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Coverage Strategies for Wireless Sensor Networks

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Abstract**—**Coverage is one of the main research interests in wireless sensor networks (WSN), it is used to determine the quality of service (QoS) of the networks. Therefore this paper aims to review the common strategies use in solving coverage problem in WSN. The strategies studied are used during deployment phase where the coverage is calculated based on the placement of the sensors on the region of interest (ROI). The strategies reviewed are categorized into three groups based on the approaches used, namely; force based, grid based or computational geometry based approach.

Keywords**—**Computational geometry, coverage, Delaunay triangulation, force, grid, Voronoi diagram, wireless sensor networks.

I. INTRODUCTION

IN recent years wireless sensor networks (WSN) have become one of the most active research areas due to the bright and interesting future promised to the world of information technology. Nowadays the Internet provides us with the latest information, but these information could easily be outdated if the moderator failed to update the information. However this kind of problem would not be an issue in WSN as the network is simultaneously monitoring and reporting the situation of the task assigned to it [1]. The advantage of WSN can be seen in the following scenario; a motorist is planning to take a highway which is monitored by WSN, using the data supply by WSN the motorist could check the traffic flow along the highway prior to the journey. Therefore should an accident occur that causes massive traffic congestion, the motorist could change the original route plan and opt for a different route thus avoiding from being trapped in the traffic. In this situation the motorist received the information much faster by using WSN than typical information channels.

Traffic monitoring as describe above is one of the many applications of WSN. In general the applications of WSN can be divided into military, civilian and health care [2]. Among the military use of WSN are targeting system and battlefield surveillance. For the civilian application, WSN can be applied in environmental monitoring, building monitoring and control, wildlife monitoring, security, smart agriculture system and many other applications. In health care, WSN can be used to monitor the vital signs of critical illness patients and it is very useful in elderly care, where the sensors can be used to track down the location of the elders.

So what is WSN? WSN is a group of low-cost, low-power, multifunctional and small size wireless sensor nodes that work together to sense the environment, perform simple data processing and communicate wirelessly over a short distance [3]. Some of these sensor nodes are able to move on their own, this is achieved by mounting the sensors on mobile platforms such as Robomote [4]. With the ability to move independently these mobile sensors are able to self deploy and self repair thus adding more to its value [5].

However these wireless sensors have several constraints such as restricted sensing and communication range as well as limited battery capacity [3]. These limitations bring issues such as coverage, connectivity, network lifetime, scheduling and data aggregation. In order to prolong the WSN lifetime, energy conservation measures must be taken, scheduling and data aggregation are among the commonly used methods. Scheduling conserves energy by turning off the sensor whenever possible, while data aggregation try to conserve energy by reducing the energy used in data transmission. Connectivity and coverage problems are caused by the limited communication and sensing range. To solve both problems the solution lays in how the sensors are positioned with respect to each others. Coverage problem is regarding how to ensure that each of the points in the region to be monitored is covered by the sensors. It is a unique problem, in maximizing coverage the sensors need to be placed not too close to each other so that the sensing capability of the network is fully utilized and at the same time they must not be located too far from each other to avoid the formation of coverage holes (area outside sensing range of sensors). On the other hand from connectivity point of view, the sensors need to be placed close enough so that they are within each other communication range thus connectivity is ensured.

This paper studies the works done in solving the coverage problem. Overall the body of literature reviewed here can be grouped into three different focus directions; force based, grid based and computational geometry based. Force based methods use attraction and repulsion forces to determine the optimal position of the sensors while grid based methods use grid points for the same objective. As for the computational geometry approach, Voronoi diagram and Delaunay triangulation are commonly used in WSN coverage optimization algorithm. The aim of this paper is to compare and contrast the different strategies for WSN coverage.

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The rest of this paper is organized as follows. Section 2 will discuss on the definition of the coverage problem. Then the strategies used in solving the problem and examples of the algorithm will be presented in section 3. After that, future research directions on WSN coverage problem is discussed in section 4. The paper is ended with conclusion in section 5.

II. COVERAGE

A sensor's prime function is to sense the environment for any occurrence of the event of interest. Therefore coverage is one of the major concerns in WSN. In fact it is a key for evaluating the quality of service (QoS) in WSN [6]. According to [6], coverage can be classified into three classes; area coverage, point coverage and barrier coverage. Area coverage, as the name suggest is on how to cover an area with the sensors, while point coverage deals with coverage for a set of points of interest. Decreasing the probability of undetected penetration is the main issue in barrier coverage. Most of the works discuss in this paper deal with area coverage where the objective is to maximize the coverage percentage; ratio of area covered by at least one sensor to the total area of the region of interest (ROI). Coverage problem can also be seen as a minimization problem [7], where from the minimization point of view the objective is to make sure the total area of the coverage holes in the network is as small as possible.

