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Review

A survey on coverage and connectivity issues in wireless sensor networks

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ABSTRACT

A wireless sensor network (WSN) is composed of a group of small power-constrained nodes with functions of sensing and communication, which can be scattered over a vast region for the purpose of detecting or monitoring some special events. The first challenge encountered in WSNs is how to cover a monitoring region perfectly. Coverage and connectivity are two of the most fundamental issues in WSNs, which have a great impact on the performance of WSNs. Optimized deployment strategy, sleep scheduling mechanism, and coverage radius cannot only reduce cost, but also extend the network lifetime. In this paper, we classify the coverage problem from different angles, describe the evaluation metrics of coverage control algorithms, analyze the relationship between coverage and connectivity, compare typical simulation tools, and discuss research challenges and existing problems in this area.

Contents

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1. Introduction

The advancing in the sensor technology, micro-electromechanical systems, modern networking and wireless communications technology has greatly promoted the emergence and development of modern WSNs (Pottie, 1998; Stankovic, 2008). WSNs are currently of concern in the world wide involving a high degree of cross-multidisciplinary, highly integrated, cutting-edge knowledge of hot research field. WSNs extend the ability of people to access information, communicate physical information of the objective environment with transmission networks, and the next generation network will provide people with the most direct, effective and authentic information. Thus, WSN technology has very broad application prospects, which can be used in military, industrial and agricultural control, urban management, biomedical, environmental testing, disaster relief and other fields. Academia and industry of many countries attach great importance to WSN technology, which is considered as one of the most influential technologies in the 21st century.

An important problem receiving increased consideration recently is the coverage problem, which focuses on how well the sensors observe the physical space they deployed. Coverage is one of the measurements of WSNs QoS (Quality of Service), and it is closely related with energy consumption. In some cases it is possible to obtain energy from external environment (Want et al., 2005) (e.g., by using solar cells as power source). However, in many applications and scenarios, nodes of WSNs are often dropped or thrown into the sensor field randomly. External power supply sources often exhibit a non-continuous behavior so that an energy buffer is needed as well, and even no power supply at all. In any case, energy is a very critical resource and must be used very sparingly. Therefore, energy conservation is a key issue in the design of systems based on WSNs. Due to the limited energy resource in each sensor node, we need to utilize the sensors in an efficient manner so as to increase the lifetime of the network.

The researches about coverage and connectivity issues in WSNs have been involved a lot, which mainly confined to explaining "what is" and "how to realize". In this article, not only "what is" and "how to realize" are concerned, but also "why" is taken into consideration. Here, "why" is described by energy consumption, which shows the basis of classification. There are three different approaches to the problem of conserving energy in WSNs, and all of the approaches must keep the initial coverage QoS. The first approach is to optimize coverage deployment strategy. The second approach is to plan a schedule of active sensors that enables other sensors to go into a sleep mode. The third approach is adjusting the sensing range of sensors for energy conservation.

In this paper, we analyze coverage and connectivity issues primarily based on the angle of energy consumption, especially in coverage deployment strategy, sleep scheduling mechanism and adjustable coverage radius. In Section 2, we introduce the basic knowledge of coverage concepts, such as node properties, sensing models, and evaluation metrics. Section 3 coverage deployment strategy is described. Recent research issues about static coverage and dynamic coverage are described here as well as the solution to optimize coverage deployment. Section 4 discusses sleep scheduling mechanism through some typical examples. It is a very efficient solution of energy conservation to coverage problem. In Section 5, we focus on adjusting the sensing range of each sensor in order to reduce the overlaps among sensing ranges while maintain the QoS of coverage above a predefined detection level. In Section 6, we introduce the relationship between coverage and connectivity, and prove that a network is connective when $R_c \geq 2R_s$. Section 7 introduces the simulation tools on coverage and connectivity, compares the differences among several popular simulators. In Section 8, we summarize typical issues on coverage and connectivity in WSNs, and discuss existing problems and research challenges in this area. Finally, in Section 9, a simple conclusion is given.

2. Preliminaries

The solutions to coverage and connectivity issues in WSNs involve a lot of basic theories and assumptions. The basic knowledge of coverage concepts is essential. In this section, we describe sensor node properties, sensing models, centralized/distributed algorithms, and the evaluation indicators of coverage quality.

2.1. Node properties

Definition 1 (*Fixed node*). A fixed node has the ability to collect sensed data, send or receive messages, process data and messages, and do other types of computation in static Wireless Ad hoc Sensor Networks (WASNs). Typically, these sensor nodes do not move once they are deployed.

Definition 2 (*Mobile node*). A mobile node not only has all the features of the fixed nodes, but also has some mobility. Since coverage and connectivity are crucial considerations for WSNs, the failure of a node may cause the network to be partitioned into disjoint segments and/or brought alone with a hole in the original coverage area. A mobile node can act as a router when it is in a low or even no coverage area, and accomplish the recovery task.

Definition 3 (*Coverage & k-coverage*). Given a set of sensors, $S = s_1, s_2, \ldots, s_n$, in a 2D area X. Each sensor $s_i, (i = 1, \ldots, n)$, is located at coordinate (x_i, y_i) inside X and has a sensing range of r_i which is usually called sensing radius. Any point in X is said to be covered by s_i if it is within the sensing range of s_i, and any point in X is said to be k-covered if it is within at least k sensors' sensing ranges.

Definition 4 (*Connectivity*). Suppose that two sensors s_1 and s_2 are located inside X. s_1 and s_2 are connected if they can communicate with each other.

2.2. Sensing models

WSN nodes generally have widely different theoretical and physical characteristics. Hence, numerous models of varying complexity can be constructed based on application needs and working environment. Interestingly, most sensing device models share two facets in common (Megerian et al., 2002):

(1) Sensing ability diminishes as distance increases.
(2) Due to diminishing effects of noise bursts in measurements, sensing ability can improve as the allotted sensing time (exposure) increases.

