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The Deployment Algorithms in Wireless Sensor Net Works: A Survey

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Abstract: In this survey we focus on a variety of sensor nodes deployment algorithms that have been proposed and studied by researchers through the years. Some recent development of this research topic is introduced in a classified manner. We discuss the random deployment, incremental deployment and movement-assisted deployment algorithms and make comparisons between them in term of features, pros and cons, etc. Some related research topics such as the sensor model, localization techniques, communication range and sensing range, convergence and termination conditions are investigated in detail.

Key words: Sensor deployment, wireless sensor networks, coverage, virtual force, movement-assisted

INTRODUCTION

With the recent development in MEMS (Micro-Electro-Mechanical Systems), a large number of tiny sensor nodes with detecting, computing and communication abilities emerge in research frontiers. A Wireless Sensor Network (WSN) is composed of such tiny sensor nodes which collaborate to form an ad-hoc network by the usual medium of wireless connection. Generally the sensor nodes are deployed inside or close the aimed phenomenon to carry out detecting, processing data and reporting to the collection point called sink or base station. Potential civil and military applications of WSNs include surveillance and target tracking in battle field, monitoring environmental conditions, disaster recovery, health and home applications, etc. (Chong and Kumar, 2003).

A hierarchy of research challenges of the WSNs range from the physical layer to the application layer, addressing design, operational as well as management issues. These issues include MAC protocol design (Shih *et al*., 2001; Woo and Culler, 2001; Ye *et al*., 2002), network topology control, time synchronization, routing protocol design (Braginsky and Estrin, 2002; Ganesan *et al*., 2001), energy saving, sensor deployment (Howard *et al*., 2002a; Heo and Varshney, 2003), etc. A typical protocol stack of the WSNs consists of five layers and three planes, namely the application layer, transport layer, network layer, link layer, physical layer, power management plane, mobility management plane and task management plane (Akyildiz *et al*., 2002). Of all the issues mentioned above, the energy constraint (Slijepcevic and Potkonjak, 2001; Cardei and Du, 2005), is a distinguishing feature of sensor networks, comparing to the traditional ad-hoc networks. Since the sensors are to be densely deployed in a wide range of sensing field, each of them must be made with relatively low cost and certain power amount incorporated.

When it comes to the QoS problem of the WSNs, a research topic on the deployment of sensors has long been studied. The deployment of sensors in the target field directly determines the topology of the network, which will further influence the coverage and efficiency of the WSNs. The coverage control problem, which results from the deployment, has become one of the fundamental research topics in WSNs. A good deployment will augment the degree of resource allocation in the network and enable a better performance on information gathering and communication. Meanwhile the topology maintenance turns out to be a challenging task because of the possible device failure due to energy depletion or destruction.

In this study, we discuss various sensor deployment algorithms and present state of the art in research related to these algorithms, which are classified into random deployment, incremental deployment and movement-assisted deployment. Comparisons between these algorithms are made in terms of computational complexity and convergence property, etc. Also we will discuss several key research topics such as the modeling of obstacle and hotspot, to show the pros and cons of the deployment algorithms, respectively.

PROBLEM DEFINITION

We formally define here the deployment problem in wireless sensor networks and discuss several key modeling factors. Although the deployment problem and

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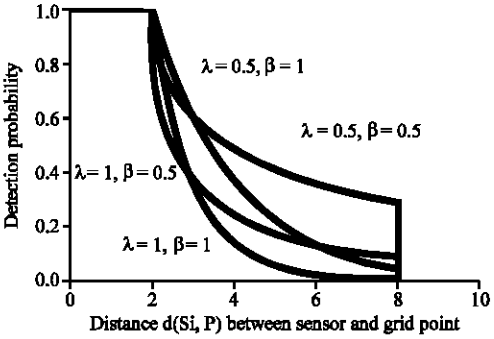

Fig. 1: Probabilistic sensor detection model

its derivative coverage problem have been interpreted in a variety of ways in existing literature, a general interpretation is defined as follows. Given a set of sensors and a target field, the sensors are deployed with a goal of maximizing the area that covered by the sensors. Please note that the covered here can be single coverage or multiple coverage according to the specific application requirements. Although several related works on coverage control have incorporate static or moving targets (Meguerdichian *et al*., 2001; Lin and Chiu, 2005; Chakrabarty *et al*., 2002), we focus present investigation on deployment problem in this study. Figure 1 discuss several modeling factors.