Coverage problem in WSN basically is caused by three main reasons; not enough sensors to cover the whole ROI, limited sensing range and random deployment. Since the sensors are operated using limited power supply some of them might die out therefore resulting in inadequate sensors to fully cover the whole ROI, causing holes to exist. A sensor's sensing range is restricted to certain radius which consequently brings coverage problem. Of course this problem can be solved by using sensor with larger sensing range, but this type of sensor is more expensive [8]. One of the appealing aspects of WSN is the ability to be randomly deployed without the need to do it manually. The random deployment can be done using method such as air drop, this enable the WSN to be applied in hostile and unreachable environment such as battlefield and a steep terrain. However random deployment could cause some of the sensors being deployed too close to each other while others are too far apart. In both situations coverage problem will arise, for the first condition, the sensing capabilities of the sensors are wasted and the coverage is not maximized, while in the later state, blind spots will be formed.

As stated above coverage can be enhanced by using sensors with larger sensing range but this is costly, thus among the commonly used solutions, is to address the problem during deployment phase. Other than random deployment, the deployment of WSN can be done using a predetermine plan [3]. In predetermine deployment the WSN coverage is improved by carefully planning the positions of the sensors in the ROI prior to their deployment. The sensors later are placed according to the plan either by hand or with the help of mobile robot. For random deployment, the initial coverage can be enhanced by manipulating the locomotion capability of the sensors or by using incremental deployment after the initial one. The sensors with capability to move independently are able to self configure after early deployment so that a better arrangement is achieved and coverage is increased. Overall for both deployment methods the aim is to solve the coverage problem using sensors' placement, hence the problem can be expressed as; given a set of N number of sensors, $S = \{s_1, s_2, \ldots, s_N\}$ and a ROI, the coverage problem is how to position the sensors in the ROI so that the coverage percentage is maximized and coverage holes is minimized. The following section will review the various strategies use to achieve this.

III. STRATEGIES

This section reviews the strategies used in solving coverage problem in WSN which are done during deployment stage. The strategies are divided into three categories force based, grid based and computational geometry based.

A. Force Based

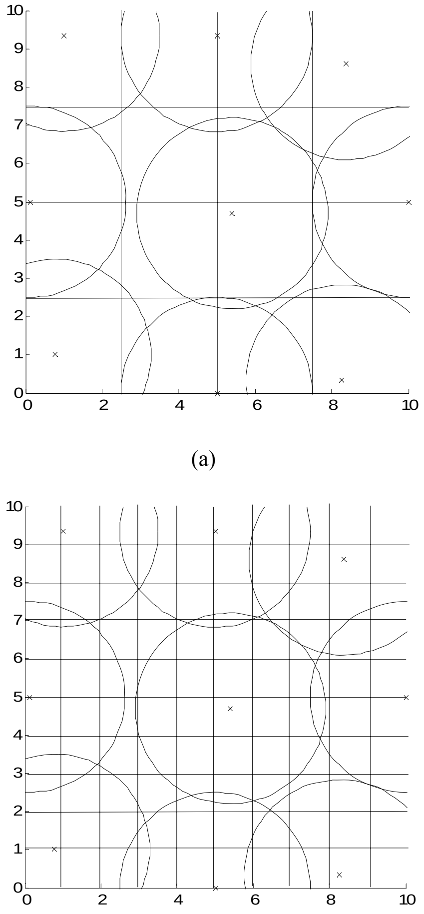
Force based deployment strategies rely on the sensors' mobility, using virtual repulsive and attractive forces the sensors are force to move away or towards each other so that full coverage is achieved. The sensors will keep moving until equilibrium state is achieved; where repulsive and attractive forces are equal thus they end up canceling each other.

In [9] the sensors and objects in the ROI exert virtual repulsive force that pushes sensors away from the objects and also from each other so that their sensing areas are not overlapping. The sensors will keep moving until static equilibrium state is reached. The static equilibrium state is reached based on the fact that the total energy is reduced with time. In changing environment, whether the change occurs periodically or sporadically, the network arrangement will be different with every change. However this strategy did not consider the network's connectivity. Thus it was further extends to consider network connectivity [5]; node degree (number of neighbors each sensor can communicate with) is used to provide attractive force so that full connectivity is maintained. The advantages of potential field method are; it does not need any prior information on the environment, localization or nodes communication making it a distributive, robust and scalable deployment strategy. Although this method does ensure full coverage and full connectivity, but it extremely depends on mobility, which is a high power consumption task [4]. Other than that this method is also reported to be computationally expensive [3].