Assume sensor S_i is deployed at point (x_i, y_i). For any point P at (x, y), we denote the Euclidean distance between S_i and P as $d(S_i, P)$, i.e., $d(S_i, P) = \sqrt{(x_i - x)^2 + (y_i - y)^2}$. Eq. (1) defines the general sensibility $S(S_i, P)$ of S_i at an arbitrary point P as

$$S(S_i, P) = \frac{\lambda}{[d(S_i, P)]^K} \quad (1)$$

where $d(S_i, P)$ is the Euclidean distance between the sensor S_i and the point P, and positive constants λ and K are sensor technology-dependent parameters. The less $d(S_i, P)$ is, the stronger sensing ability will be. Obviously, the denominator cannot be zero in (1). Hence, a common denominator can modify for $[d(S_i, P) + \delta]^K$ so that (1) is meaningful, where δ is lager than 0, but infinite close to zero.

2.2.1. The binary disc sensing model

The simplest model is the binary disc model, according to which a node is capable of sensing only from points that lie within its sensing range and not from any point beyond it. Thus, in this model the sensing range for each node is confined within a circular disk of radius r, and is commonly referred to as the sensing radius

$$c_{xy}(S_i) = \begin{cases} 1 & \text{if } d(S_i, P) < r \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

2.2.2. The probabilistic sensing model

The probabilistic sensing model is a more actual perception, which can be taken as an extension of the binary disc sensing model

$$c_{xy}(S_i) = \begin{cases} 0 & \text{if } r + r_e \le d(S_i, P) \\ e^{-\lambda \alpha^{\beta}} & \text{if } r - r_e < d(S_i, P) < r + r_e \\ 1 & \text{if } r - r_e \ge d(S_i, P) \end{cases} \quad (3)$$

where $r_e (r_e < r)$ is a measure of the uncertainty in sensor detection, $\alpha = d(S_i, P) - (r - r_e)$, and λ and β are parameters that measure detection probability when a target is at distance greater than r_e but

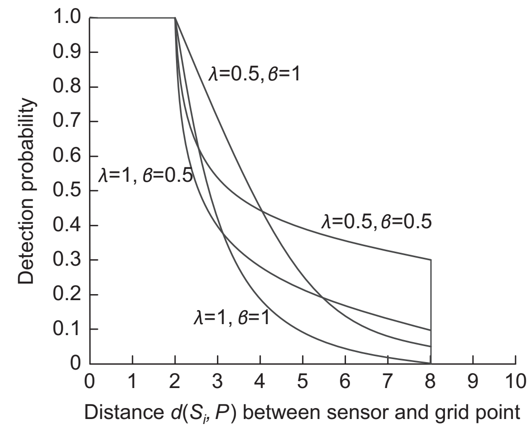

Fig. 1. Probabilistic sensor detection model.

within a distance from the sensor. This model reflects the behavior of range sensing devices such as infrared and ultrasound sensors. As shown in Fig. 1, different values of the parameters λ and β yield different translations reflected by different detection probabilities, which can be viewed as the characteristics of various types of physical sensors.

2.3. Centralized/distributed algorithms

Once sensors are deployed, an algorithm is run to determine whether sufficient coverage exists in the area. Traditionally, a centralized algorithm requires each sensor node to forward all its observations to the fusion center, which results in large energy in communication. A distributed algorithm, on the other hand, is run on nodes throughout the network, and allows each sensor node to decide its own working mode by the neighbors' information each has gathered. Compared to centralized algorithms, distributed algorithms reduce communication energy and detection accuracy while increase the processing energy. Overall, distributed algorithms are more suitable for large-scale networks.

Zhou, Das, and Gupta develop both centralized and distributed algorithms for connected k-coverage in Raghunathan et al. (2002). They find that both centralized and distributed algorithms return a near optimal solution. The authors in Hill et al. (2000) also present both centralized and distributed version algorithms. The experiment results show that the algorithm proposed by them runs faster, activates a near optimal number of sensors and consumes less energy than similar algorithms.

One example of a centralized method is given by Cardei, Thai, Li, and Wu in Chamberland and Veeravalli (2003). They employ a central data collector node known as a base station to collect data and determine which sensors to deactivate in order to conserve energy and preserve k-coverage. The authors in Zhu et al. (2000) also use a central data collector node to gather information from the other sensor nodes to decide which sensors to put into sleep mode.

2.4. Evaluation metrics of coverage control algorithms

How to evaluate the performance of coverage and its algorithm is very important for the network's usability and effectiveness. The main factors are considered as follows.

QoS of coverage: The Qos of coverage decides the completion of network tasks, reflects the network's sensing ability to the physical world, and is the basis standard of algorithm evaluating.

Number of active nodes: In the case of meeting the coverage requirements, the fewer number of active nodes are, the larger effective coverage area will be. In other words, reducing active nodes do well in the performance of energy consumption.

Associating with the node location or not: Coverage control algorithms associated with a node location depend on external infrastructure (such as GPS) or some position mechanisms, relatively cost high and need to consume large amounts of energy. Meanwhile, there are still some accuracy issues on position. Therefore, coverage control algorithms, not involving position information, have a greater advantage.

Energy efficiency: Coverage control algorithms not only require lowest energy consumption in a single monitoring task, but also maintain energy balance of the network in a series of monitoring tasks.

Communications overhead: Data transmission is the main source of a sensor node energy consumption. Coverage control algorithms with low cost in the process of communication have a greater advantage.

Network scalability: Coverage control algorithm should be able to adapt to both the scale of different WSNs and the network topology dynamically changed.

3. Coverage deployment strategy

Coverage has attracted a great deal of research attention due to its relation to optimization of resources in a sensing field. Maximizing the coverage and maintaining a lower cost of deployment have always been a challenge, especially when the monitoring region is unknown and possibly hazardous. An effective approach for energy conservation in WSNs is coverage deployment strategy. Many simulation results show that optimal deployment strategy can achieve a certain degree of coverage results with less number of nodes. In this section, according to whether there are mobile nodes or not in WSN, we divide coverage deployment strategies into two main parts: static coverage and dynamic coverage.

