], [9], [10]. R_u indicates the circular area outside of sensing area, which is still sensible but with some probability. So in such works, the sensing coverage can be defined as follows:

- If the object be in R_s range, it will be sensed for sure.
- If the object be between R_s and R_u there is the probability p to capture it.
- If the object be out of R_u range, it is not sensible.

Another method to determine the sensing coverage is circular probabilistic model [11], [12], [13]. It is like circular model with shadowing effect but $R_s = 0$. The sensing function could be defined as follows:

- If the object is in the R_u range, there is the probability p to capture it.
- The value of p decreases by getting far from sensors.
- If the object is out of the R_u range, it is not sensible.

In non-unit circular model [14], which is a different technique for measuring the sensing coverage, the sensing area is an ellipse where the sensor can change it by choosing different energy values for sensing. If the sensors could change the ellipse radiuses, they could make it narrower or wider to improve the network coverage significantly.

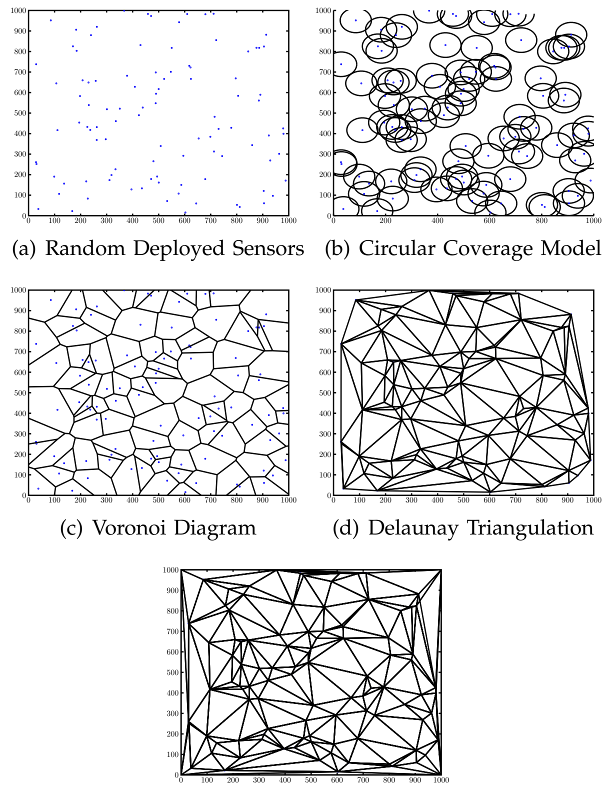
Voronoi algorithm, as another calculation method, partitions the field in such way that every point is in a polygon of its closest sensor [15], [16], [17], [18]. The polygons created by Voronoi algorithm are convex and the area of each polygon is also called the area of influence. However, all methods used Voronoi as a clustering system to determine the scheduling for sensors, the coverage measurement is still based on the circular model.

To the best of our knowledge, circular model with shadowing effect, circular probabilistic model, non-unit circular model and Voronoi algorithm have not been used to calculate the complete coverage of the network. These methods have been used only to find out whether or not a particular event can be detected near by a sensor. However, the grid base model and the circular model have been used as a network coverage measurement tool to determine how much of the desired area is sensible.

3 Coverage Measurement Model

The current coverage measurement tools provide a percentage of the sensible area to the desired area. This supplied result could not clarify that how the uncovered areas are distributed among the sensible area which is defined as the uniformity of coverage. It has been shown that the uniformity of coverage has a great influence on efficiency of WSN in target tracking applications [19]. The new coverage measurement tool, proposed in this paper, uses a partitioning concept to identify the coverage level in different areas of the field.

As a new coverage model, we propose area segmentation using triangulation algorithms. There are different types of triangulation methods. However, an optimized triangulation algorithm maximizes the minimum angles of each triangle. This makes them more like equilateral triangles that are used as an approximation in the proposed method. Delaunay Triangulation (DT) is an optimized triangulation algorithm. A triangulation $T(P)$ is a Delaunay Triangulation of P, denoted as $DT(P)$, if and only if, the circumcirlce of any triangle of T does not contain any other point of P in its interior. For more information about DT's algorithm and application, readers may refer to [20].



(a) Random Deployed Sensors (b) Circular Coverage Model

(c) Voronoi Diagram (d) Delaunay Triangulation

(e) DT (Corrected)

Fig. 1. A Sample With Different Coverage Model Approaches

The DT coverage measurement tool needs global information about sensors' positions. So this method is applicable to those applications that supply the network coverage by global information. Moreover, as a comparison tool for results, this method is also useful for applications working with local data.

Fig 1 shows a random deployment of sensors, circular coverage model, Voronoi diagram and DT. As its clear from the Fig. 1(d), the outer polygon of the coverage model may not cover all the field. To solve this problem, since the outer polygon in DT is always a convex hull [20], we put four additional sensors on the corners to have a full triangulation over the field as in Fig. 1(e). These four points also applied to circular and Voronoi models in order to have similar sensors' distribution of our proposed DT method.