Virtual force algorithm (VFA) as suggested in [10] is using almost similar approach as in [5&9] however instead of physically moving the sensors, VFA does the simulation of the movement first and the physical movement is only done one time at the very end of the process. VFA is meant to be executed by the cluster head where computational power is higher compared with the sensor nodes. A sensor can produce either repulsion or attraction force; whenever they are closely placed together the sensors will repel each other to enhance coverage, when they are too far apart attractive force will be produced so that global uniform distribution of sensors is achieved. Other than the sensors, obstacles and areas of preference also exert forces. The obstacles exert repulsive force to push the sensors away from them while areas of preference produced attractive force to pull sensors to cover these areas. The coverage is evaluated in this work using ratio of grid points covered to total grid points. The algorithm stops either when the coverage requirement is met or the maximum iteration is exceed. For *n*×*m* grid points and *k* number of sensors the complexity of VFA is *O(nmk)*.

B. Grid Based

Grid points are used in two ways in WSN deployment; either to measure coverage as used in VFA or to determine sensors positions. Coverage percentage as stated before is; ratio of area covered to the area of ROI. However to calculate the area covered is not an easy task especially when we might end up having irregular shape of area due to overlapping sensing range, therefore researcher had resort to using sampling methods, where only a set of points in side the ROI is used to evaluate the coverage.



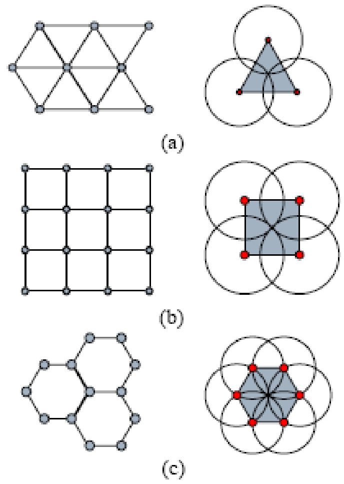
(a)

(b)

Fig. 1 Grid based coverage estimation for 9 sensors with sensing range equal to 2.5 in ROI of 10x10.(a) Grid size: 2.5x2.5; coverage estimated: 100% (b) Grid size: 1x1; coverage estimated: 95%

Grid is among the sampling method commonly used such as in [7&10]. The coverage is estimated as ratio of grid points covered to total number of grid points in the ROI. The cost of this method is determined by number of grid points; *n*×*m* and amount of sensors deployed; *k* [7]. The accuracy of the estimation is determined by the size of each grid, the smaller the size the more accurate the estimation is, this can be observed in Fig. 1, where 9 sensors with sensing range equal to 2.5 are deployed over ROI of area 10x10. In Fig. 1(a) the grid size is 2.5x2.5 which is equal to sensing range, in this case as all grid points are covered, hence the coverage estimated would be equal to 100%. But as what can be seen, clearly this is not true, thus when a smaller grid size adopted as in Fig. 1(b) where grid size is change to 1x1, a more accurate result can be obtained, the coverage value given here is equal to ≈95%.

Grid points can also be used in predetermine deployment method. The sensor nodes in this method need to be carefully placed exactly at the designated grid points [11]. This method promises to provide certain percentage and degree of coverage (number of sensors covering each point in ROI) and also the connectivity [12]. There are three types of grids commonly used in networking; triangular lattice, square grid and hexagonal grid (Fig. 2). Triangular lattice is the best among the three kinds of grids as it has the smallest overlapping area hence this grid requires the least number of sensors, square grid provide fairly good performance for any parameters while hexagonal grid is the worst among all since it has the biggest overlapping area [13]. Other than type of grid the size of grid also plays an important role. The size of grid need to be chosen based on how dense the WSN going to be. For a highly dense network small size grids help in reducing coverage holes thus providing better result. But in a sparse network large grid size is better as it will avoid overlapping of sensors' sensing range therefore ensuring full utilization of their sensing capabilities. The guaranteed coverage assured by grid based deployment can be compromised by errors such as misalignment and misplacement [11].