Sensor model: A sensor is a device that produces a measurable response to a change in a physical condition, such as temperature or magnetic field. Although there exist several sensor models with varying degree of complexity, they share one thing in common-the sensing ability directly depends on distance. In literature most studies discussing the deployment problem use isotropic sensors which are associated with a sensing area presented by a circle. For the isotropic sensor, two models with different certainty, namely the binary sensor and the probabilistic sensor have been discussed. In most study the binary sensor model, i.e., the perfect sensor detection, is applied due to its simplicity. However, in reality the probability that the sensor detects a target depends on the relative position of the target. Therefore, Dhillon *et al*. (2002) suggested that sensor detection must be modeled probabilistically. Besides the isotropic sensors, the directional sensor whose detecting range is a sector rather than a disk has been discussed with the advantage of its proximity to the real applications (Ai and Abouzeid, 2006). By any means we should be aware that the sensor model does not limit the applicability of the deployment algorithm in any way. The detection model is simply an input parameter to the deployment algorithm. For a certain placement algorithm, alternative sensor models can thus be considered without a major redesign of the algorithm.

Localization techniques: Localization techniques are close in relationship with the deployment problem since the location information of the sensors is more of less needed in different approaches. In addition, position awareness is essential to wireless sensor networks in that the functional operations such as environmental monitoring and target tracking depend on the location messages of the sensor nodes. The Global Positioning System (GPS) (Hoffman-Wellenhof *et al*., 1997) is a most popular solution for outdoor applications while it is not cost effective or work well indoors.

For indoor systems, a grid-based approach is often used when global position information is needed for deployment. The grids are utilized as landmarks where sensors are placed. Howard *et al*. (2002b) has shown that when the required prior models of the environment are unavailable, incomplete or inaccurate, it is possible to determine the location of network nodes by using the nodes themselves as landmarks. For the decentralized placement approach, many techniques have been proposed to enable each node to determine its location with only limited communication with nearby nodes. Most of these methods exploit received signal strength (Patwari and Hero, 2003), time difference of arrival of two different signals (Savvides *et al*., 2001) and angle of arrival (Niculescu and Nath, 2003). Detailed discussion of these techniques has been provided by Hu and Evans (2004).

Communication range versus sensing range: The sensing unit and communication unit (i.e., transceiver) are independent components in a sensor node (Akyildiz *et al*., 2002). Therefore the communication range and sensing range are not directly associated from a hardware point of view. In wireless sensor networks, however, the two factors are integrated because coverage and connectivity need both to be guaranteed. Therefore Wang *et al*. (2003) gave an extensive study of the relationship between the two factors and proved that protocols which work on the assumption that the communication range is at least twice the sensing range, only need to guarantee coverage and it will satisfy the connectivity constraint as well for the single coverage requirement.

Degree of coverage: The requirement for the degree of coverage may vary in different applications. Most of the deployment algorithms have focused on the single coverage while several approaches highlight the multiple coverage. In present investigation we found that the computational geometry approach, such as in (Wang *et al*., 2006; Lam and Liu, 2005) is desirable in solving the single coverage problem. Meanwhile for the virtual force-based method and incremental method, the degree of coverage can be controlled by a threshold, which is an input factor of the algorithm. In reference, Huang and Tseng (2003) gave a generalized provable solution for the k-covered' problem.

DEPLOYMENT ALGORITHMS

Here, we explore several representative deployment algorithms and make comparisons between them. According to the manner of placement, the algorithms can be classified into random deployment, incremental deployment and movement-assisted deployment. The features as well as the pros and cons of each approach are investigated as shown in Fig. 2.