3.1. Static coverage

Several different coverage formulations arise naturally in many domains. The Art Gallery Problem (O'Rourke, 1987), for example, deals with determining the number of observers and their placement necessary to cover an art gallery room such that every point is seen by at least one observer. It has found several applications in many domains such as for optimal antenna placement problems in wireless communication. The Art Gallery Problem was solved optimally in 2D and was shown to be NP-hard in the 3D case. Here, static coverage is mainly concerned.

3.1.1. Efficient Coverage Area

In order to achieve deterministic coverage, a static network must be deployed according to a predefined shape. The predefined locations of the sensors can be uniform in different areas of the sensor field or can be weighted to compensate for the more critically monitored areas. The maximum of net Efficient Coverage Area (S_{ECA}) of a node and its maximum of net Efficient Coverage Area Ratio (R_{ECA}) in WSNs' field are fully and seamlessly covered by sensor nodes, and have significant influence on energy conservation. In this part, the given analysis formula is based on the assumptions as follows:

(1) A sensor's sensing ability is omni-directional, that is, its coverage range is a disk whose radius is r and whose area is $D(D=\pi r^2)$.
(2) In a sensor field, all sensors' radio power are uniform, that is, the radio radius r of all sensors is equal.
(3) In a sensor field, all sensors are in the same plane.

In the sensor field of a WSN, a piece of Zone Z is possibly covered by several sensor nodes (as show in Fig. 2). In this case, the coverage resulted from Node C_1 among these nodes is redundant for Zone Z (in allusion to single coverage). It's because the information of Zone Z can be sensed and acquired by other nodes. Therefore, Efficient Coverage Area (S_{ECA}) and Efficient Coverage Area Ratio (R_{ECA}) are defined as follows:

Definition 5 (*Efficient Coverage Area S_{ECA}*). Efficient Coverage Area S_{ECA} is the coverage area that is overlapping coverage Zone Z's area S_Z subtracted from Node C_1's coverage range $D(\pi r^2)$, namely,

$$S_{ECA} = D - S_Z = \pi r^2 - S_Z \tag{4}$$

Definition 6 (*Efficient Coverage Area ratio R_{ECA}*).

$$R_{ECA} = \frac{S_{ECA}}{D} = \frac{D-S_Z}{D} = 1 - \frac{S_Z}{D} = 1 - \frac{S_Z}{\pi r^2} \tag{5}$$

As shown by (a) in Fig. 3, in order to realize full seamless coverage, a point in Circle C_1 is at least between Point A and Point B, which are intersecting points of Circle C_2 and Circle C_3. As shown by (b) in Fig. 3 obviously, the efficient coverage area

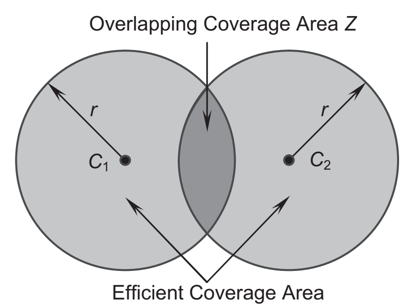

Fig. 2. Efficient Coverage Area.

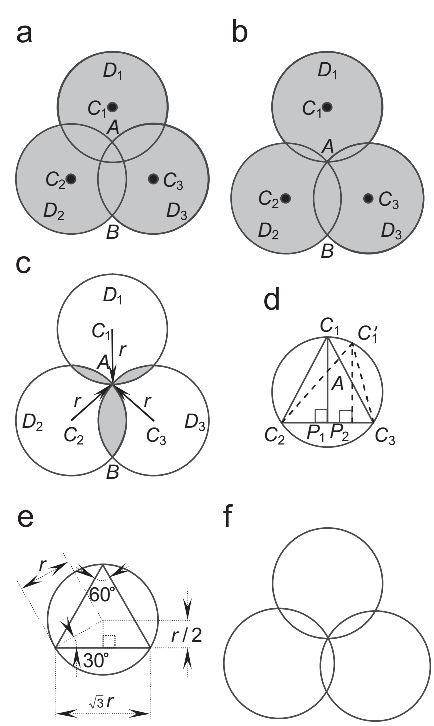

Fig. 3. Optimized seamless coverage.

of Disk D_1, D_2 and D_3 is possible only if Circle C_1 (it encloses Disk D_1) is through Point A or Point B, and Center C_1 is outside D_2 and Disk D_3. If let the efficient coverage area of (b) in Fig. 3 be maximum, obviously then let the gray area of (c) in Fig. 3 be minimum. Wang and Zhang (2009) proves that seamless topology area of three seamless topology disks: D_1, D_2 and D_3 is maximum and its value is $(4\pi+3\sqrt{3}/2)r^2$ (as show in Fig. 3(f)), if three circles: C_1, C_2 and C_3 correspondingly encircling D_1, D_2 and D_3 intersect at a point and $\Delta C_1\Delta C_2\Delta C_3$ as shown in Fig. 3(d) and (e)) is equilateral triangle.