(a)

(b)

(c)

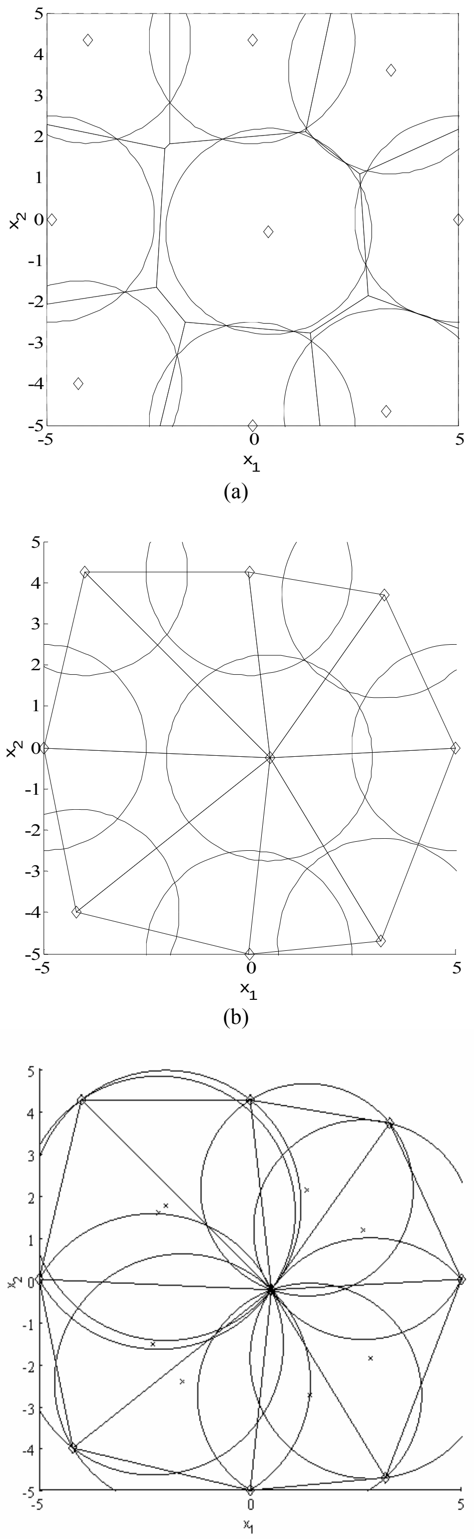
Fig. 2 Types of grids (a) Triangular lattice (b) Square grid (c) Hexagonal grid

Grid-based sensor networks as described in [14] divide the ROI into square grids and the sensors can only be placed at the center of the square. The authors then study the effect of the size of grids with respect to the sensing range to object penetration. The result is the bigger the grid size with respect to the sensing range the higher the probability that an object can penetrate the area without detection, provided that the object is traversing along the grid lines. Chakrabarty [8], also used square grid in his work, the grid points are used to conduct surveillance in WSN. He proposed that if each grid points are covered by a unique subset of sensors the target's location inside the ROI can be identified easily. This work also considers heterogeneous WSN where sensors with different specifications such as sensing range are considered.

C. Computational Geometry Based

Computational geometry is frequently used in WSN coverage optimization, the most commonly used computational geometry approach are Voronoi diagram and Delaunay triangulation. Voronoi diagram is partition of sites (shown as ◊'s in fig. 3a) in such a way that points inside a polygon are closer to the site inside the polygon than any other sites, thus one of the vertices of the polygon is the farthest point of the polygon to the site inside it. Therefore Voronoi diagram can be used as one of the sampling method in determining WSN coverage; with the sensors act as the sites, if all Voronoi polygons vertices are covered then the ROI is fully covered otherwise coverage holes exist [11]. Delaunay triangulation is the dual of Voronoi diagram [15]. A Delaunay triangle is formed by three sites provided if and only if the sites' circumcircle does not contain other sites (Fig. 3b). The centre point of the circle is a Voronoi vertex with equal distance from each of the three sites (shown as x's in Fig. 3c).

[16] is among the works that used Voronoi diagram in enhancing WSN coverage using sensors' mobility. The protocols suggested start with initial random deployment of the sensors. Based on the sensors positions the Voronoi diagram of the network is constructed and the decision whether the sensors need to reposition or to stay will be made based on the diagram. The first protocol suggested is Vector-based algorithm (VEC), according to this algorithm; a sensor that fully covers its Voronoi polygon will exert expulsion force to push its neighbor away to improve coverage. Voronoi-based algorithm (VOR) is the second algorithm proposed; this algorithm tries to cover holes by moving the sensor towards its local maximum holes which is located at its farthest Voronoi vertex. In the last algorithm; Minimax algorithm, coverage hole is reduced by moving sensor towards the farthest Voronoi vertex but not as far as VOR algorithm. Another work that use Voronoi diagram is [17], in this paper, combination of static and mobile sensors were used. The static sensors will construct Voronoi diagram which will be used to detect coverage holes. Based on the size of a hole, a bid will be made by a static sensor to its closest mobile sensors with base price lower than the bid. Mobile sensors will decide where to move based on the highest bid received. This algorithm will stop when all the bids are lower than the base prices.