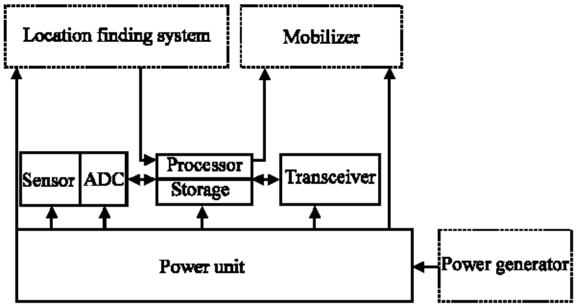

Fig. 2: The components of a sensor node

Random deployment: Random deployment is the most practical way in placing the sensor nodes. When the target region is subject to severe change in condition or no a priori knowledge is available, random deployment is often desirable to achieve a relatively satisfactory coverage. Random deployment is also practical in military application, where wireless sensor networks are initially established by dropping or throwing.

Though many scenarios adopt random deployment because of practical reasons such as deployment cost and time, random deployment may not provide a uniform distribution which is desirable for a longer system lifetime over the region of interest. By random deployment, the sensors are easily overly clustered and there is a small concentration of sensors in certain parts of the sensor field.

The random deployment always serves as an initial phase of the movement-assisted deployment strategy, which we will discuss in Part C in this section. In movement-assisted deployment methods, locations of sensors are adjusted based on the outcome of the random placement.

Incremental deployment

Description and highlight: Differing from the random deployment scheme, the incremental placement strategy is a centralized, one-at-a-time approach to place the sensors. Each node makes use of information gathered by the previously deployed nodes to determine its ideal deployment location, which is calculated at a powerful base station. Each deployed node is responsible for communicating its local information back to the base station for utilization in the next iteration. This implies that each node has to maintain bidirectional communication with the sink.

One of the features of the incremental deployment strategy is that no auxiliary localization technique, such as the GPS and some grid-based localization method, is needed. This sequential placement algorithm can determine the location of the networks nodes by using the nodes themselves as landmarks when the environment model is not available. Another feature is the greedy property of the scheme. The algorithm is greedy in the sense that it attempts to determine, for each node, the location that will produce the maximum increase in the network coverage in each step. Once a sensor node is deployed, it does not change its position any more. Therefore the incremental deployment commonly deals with fixed sensor nodes.

Representative works: The representative work of the incremental deployment algorithm is proposed by Howard *et al.* (2002a). The introduced the general idea of the incremental algorithm and clarified the assumptions and constraints. They gave the four phases: initialization, selection, assignment and execution of the algorithm. In addition, the algorithm maintains the line-of-sight relationships among the nodes, which is necessary for localizing the nodes by using existing deployed nodes as landmarks when an unknown environment is given in Fig. 3.

In their study on sequential sensor placement problem, the terrain properties are considered in terms of obstacles and preferential area, which will influence the calculation of coverage probability in the target field. Zou and Chakrabarty (2004) extended the discussion to a Gaussian probabilistic model when the exact locations of the sensors are not known.

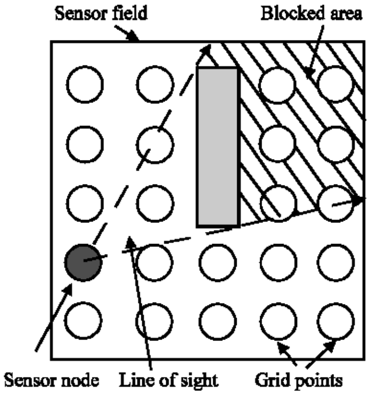

Fig. 3: Illustration of line-of-sight principle

Merits and demerits: The advantage of the incremental deployment algorithm resides in its certainty of optimal location in each step. Compared to random placement, the incremental approach utilizes the terrain properties to optimize the overall coverage. Since the sensors are fixed once they are deployed, little energy is consumed to carry out movement as in the mobile sensor deployment. However, the demerits of this approach are obvious. Since the sensors are deployed one by one, there exists a lot of work in the computation of a new location and thus the deployment time is very long, which can significantly increase the network initialization time. Besides, this algorithm is not scalable and is computationally expensive.