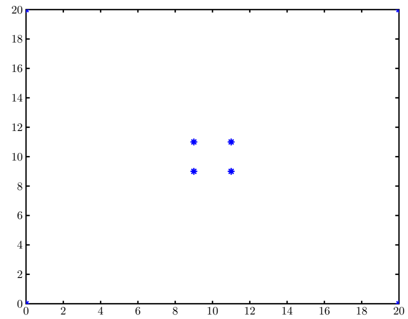
In this paper, we propose two approaches to analyze the DT coverage model. In the first step, the area of each triangle is used to get more information about the coverage. As a second step, the length of the triangle's edges is examined to find many useful information about the coverage.

TABLE 1
Random Deployment of 50 Sensors in 20*20 Area

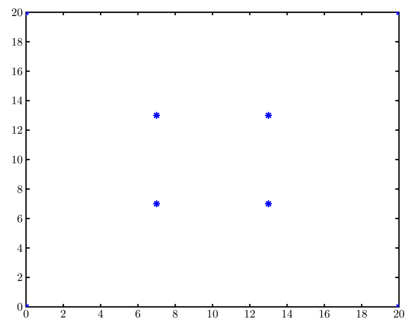
Circular			Voronoi	Delaunay
Radius	Coverage	Area	Frequency	Frequency
0.5	40.85	0-2	7	34
1	136.32	2-4	8	28
1.5	244.66	4-6	10	20
2	320.50	6-8	7	14
2.5	361.20	8-10	7	1
3	381.22	10-12	7	0
3.5	393.36	12-14	4	0
4	399.77	14-16	2	4
		16-18	0	0
		18-20	0	1
		20-22	2	0

TABLE 2
Difference Between Voronoi and DT Coverage Models

	Voronoi		DT	
	Area	Number	Area	Number
First Scenario	4	40.5	2	2.0
	4	59.0	4	9.0
			4	90.0
Second Scenario	4	24.5	2	18.0
	4	75.0	4	21.0
			4	70.0



(a) Scenario One



(b) Scenario Two

Fig. 2. Comparing The Voronoi And DT Coverage Models

4 The Area of Triangles

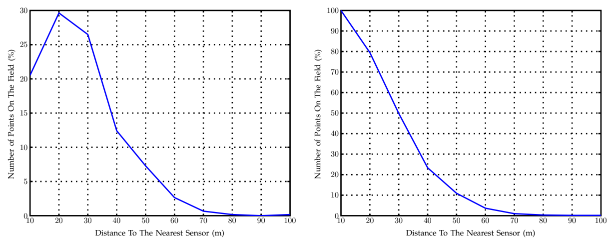
Both DT and Voronoi coverage models can offer a detailed information about the coverage pattern in the field by providing the areas of the triangles or polygons. The area and the frequency of each area show the uniformity of the sensors in the field while the circular coverage model just provide one number or percent of coverage which has very limited information about the dispersion of sensors in the field. Table 1 compares the circular coverage model with Voronoi and DT. In this comparison, the areas of polygons and triangles and the frequency of them explore the uniformity of sensors' dispersion. However, in circular model, base on the sensing radius, just one number as the coverage value is presented in the table.

Although Voronoi and DT coverage models both provide useful information about the uniformity of distribution of sensors on the field, the Voronoi model may provide false information about the field in some cases like the following. We placed eight sensors in the field in two different positions as in Fig. 2 where four of them are in the center and other are in the corners. As we can see in the Fig. 2(a) sensors are very close together while in Fig. 2(b) there are more space between them than previous one. The areas for polygons and triangles of both Voronoi Diagram and DT model are presented in Table 2.

As it is shown in Table 2, four sensors are very close in the first scenario with a huge empty space around them, while in Voronoi coverage model these information is not retrievable by the areas of polygons. However, DT shows the dense area by 2 triangles with area size of 2.0 and the empty space with 4 triangles with the area size of 90.0. In addition, in second scenario, sensors create more scattered pattern than first one, according the Voronoi results, it seems that this scenario has an area which is more dense than previous one (4 triangles with area size of 24.5 versus same number of triangles with the area size of 40.5 in first scenario). In DT coverage model, the results can describe the dispersion of sensors in the field. Two small triangles with the area size of 2.0 are bigger now with the size of 18.0 as well as the four big triangles which are smaller in the second scenario. The reason that Voronoi analysis may lead to wrong conclusion is that the computed area is based on the polygon which is around sensor where sensor could be very close to each edge of this polygon and the polygon may have any size. However, DT is based on the triangles which their edges are distances between sensors. Therefore, when sensors are close together the area of the triangles are smaller and vice versa.