(a)

(b)

(c)

Fig. 3 (a) Voronoi Diagram (b) Delaunay Triangulation (c) Circumcircles of Delaunay Triangles

Voronoi diagram and Delaunay triangulation are used in [18] to estimate the worst and best case coverage. This work focuses in finding the maximal breach path (worst case coverage) – a path where an intruder can go through with the least probability of being detected, and the maximal support path (best case coverage) – a path with highest coverage. The work proved that a maximal breach path must lie on the edges of Voronoi diagram while maximal exposure path lie on the edges of Delaunay triangulation. The information obtained can be used in incremental deployment in order to decide where is the best place to deploy additional sensors to improve the coverage. Delaunay triangulation is also used in [19], the paper focused on how to add additional sensors after an initial random deployment so that the coverage is increased. It proposed a two stages method in adding the additional sensors. In the first phase coverage holes along the boundary and obstacles are eliminated by placing sensors with distance $\sqrt{2}*R$ (R: sensors' sensing radius) from each other along the border of ROI and obstacles. For the second phase, the deployment is refined using Delaunay triangulation and circumcircles. Since the circumcircles' centers are the least covered points in the circle, they are then taken as the possible positions for the new sensors. Each of the positions will be given a score and sensor will be deployed at the position with the highest score. The authors proved that their Delaunay triangulation method performs better than grid based algorithm and random deployment.

The complexity of the approach using computational complexity of computational geometry methods are controlled by the number of sensors/sites (N) and the algorithm used. The lower bound for the computational complexity of constructing Voronoi diagram is $\Omega(N \log N)$ [15]. As for the Delaunay triangulation there are several construction algorithms with computational complexity as low as $O(N \log N)$ [20].

IV. FUTURE RESEARCH DIRECTIONS

Even though there are already quite a number of researches conducted on the coverage problem of WSN, more works still need to be done so that a global solution can be achieved. Following is the list of potential research areas;

A. *Coverage with Constraints*

There are several issues in WSN that need to be addressed other than coverage. However some of these issues create conflicts and constraints to coverage optimization. Therefore works not only focusing in maximizing coverage but also optimizing these issues should be conducted so that a better WSN can be achieved. Among the issues are:

1) *Mobility*

There are a lot of works that depends on the locomotion capability of the sensors, such as discussed in 3.1. However for mobile sensors mobility is the most power consuming task [4], therefore more research that not only utilize the mobility but try to conserve energy by limiting and balancing the distance moved by the sensors should be conducted.

2) *Connectivity*

Connectivity has inverse relationship with coverage. While coverage can be increase by not placing the sensors too close to each other the connectivity requires the sensors not to be placed too far apart.

3) *K-Coverage*

Future research should focus on balancing coverage degree throughout the ROI which is to guarantee that each point in the ROI is covered by at least k (>1) number of sensors. Higher value of k will make the network become more robust to occurrence of any nodes failure.

4) *Scheduling*

Scheduling is related to k-coverage problem. When each points in a ROI is ensured to be covered by at least k sensors, some of these sensors can be put in sleep mode so that the energy can be conserve and network's lifetime is prolong.

B. *Heterogeneous Networks*

Most of the researches to date tend to only consider homogeneous sensors, where all the sensors have same specifications, including their sensing range. However in real life usually a WSN requires collaboration among multiple types of sensors with different specifications, thus forming a heterogeneous WSN.

C. *Irregular Sensing Range*

A sensor's sensing range is not always a perfect disk it could be an elliptic shape or other shapes with the sensing strength could varies with distance from the sensor. Therefore a coverage solution that can be used for any type of sensing range should be proposed.

D. *Coverage for Higher Dimensional Region of Interest*

In most of the works done in the field of WSN the coverage problem is considered only for 2 dimensional ROI, therefore research extended to higher dimensional ROI should be done so that the result would be closed to real world applications.

V. CONCLUSION

This paper reviewed researches done in maximizing coverage of WSN by sensors positioning. The works are categorized into three different approaches; force based, grid based and computational geometry based. Theory and concept along with examples of algorithms proposed using these approaches were presented. The reviewed strategies commonly used to solve the WSN coverage problem each have their benefits and costs. However there are still more work to be done in the field of WSN's coverage so that a global solution can be achieved. Areas for future research include coverage with constraints, heterogeneous networks, irregular sensing range and coverage for higher dimension ROI.

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