Movement-assisted deployment: Deployment scheme are prone to suffer from inaccuracy, because the actual landing positions cannot be controlled due to the existence of wind and obstacles. Furthermore, in many cases, such as during in-building toxic leaks (Howard *et al*., 2002), the sensors must be placed inside a building from the outside. In these scenarios, it is necessary to make use of mobile sensors, which can move to the desired places to provide the required coverage. The self-deployment problem of mobile sensors is quite similar to the problems considered in cooperative mobile robotics (Cao *et al*., 1997). Recently the study of movement-assisted sensors (i.e., mobile sensors) is thriving. Many of them are inspired from the multi-robot exploration problem (Burgard *et al*., 2000). A variety of algorithms are devised to maximize the coverage over a target region after an initial random deployment. This approach tries to combine the practicality of random scattering with the optimality of re-deployment of the mobile sensors. Within the movement-assisted deployment problem, basically two different approaches have been studied.

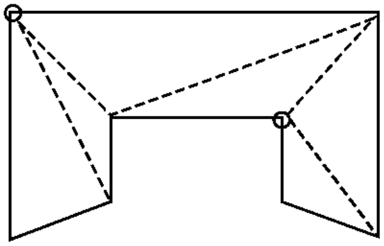

Fig. 4: AGP: A possible deployment of cameras

Computational geometry approach

Description and highlight: Since there exists a close resemblance between the sensor placement problem and the Art Gallery Problem (AGP) addressed by the art gallery theorem (O'Rourke, 1987), the computational geometry approach has always been a representative method studying the sensor deployment problem. This approach perceives the target sensing region as being constructed by a set of grids or polygons. The grids and polygons are either fixed (Lam and Liu, 2005; Wang *et al*., 2006) or changing (Wang *et al*., 2006), aiming at providing location indications for the sensor nodes when they are moving. Since the study of computational geometry, especially the coverage problem, bears a strong resemblance to the deployment problem, it can be used in context of wireless sensor networks with slight modifications.

Representative works: A successful application of the computational geometry in wireless WSNs deployment problem is the Voronoi Diagram approach investigated by Wang *et al*. (2006). In this study, Wang *et al*. (2006) uses Voronoi diagrams to discover the existence of coverage holes once all the sensors have been initially randomly deployed in the target area (Fig. 4). Two sets of distributed protocols have been devised to calculate the optimal locations of the mobile sensors. A node needs to know the location of its neighbors to construct the Voronoi diagrams. The diagram partitions the whole target field into Voronoi polygons (Fig. 5). Each polygon has a single node with the property that every point in this polygon is closer to this node than to any other nodes. A sensor node compares its sensing range with the area of its Voronoi polygon to estimate any local coverage hole. At each iteration, every sensor node moves to an improved location and then the Voronoi diagrams are re-constructed (Fig. 6).

Three self-deployment algorithms have been proposed: VECtor-based (VEC), VORonoi-based (VOR) and Minimax algorithm. We only give a brief introduction of the Minimax algorithm because it outperforms the other