3.1.2. k-coverage

Applications requiring $k>1$ may occur in situations where a stronger environmental monitoring capability is desired, such as military applications. Such a problem can be formulated as a decision problem, whose goal is to determine whether every point in the area (monitored or tracked by sensors) is covered by at least k sensors, where k is a predefined value. One simple solution is to find out all sub-regions divided by the sensing boundaries of all n sensors (i.e., n circles), and then check if each sub-region is k-covered or not. Managing all sub-regions could be a difficult and computationally expensive job in geometry. There may exit as many as $O(n^2)$ sub-regions divided by the circles. Also, it may be difficult to calculate these sub-regions. An example of determining the perimeter-coverage of a sensor's perimeter is shown in Fig. 4. Each sensor determines which segments of its perimeter are covered by its neighboring nodes. As shown in Fig. 4(a), curve segments $[0,a]$, $[b,c]$ and $[d,\pi]$ of sensor node S's perimeter are covered by three of its neighbor nodes. Those segments are then sorted in an ascending order on the line segment $[0,2\pi]$, as shown in Fig. 4(b). By traversing the line segment $[0,2\pi]$, the perimeter-coverage of the sensor can be determined. In this example, the perimeter-coverage of S from 0 to b is one, from b to a is two, from a to d is one, from d to c is two, and from c to π is one. Huang and Tseng (2005) proves that as long as the perimeters of sensors are sufficiently covered, the whole area is sufficiently covered. The solution proposed in this paper can be easily translated to a distributed protocol where each sensor only needs to collect local information to make its decision. The result can be applied to unit and non-unit disk sensing regions, and can even be extended to irregular sensing regions of sensors. It is valuable to use the results for discovering insufficiently covered area, conserving energy, and supporting coverage of hot spots.

3.1.3. Path coverage

Path coverage is one of the monitoring examples, where nodes are deployed to sense a specific path and report possible efforts made by intruders to cross it. In a manual deployed network, the desired level of the path coverage can be achieved by proper placement of the sensors over the area. When it is not possible to deploy the network manually, random deployment, for example, dropping sensors from an aircraft, is used. Due to the randomness of the sensors location, network coverage expresses a stochastic behavior and the desired (full) path coverage is not guaranteed. Thus, a detailed analysis of the random network coverage can be ultimately useful in the network design stage to determine the node density for achieving the desired area/path coverage.

Path coverage by a random network (or barrier coverage which is a relaxed version of the path coverage) has been the focus of some previous work (Ram et al., 2007; Harada et al., 2008; Kumar et al., 2007; Liu et al., 2008; Chen et al., 2007, 2008). In Ram et al. (2007), assuming that a random network is deployed over an infinite area with nodes following a Poisson distribution, authors investigate the path coverage of the network. They first study the path coverage over an infinite straight line when each sensor node has a random sensing range. Then, they show that in the asymptotic situation, where the sensing range of the sensors tends to 0 and the node density approaches infinity, the results are extendible to finite linear and curvilinear paths. Further, a path coverage analysis is proposed for a high density Poisson-distributed network (Harada et al., 2008) where sensors have a fixed sensing range. The path coverage analysis of Ram et al. (2007) and Harada et al. (2008) is based on the Boolean model of West (1996), where a Poisson point process is justified.

Cao et al. (1997) defines the maximal breach path and the maximal support path as paths on which the distance from any point to the closest sensor is maximized and minimized, respectively. The maximal exposure path problem is proved to be NP-hard, and thus, heuristics is provided to generate approximate solutions. The key idea is to use the Voronoi diagram and the Delaunay triangulation of sensor nodes to limit the search for the optimal paths in each case. The Voronoi diagram is formed from the perpendicular bisectors of lines that connect two neighboring sensors, while the Delaunay triangulation is formed by connecting nodes that share a common edge in the Voronoi diagram. Besides, polynomial-time algorithms are proposed to such paths. Examples of the Voronoi diagram and Delaunay triangulation are shown in Fig. 5.

The maximal breach path finds a path such that at any time the exposure no more than some particular value. Because the line segments of the bounded Voronoi diagram formed have the maximal distance to the closest sensors, the maximal breach path must lie on such line segments.

In order to find the maximal breach path, each line segment is given a weight which equals to its minimum distance to the closest sensor. The proposed algorithm then performs a binary search between the smallest and largest weights. In each step, a breadth-first-search (BFS) is used to check the existence of a path from the source point S to the destination point D using only line segments with weights that are larger than the search criterion which is called breach-weight. If a path exists, the breach-weight is increased to further restrict the lines considered in the next search iteration. Otherwise, the breach-weight is decreased on the search. An example of the maximal breach path is shown

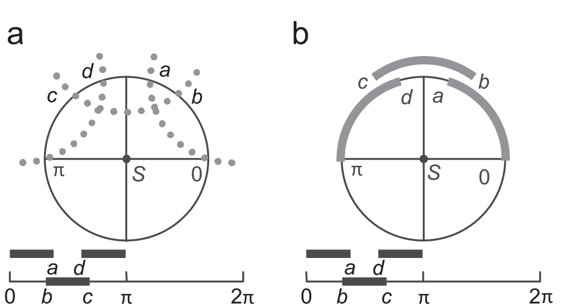

Fig. 4. Determining the perimeter-coverage of a sensor S's perimeter.

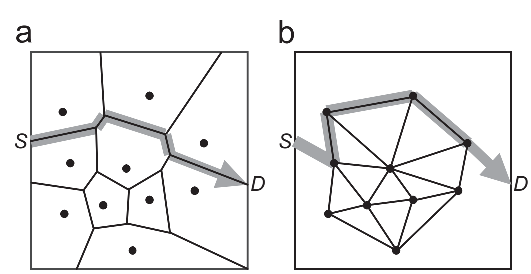

Fig. 5. Examples of (a) the Voronoi diagram and the maximal breach path, and (b) the Delaunay triangulation and the maximal support path. S and D are the source and destination points.

in Fig. 5(a). The goal of the maximal support path is to find a path that at any given time, the exposure on the path is no less than some particular value, and this value should be maximized. Here, the Voronoi diagram is replaced by the Delaunay triangulation as the underlying geometric structure. Because the Delaunay triangulation produces triangles which have minimal edge lengths among all possible triangulations, the maximal support path must lie on the lines of the Delaunay triangulation of sensors. To find the maximal support path, the weights of line segments of the Delaunay triangulation are assigned the lengths of the line segments. The rest of the search steps are the same as above. An example of the maximal support path is shown in Fig. 5(b).