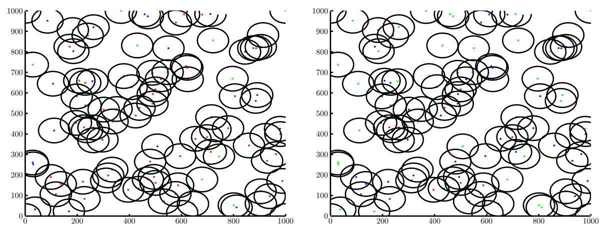
5 The Length of The Lines

In DT method, we are sure that at least the two closest sensors to a specific one are connected to it by the triangle's edges. So the first part of information revealed from DT line analysis is to find out the nearest sensors to each one. This information is very useful in radio coverage analysis to find out that is there any node outside of the coverage area. This data shows that how many of sensors are completely alone in terms of having a enough closed neighbor. Fig. 3(a) shows a histogram of distribution of the nearest neighbors for sensors in a random distribution network where the field area is the 1000*1000 meter and there are 600 sensors in the field.



(a) PDF (b) CDF

Fig. 3. The Nearest Distance From Points on The Fields to The Sensors



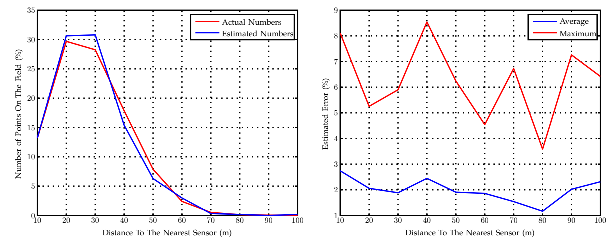
(a) $K_1 = 3, K_2 = 1$ (b) $K_1 = 5, K_2 = 2$

Fig. 4. Finding Dense, Scatter And Border Area Sensors

Clearly, the largest distance between sensors is about 100 meters and majority of them are in 20 meters to 30 meters of each other. Moreover, the CDF plot (Fig. 3(b)) shows that about 10% of sensors are in more than 50 meters of each other. This information is very useful to both examine the communication coverage of the network and find out that with what resolution sensors are harvesting data from the field.

As one of the DT properties, when the number of vertexes is more than 4, and they are not on a straight line, the degree of each vertex is more than or equal to three. This means that for each sensor, distances to the more than three closest sensors are available. By defining a limit value, three different types of sensors are defined: sensors inside dense areas, sensors outside dense areas and sensors which are on borders of two former types. A sensor is in the dense area if it has K_1 neighbors than the limit value. Sensors are in scattered areas if it has fewer than K_2 neighbors closer than limit value, and otherwise it is a border sensor. Fig. 4 shows how this method can categorize between sensors when they have to have at least a number of neighbors to be a sensor in the dense area. Finding the percentage of border nodes could be very useful, because these sensors usually carry a high burden of network transmissions to other sensors, and they may lose their energy sooner than others. Moreover, the percentage of the sensors in dense areas can reveal that how much a scheduling algorithm is needed to inactivate the unnecessary sensors.

The next part of information retrieved from DT line analysis is the coverage resolusion. Consider $S1, S2$ and $S3$ are three neighbors where their distances to each other are the same and they create an equilateral triangle. The farthest point from $S1, S2, S3$ inside the triangle is the center of its circumcircle and the radius of that circle



(a) A Sample Of Distance Estimation (b) Estimation Error

Fig. 5. Finding The Distance of All Points of The Field to Their Nearest Sensor

is the distance from each sensor to the farthest node. Let d_s as the distance between $S1$ and $S2$ and d_o as the distance from each sensor to the center of circumcircle. The relation between d_s and d_o is $d_o/d_s = 0.58$.

As a sampling procedure for finding the distances between every point in the field to its nearest sensor, we propose these steps. First, we find the two nearest neighbor distance by running the DT algorithm. Next, we calculate the average value of these two distances. By estimating that triangles are close to equilateral triangles, we find the distance to the circumcircle center by the formula discussed in previous paragraph. These values are used as the sampling points to identify the distances of all points of the fireld to thier nearest sensors. The results show that the histogram of distribution of these sample points is very close to the real distance of all points in the field to their nearest sensor.

6 Conclusion

The proper information about the coverage attributes in a Wireless Sensor Network could take the positive impact on the algorithms which work to keep coverage for the network. The previous coverage measurement tools just add a single percent of the sensible area to the desired area. However, finding the structure of the coverage on the field could help the researchers to create more uniform coverage areas in order to prolong the network lifetime. In this paper, we proposed a new coverage evaluation method based on DT which it can obtains detailed information about the areas between sensors, distance between sensors, dense, scatter and border area sensors. This information can help to have a better understanding of the coverage properties of different coverage promising algorithms, and also it is a better comparison tool for them.

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