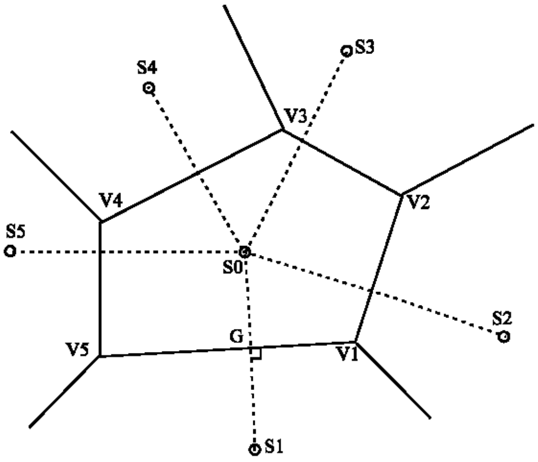

Fig. 5: Voronoi polygon G_0 of s_0

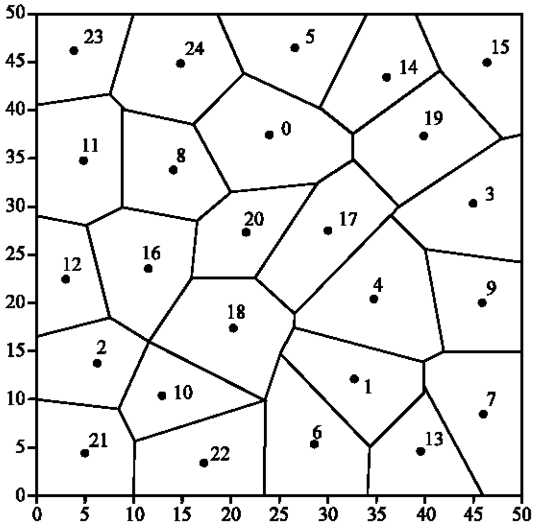

Fig. 6: Voronoi diagram

two. In Minimax, the sensor keeps track of distances to all the vertices and finds a target position inside the polygon from where the distance to the farthest vertex is minimized. The Minimax point is the center of the smallest enclosing circle of the Voronoi vertices and can be calculated by the algorithms described in (Megiddo, 1983; Skyum, 1991; Welzl, 1991).

Another representative study utilizing the computational geometry is the ISOGRID (ISOmetric GRID-based algorithm) (Lam and Liu, 2005). This study is less complex than the Voronoi method since it simply consider the ideal coverage pattern, say the ISOGRID. In this distributed algorithm, each sensor calculates the magnitude and relative orientation of the force that exerts on its neighbors so as to form an ISOGrid. Each sensor node drives all its neighbors to its subjective desired

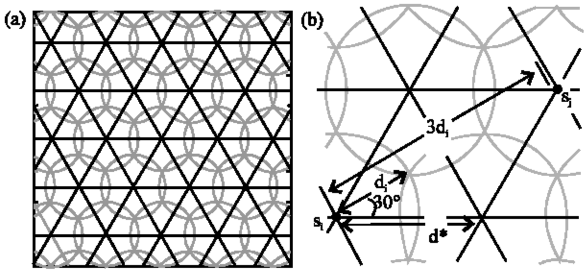

Fig. 7: ISO metric GRID, (a) Ideal deployment and (b) Constraints of d_e

positions. In other words, each node is simultaneously driven by all its neighbors to various directions and magnitudes. The movement of a certain node is defined by the vector summation of all the driving motions imposed on it.

Merits and demerits: The computational geometry method has the advantages of uniformly planning the desired locations of the sensor nodes and solving the deployment problem in a distributed way. However, it suffers from two main limitations. On one hand, it is not easy to encompass the influence of obstacles and the preferential areas in the algorithm because the computational geometry approach requires the target field to be modeled as certain geometry patterns which are associated with the positions of the sensor nodes (Fig. 7). While the obstacles and the preferential areas cannot be simply associated with that pattern. On the other, since each node do the real move after calculating its next position in each iteration, the energy consumption for driving the sensor nodes are relatively high. If the algorithm cannot converge soon, the energy cost will be enormous. Although Wang *et al*. (2006) have proposed a virtual-move solution to this problem, but the communication cost for the broadcast of the current positions will largely increase the complexity after several iterations.