3.2. Dynamic coverage

Liu et al. (2005) study the dynamic coverage of a sensor network. It shows that if the mean coverage at any given time instance remains unchanged, a larger area will be covered during a time interval because of sensor movement. A similar concept called sweep coverage is studied in Cheng et al. (2008a). Different from static coverage, some or all the nodes in dynamic coverage usually have the ability of moving. Hence, compared to static coverage, mobile coverage is more complex. The deployment cannot be determined a priori when the environment is unknown or hostile in which case the sensors may be air-dropped from an aircraft (Dhillon and Chakrabarty, 2003a) or deployed by other means generally resulting in a random placement (Howard et al., 2002). In this part, the self-deployment of mobile sensor nodes is considered. This is quite similar to problems considered in cooperative mobile robotics (Cao et al., 1997). Mobile sensors are often desirable, since they can patrol a wide area, and can be repositioned for better surveillance (Qi et al., 2001). Some researchers have considered the use of mobile robots in sensor networks.

A recent work on mobile sensor networks presents a distributed and scalable potential field-based approach for the deployment of mobile sensors (Howard et al., 2002). The fields are constructed such that each sensor is repelled by both obstacles and by other sensors, thereby forcing the network to spread itself through the environment. Winfield (2000) considered autonomous dispersion of mobile nodes in a scenario where mobility is required to cover the entire region due to a lack of wireless-network connectivity. He used a random diffusion method for node deployment while collecting data over a fixed surveillance region. In the incremental deployment algorithm (Howard et al., 2002), nodes are added one at a time. The goal is to maximize network coverage under the constraint that nodes maintain line-of-sight with each other. Loo et al. (2002) considered a system consisting of a number of cooperating mobile nodes that move toward a set of prioritized destinations under sensing and communication constraints. They show how individual agents know when cooperation between agents improves the performance and when they should suspend cooperation.

3.2.1. Based on virtual force

A random placement of sensors in the target area is often desirable as an initial deployment, especially if no a priori knowledge of the terrain is available. Random deployment is also practical in military applications, where distributed sensor networks are initially established by dropping or throwing sensors into the sensor field. However, random deployment does not always lead to effective coverage, especially if the sensors are overly clustered and there is a small concentration of sensors in certain parts of the sensor field. The virtual force algorithm (VFA) acts as a sensor deployment strategy to enhance the coverage after an initial random placement of sensors. The VFA algorithm is inspired by the ideas of potential field (Howard et al., 2002) and disk packing (Locatelli and Raber, 2002).

We now describe the virtual forces and virtual force calculation in the VFA. Let the total force action on sensor S_i be denoted by $\overrightarrow{F_i}$. Note that $\overrightarrow{F_i}$ is a vector whose orientation is determined by the vector sum of all the forces acting on S_i. Let the force exerted on S_i by another sensor S_j be denoted by $\overrightarrow{F_{ij}}$. In addition to the positive and negative forces due to other sensors, a sensor S_i is also subjected to forces exerted by obstacles and areas of preferential coverage. The knowledge of obstacles and preferential areas implies a certain degree of a priori knowledge of the terrain. In practice, the knowledge of obstacles and preferential areas can be used to direct the initial random deployment of sensors, which in turn can potentially increase the efficiency of the VFA algorithm.

Zou and Chakrabarty (2003) assumes that obstacles exert repulsive (negative) forces on a sensor. Likewise, areas of preferential coverage exert attractive (positive) forces on a sensor. If more detailed information about the obstacles and preferential coverage areas is available, the parameters governing the magnitude and direction (i.e., attractive or repulsive) of these forces can be chosen appropriately. In this work, we let $\overrightarrow{F_{iA}}$ be the total (attractive) force on S_i due to preferential coverage areas, and let $\overrightarrow{F_{iR}}$ be the total (repulsive) force on S_i due to obstacles. The total force $\overrightarrow{F_i}$ on S_i can now be expressed as

$$\overrightarrow{F_i} = \sum_{j=1, j \neq i}^{k} \overrightarrow{F_{ij}} + \overrightarrow{F_{iR}} + \overrightarrow{F_{iA}} \tag{6}$$

We next express the force $\overrightarrow{F_{ij}}$ between S_i and S_j in polar coordinate notation. Note that $\vec{f} = (\gamma, \theta)$ implies a magnitude of γ and orientation θ for vector $\vec{f}$

$$\overrightarrow{F_{ij}} = \begin{cases} (W_A(d_{ij} - d_{th}), \alpha_{ij}) & \text{if } d_{ij} > d_{th} \\ 0 & \text{if } d_{ij} = d_{th} \\ \left(W_R \dfrac{1}{d_{ij}}, \alpha_{ij} + \pi \right) & \text{if } d_{ij} < d_{th} \end{cases} \tag{7}$$

where d_{ij} is the Euclidean distance between sensor S_i and S_j, d_{th} is the threshold on the distance between S_i and S_j, α_{ij} is the orientation (angle) of a line segment from S_i to S_j, and $W_A(W_R)$ is a measure of the attractive (repulsive) force. The threshold distance d_{th} controls how close sensors get to each other. The simulation result of Zou and Chakrabarty (2003) shows that a sensor deployment technique based on virtual forces can increase the area coverage after an initial random deployment.