Virtual force-based approach

Description and highlight: The virtual force-based approach is another kind of typical solution to the deployment problem. In this approach the sensor nodes and the obstacles (or the preferential areas) are modeled as points subject to attractive or repulsive force according to the distance between each two sensors. The virtual force exerted on the sensors is quite similar with the Coulomb force. By setting a threshold of the desired distances between sensors, each sensor moves in accordance with the summation of the force vectors and eventually a uniform deployment is achieved. Differing from the computational geometry approach, the virtual force-driven algorithm does not move sensors to a pre-defined position in the some grids or polygons but relies on the interaction between the sensors.

Representative works: A representative work is the Virtual Force Algorithm (VFA) proposed by Zou and Chakrabarty (2004). The VFA algorithm is based on disk packing theory (Locateli and Raber, 2002) and the virtual force field concept from robotics (Howard *et al*., 2002). For a given number of sensors, VFA attempts to maximize the sensor field coverage using a combination of attractive and repulsive forces. During the execution of the force-directed VFA algorithm, sensors do not physically move but a sequence of virtual movement paths is determined for the randomly placed sensors. Once the effective sensor positions are identified, a one-time movement is carried out to redeploy the sensors at these positions.

In contrast with other works, two sensor models are respectively used with different complexity. The author first discusses the binary model, i.e., perfect detection, which associates with no detection uncertainty. Then the probabilistic model which has a practical background is introduced and applied to the VFA algorithm (Table 1).

Prior to the VFA algorithm, Howard *et al*. (2002) introduced a potential field-based approach for self-deployment of mobile sensor networks. Nodes are treated as virtual particles and the virtual forces due to potential fields repel (no attraction) the nodes and the obstacles. This approach does not require and communication among the nodes for movement or localization information. Instead the nodes only use their sensed information in making the decision to move, making it a cost effective solution to the coverage problem. Thus this algorithm is decentralized, which is in contrast with the centralized VFA algorithm. A final static equilibrium status is guaranteed and proved by the addition of vicious force to counteract the potential energy.

Merits and demerits: The advantages of the virtual force-based method are twofold. First, the possible obstacles, preferential areas and the boundary of the target are easy to deal with. These three factors are common in reality, especially in battle field and other severe conditions. In virtual force-based algorithms, these factors are modeled as either attractive or repulsive virtual points to all the sensors. The magnitude of the force represents the degree of tolerance of the coverage in these special areas. Second, the degree of coverage can be controlled by a pre-defined threshold. Through defining different virtual force expressions, the eventual distance between sensor nodes can be adjusted by the threshold. Therefore the virtual force approach is both applicable to single and multiple coverage.

The drawback of the VFA approach is also obvious, which is the general problem associating with a centralized approach. In VFA, a powerful cluster head is responsible for collecting the sensor locations and determine the target locations of the mobile sensors. However, in many sensor deployment environments such as disaster areas and battlefields, a base station may not be available. It may also be hard to organize sensors into clusters due to network partitions. Further, centralized approaches introduce the danger of a single point of failure. Besides, it assumes all sensor nodes are able to communicate with their cluster head, which is not practical since it is energy consuming. The potential field approach proposed by Howard *et al*. (2002) did not consider some crucial problems like connectivity maintenance and topology control.

SEVERAL RELATED RESEARCH TOPICS

Distributed versus centralized: All the sensor deployment algorithms we have discussed above are either distributed or centralized. Generally speaking, the distributed method is more desirable due to its scalability

Table 1: Comparisons between different deployment algorithms

Category	Proposed solution	Sensor model	C-range vs. S-range	Degree of coverage	Main drawbacks	Distributed or centralized	Termination condition
Random	Random deployment	N/A	N/A	N/A	Sensor locations cannot be controlled	N/A	N/A
Incremental	(Howard *et al*., 2002a, b)	Binary	NDR*	Single	Computational expensive	Centralized	Overall coverage
	(Dhillon and Chakabarty, 2003; Zou and Chakabarty, 2004a)	Probabilistic	NDR	Controllable	Computational expensive	Centralized	Overall coverage
Movement-assisted	VFA (Zou and Chakabarty, 2004b)	Both	NDR	Controllable	Long-distance force, single point failure	Centralized	Overall coverage
	Potential (Howard and Chakabarty, 2002)	Binary	NDR	Single	Connectivity maintenance, topology control	Distributed	Energy depletion
	DSSA (Heo and Varshney, 2003)	Binary	Rc=2Rs	Controllable	No attractive force	Distributed	Stable status or oscillation
	Minimax (Wang *et al*., 2006)	Binary	Rc>2Rs	Single	Energy Constraint	Distributed	Local coverage
	ISOGRID (Lam and Liu, 2005)	Binary	$Rc > \sqrt{3}\,Rs$	Single	Incapable of obstacles	Distributed	Stable status or max iteration No
	TIVFA (Li *et al*., 2005)	Probabilistic	NDR	Controllable	Computational expensive	Centralized	Max iteration No.
	VRGMSD (Wang *et al*., 2006)	Binary	$Rc > \sqrt{3}\,Rs$	Single	Incapable of obstacles	Centralized	Stable status or max iteration

*NDR: No Direct Relationship required

and computational efficiency. Furthermore, in some applications the central server architecture may not be feasible and it suffers from the potential danger of a single-point failure. In Wang *et al.* (2006), the authors compare the ideal centralized deployment with their Minimax algorithm. It is shown that when the sensor density is not very large, the centralized deployment is still a good choice. When the sensor density becomes large, the decentralized approach presents a time-saving solution.

Convergence and termination condition: The convergence property of an algorithm is of vital importance since it directly influences the feasibility at least the execution time of the algorithm. The convergence property is proved by Howard *et al.* (2002) by considering the vicious force to counteract the potential energy to achieve a static equilibrium status. The total energy of the system is determined by summing the potential and kinetic energy of all nodes. For such systems, the total energy will decrease monotonically over time and eventually the total kinetic energy of the system will asymptote to zero.

There exist four typical termination conditions appearing in current works, each of which applies to certain algorithm.

Terminated by overall coverage: In centralized algorithm, such as VFA, the overall coverage (i.e., the ratio of area covered by sensors to the area of the target field) of the network is checked each iteration. On condition that the overall coverage achieves a pre-defined threshold or the changing of overall coverage is bounded by a very small value, the VFA algorithm terminates. For distributed algorithm, it is computationally expensive or even not feasible to calculate the overall coverage. So the following termination conditions are used.

Terminated by stable status: In distributed algorithms when the change of location of a certain sensor node asymptote to a threshold value, a stable status is achieved. And that node stops its movement. Such termination condition is used in Heo and Varshney (2003) and Lam (2005).

Terminated by constant oscillation: If a node moves back and forth between almost the same locations many times, this node is regarded in the oscillation status. By comparing with the history of its movement, each node can know if oscillation is going on. Then one counts the number of oscillations and if this oscillation count is over the oscillation limit, we stop that node's movement at the center of gravity of the oscillating points. This termination condition is used by Heo and Varshney (2003).

Terminated by No. of iteration: If an algorithm cannot terminate for a relative long period of time, it should end when the pre-defined max iteration number is arrived at.

CONCLUSION AND FUTURE WORK

In this survey, we investigate the deployment problem, which is a fundamental issue closely related to the quality of service of the wireless sensor networks. We first introduce the WSNs generally and shed some light on the importance of the deployment problem. Then we begin with several definition issues that are closely related to the modeling of the deployment problem, such as the sensor model, localization technique, degree of coverage and the communication range versus the detection range. We classify the deployment patterns to three types, say random deployment, incremental deployment and movement-assisted deployment. We respectively discuss the features and representative works as well as the pros and cons of each placement type. Finally we investigate the termination conditions and make comparisons between centralized and decentralized approach.

For future study, since most of the current deployment strategies do not include the target information, no optimization work has been done to incorporate the static or moving target. Besides, the modeling of the sensing field is not extensively discussed. The model of obstacles and hotspots and their involvement in the deployment algorithm have not been fully discussed. The topics mentioned above could be addressed in future study.

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