Connectivity-Preserved Virtual Force (CPVF) scheme (Tan et al., 2009) is an enhanced form of the virtual-force-based method with the additional consideration of the connectivity requirements. The scheme is designed to maximize sensing coverage while guarantee connectivity for a network with arbitrary sensor ranges or node densities, at the cost of a small moving distance. It does not need any knowledge of the field layout, which can be irregular and have obstacles/holes of arbitrary shape. Lumelsky and Stepanov's path planning algorithm (Lumelsky and Stepanov, 1987) called BUG2 to help a sensor move from a starting point *Start* to a destination point *Target* in an environment with obstacles. Roughly speaking, this algorithm works as follows. The sensor initially moves along the straight line (*Start*; *Target*), which we call the reference line, until it encounters an obstacle at some hitting point *H*; then, the sensor follows the boundary of the obstacle using the right-hand rule (i.e., the right hand maintains contact with the obstacle), until it gets back to the reference line at some point. Now, if the sensor finds that it is closer to the *Target* than from *H*, and that it can make progress on the reference line, then it resumes its straight line walk toward the *Target*; otherwise it continues to navigate around the obstacle. The above procedure repeats until the sensor reaches the *Target*. BUG2 is shown to produce a path of length at most $D+\sum_i n_i l_i/2$, where D is the distance between *Start* and *Target*, n_i is the number of times the reference line crosses the i_{th} obstacle, and l_i is the perimeter of the i_{th} obstacle. For convex obstacles, BUG2 is essentially optimal. Fig. 6 provides an example of this algorithm.

3.2.2. Graph-based

The Voronoi diagram (Aurenhammer, 1991; Fortune, 1997) is an important data structure in computational geometry. It represents the proximity information about a set of geometric nodes. The Voronoi diagram of a collection of nodes partitions the space into polygons. Every point in a given polygon is closer to the node in this polygon than to any other node. Fig. 7 is an example of the Voronoi diagram, and Fig. 8 is an example of a Voronoi polygon.

The Vector-based Algorithm (VEC) (Wang et al., 2004) is motivated by the attributes of electro-magnetic particles. When two electro-magnetic particles are too close to each other, an expelling force pushes them apart. Assume d_{ij} is the distance between sensor S_i and sensor S_j. d_{ave} is the average distance between two sensors when the sensors are evenly distributed in the target area, which can be calculated beforehand since the target area and the number of sensors to be deployed are known. The virtual force between two sensors S_i and S_j will push them to move $(d_{ave}-d_{ij})/2$ away from each other. In case one sensor covers its Voronoi polygon completely and should not move, the other sensor will be pushed $d_{ave}-d_{ij}$ away. In summary, the virtual force will push the sensors d_{ave} away from each other if coverage hole exists in either of their Voronoi polygons.

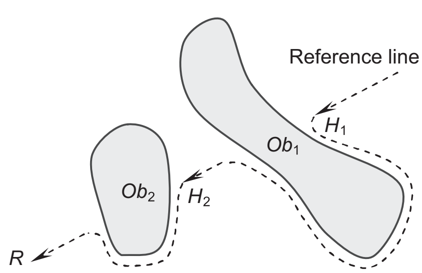

Fig. 6. An example of the BUG2 algorithm. The dashed line shows the path of a sensor moving to the point *R*. On its way to *R*, the sensor encounters two obstacles and moves around them using the right-hand rule.

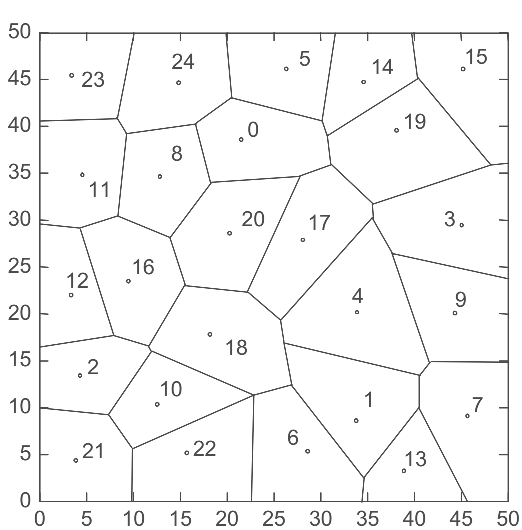

Fig. 7. Voronoi diagram.

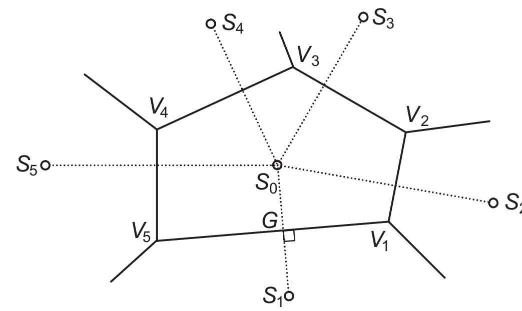

Fig. 8. Voronoi polygon of s_0.

The virtual force exerted by S_j on S_i is denoted as $\overrightarrow{F_{ij}}$, with the direction from S_j to S_i.

In addition to the virtual forces generated by sensors, the field boundary also exert forces, denoted as $\overrightarrow{F_b}$, to push sensors too close to the boundary inward. $\overrightarrow{F_b}$ exerted on S_i will push it to move $d_{ave}/2-d_b(S_i)$, where $d_b(S_i)$ is the distance of S_i to the boundary. Since d_{ave} is the average distance between sensors, $d_{ave}/2$ is the distance from the boundary to the sensors closest to it when sensors are evenly distributed. The final overall force on sensors is the vector summation of virtual forces from the boundary and all Voronoi neighbors. These virtual forces will push sensors from the densely covered area to the sparsely covered area. Thus, VEC is a “proactive” algorithm, which tries to relocate sensors to be evenly distributed.

The Voronoi-based algorithm (VOR) will pull a sensor toward a coverage gap. The movement is limited to one half of the communication range in order to avoid communication problems with the neighboring nodes. Finally the Minimax algorithm works similar to VOR except that it further limits the maximum movement of a node. The idea behind this algorithm is to create a move even Voronoi diagram so that the area covered by each sensor is more uniform. The experiments show that Minimax provides the best coverage with the fewest sensors while VEC performs the worst. Minimax does require the most sensors movement while VEC requires the least. The protocols all perform acceptably for the problem for which they were designed. However, these protocols suffer from the same shortcomings as the fuzzy logic system.

A VEC method based coverage hole recovery in WSNs will be discussed in the following part.

3.2.3. Repair policies of coverage hole

From the survey of several literature (Winfield, 2000; Tamboli and Younis, 2009; Wang et al., 2008; Wu et al., 2007), it is observed that most of the research are related to coverage and connectivity analysis either to maintain the network or to propose the deployment strategy. However, only few of the work design algorithms for coverage hole recovery or hole detection. Typically, sensors are randomly deployed in an area of interest, and no spare nodes are provisioned in the network. If either a coverage hole is observed in the network due to node damage or the active node count goes below a threshold, then the network may need to be augmented with spare nodes.

The loss of a node due to failure may not only affect the network coverage but also impact network connectivity. Repair Policies focus on maintaining network connectivity when a node fails, while sustaining the pre-failure coverage. For example, a network topology is illustrated in Fig. 9. In Tamboli and Younis (2009), nodes n_1, n_2, n_3, n_{10} and n_{11} are neighbors of n_9. The failure of n_9 would detach n_{10}, n_{11} as well as their neighbors from the rest of the network and leave a hole in coverage since no other node has its sensing range overlapping with n_9. Although replacing n_9 with another node will restore the connectivity, it only

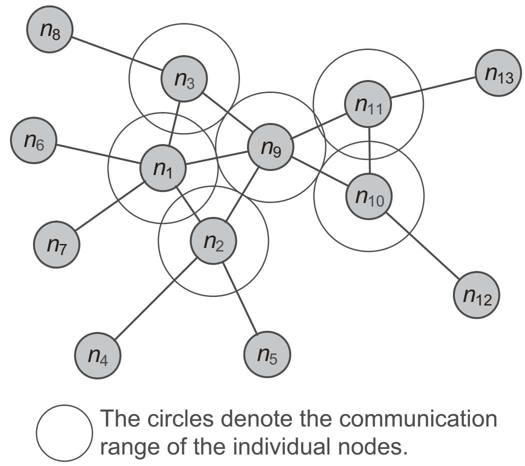

Fig. 9. An example of selecting active sensor nodes based on hop count information.

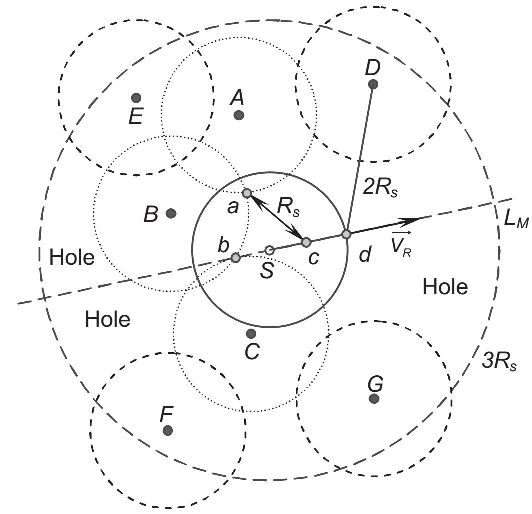

Fig. 10. An example of finding mobility distance of a mobile node *S*.

shifts the coverage hole to another part of the field, either in the inner part of the network or at the periphery.

In Tamboli and Younis (2009), both coverage conscious connectivity restoration (C^3R) algorithm and energy-centric optimized recovery (ECR) are designed to overcome this problem by temporarily replacing the failed node with one or multiple of its neighbors. The involved nodes will switch back and forth so that the network topology and the coverage stay mostly the same to their pre-failure status. In C^3R algorithm, neighbor nodes take turns in moving to the position of the failed node "*F*". After serving for sometime, a node will go back to its original position allowing for another neighbor of *F* to come forward and soon. In other words, the nodes strike a balance between temporal and spatial coverage in order to restore the connectivity. Unlike C^3R, ECR devises a recovery schedule that minimizes the ratio of travel-imposed energy to that being consumed while a node is stationary, and is suitable for networks where network longevity is a prime objective and coverage and connectivity can be traded off.

Different from the idea of taking turns to replace the failed node in Tamboli and Younis (2009), another distributed algorithm to recover the holes that use the laws of vectors as the tool to decide the magnitude and direction of the mobile nodes is proposed in Sahoo et al. (2010). Since mobility of the nodes consumes more energy, mobility of nodes in our protocol is limited within only one-hop. An example of finding mobility distance of a node is shown in Fig. 10.

Given any two nodes S_i and S_j, if $0 < d_{ij} < 2R_S$, S_i and S_j are close-workers. For any two nodes S_i and S_j, if $2R_S < d_{ij} < 3R_S$, S_i and S_j are co-workers, where d_{ij} is the physical distance between those two nodes. Let *S* be a mobile node that wants to calculate its mobility distance. Let *A*, *B*, and *C* be the close-workers and *D*, *E*, *F* and *G* be co-workers of *S*. $\overrightarrow{V_R}$ is the direction of the resultant vector, which is determined using resultant vector construction algorithm. L_M is a straight line along with $\overrightarrow{V_R}$ and passes node *S*. *a* and *b* are intersection at *S* and its neighbors. Then from *a*, put a point *c* on L_M such that $|ac| = R_S$ units. Similarly, find the co-worker of *S* that is nearest to it. Let, co-worker *D* be the nearest one. From the location of *D*, put a point *d* on L_M such that $|Dd| = 2R_S$ units. Now, the minimum of $(|Sc|, |Sd|)$ is considered to be mobility distance of *S*.

Sensor network nodes are deployed in an area by either placing them in predetermined locations or having the nodes randomly located. The choice of the deployment scheme depends highly on the type of sensors, application and the environment that the sensors will operate in. It is easier to develop a coverage scheme for deterministic placement of sensor nodes than for random placement. Once a network is constructed, coverage problem is to decide a minimum number of active nodes in the deployment region where nodes could be placed to achieve maximum coverage. One solution to coverage problem is using a variety of computational geometry tools like the Voronoi diagram and the Delaunay triangulation to provide a better coverage of the region. Besides, mobile nodes could be brought in improving the quality of coverage when the network needs to be relocated form the initial state. Last but not least, coverage hole will cause network disconnect, date collection inaccurate, and thus, it must be paid attention to.

4. Sleep scheduling mechanism

Energy is paramountly concern in WSN applications that need to operate for a long time with the limited battery power. Another effective approach for energy conservation in WSNs is scheduling sleep intervals for extraneous nodes, while the remaining nodes stay active to provide continuous service. For the sensor network to operate successfully, the active nodes must maintain both sensing coverage and network connectivity.

In order to understand the sleep scheduling mechanisms, one first needs to differentiate the various energy-saving modes that can be provided by a sensor. One complexity here is that different types of sensors may support different sets of modes and even if they support the same set of modes, they often use different terminology. To explain our presentation clearly, the major modes of a sensor are defined as follows (Wang and Xiao, 2006).

On-duty: All the components in the sensor are turned on. The sensor is able to collect sensory data, send or receive messages, process data and messages, and do other types of computation. This mode is also called the active mode in the literature. It is not an energy-saving mode.

Sensing Unit On-Duty: At least one sensing unit and the processor are turned on, but the transceiver is turned off. In this mode, the sensor is capable of sensing and processing sensory data, but not transmitting or receiving messages.

Transceiver On-Duty: The transceiver and the processor are turned on, but all the sensing units are turned off. In this mode, the sensor is capable of transmitting, receiving and processing messages, but not sensing.

Off-duty: The whole components of a sensor are turned off, but a timer or some other triggering mechanism may be running to wake up the sensor. This mode is also called the sleep mode in some literature.

4.1. Disjoint dominating sets

Reducing energy consumption to extend network lifetime is one of the most important challenges in designing WSNs. Zou and Chakrabarty (2005) proves the set of active nodes selected by a connected dominating set (CDS) provides full coverage and connectivity. One promising approach to conserving system energy is to keep only a minimal number of sensors active and put others into low-powered sleep mode, while the active sensors can maintain the communication connectivity and cover the target region completely.

The investigations in Cardei et al. (2002) and Slijepcevic and Potkonjak (2001) considered a large population of sensors, which are deployed randomly for area monitoring. The main operating constraint is available energy. How to realize the energy efficient while maintaining the initial coverage is challenging. In general, the number of sensors deployed is greater than the optimum required to perform the monitoring task. The solution proposed is to divide the sensor nodes into disjoint sets, such that each set can individually complete the area monitoring tasks. In work phase, disjoint sets are in active state on turns, that is to say if the current sensor set is active, all other node sets are in a sleep mode for energy saving. The final goal of this approach is to determine a maximum number of disjoint sets, as this has a direct impact on conserving sensor energy resources as well as on prolonging the network lifetime. Slijepcevic and Potkonjak (2001) model the area as a collection of fields, where every field has the property that any enclosed point is covered by the same set of sensors. The most-constrained least-constraining covering heuristic algorithm (Slijepcevic and Potkonjak, 2001) computes the disjoint sets successively, selecting sensors that cover the critical element (field covered by a minimal number of sensors). The theoretical analysis of the heuristic indicates that the worst runtime is $O(N^2)$, where N is the number of deployed sensor nodes.

Cardei et al. (2002) model the disjoint sets as disjoint dominating sets in an undirected graph, where sensors form the vertex set and an edge joins any two vertices that are within each other's sensing range. The maximum disjoint dominating sets computation is NP-complete, and any polynomial-time approximation algorithm has a lower bound of 1.5. A graph-coloring mechanism is proposed for computing the disjoint dominating sets. First, disjoint sets are formed by coloring all nodes, using the sequential coloring algorithm. Then, each non-dominating set is considered in an increasing color number and transformed into a dominating set by re-coloring a smallest number of higher-color vertices. When this process ends and no more dominating sets can be formed, the remaining nodes are added to the sets where they have the greatest contribution in covering parts of the uncovered given area. Simulations have shown that the number of sets computed is between 1.5 and 2 times greater than by using the algorithm in Slijepcevic and Potkonjak (2001), with lapses in area coverage less than 5%, on average.

4.2. Self-scheduling strategy

The main idea of self- scheduling strategy is similar to disjoint sets, that is, to make redundant nodes in an off-duty state. Self-scheduling strategy is to select as least as possible active nodes from all deployed sensor nodes to perform sensing task such that sufficient coverage of the monitored area can be guaranteed while reducing the energy consumption of each individual sensor node to prolong the network lifetime (Tian and Georganas, 2002; Wang et al., 2009).

Tian and Georganas (2002) proposed an energy-efficient node-scheduling-based coverage mechanism. The off-duty eligibility rule determines whether a node's sensing area is included in its neighbors' sensing area. In the self-scheduling phase, the nodes investigate the off-duty eligibility rule. Eligible nodes turn off their communication and sensing units, while all other nodes will perform sensing tasks in the sensing phase. In order to obtain neighboring information, each node broadcasts a position advertisement message at the beginning of each round. This message contains the node ID and node location. If the off-duty eligibility rule is tested simultaneously by neighboring nodes, a node and its sponsor may decide to turn off simultaneously, triggering the occurrence of blind points. To avoid this, a back-off scheme is used, where every node starts the evaluation rule after a random time, and then broadcasts a status advertisement message to announce if it is available for turning off. Before turning off, a node waits another time T_w to listen for neighboring nodes update.

Layered Diffusion based Coverage Control (LDCC) is proposed in Wang et al. (2009) as a distributed and localized coverage control protocol. The basic idea of LDCC is to apply a triangular tessellation to cover the sensor field. The normal way of applying such triangular tessellation idea for coverage control is to find sensor nodes with locations approximating to such regular positions such that the number of active sensor nodes can be reduced. In some cases, the location information may be hard to obtain for sensor nodes and we have to use some other easily obtained information instead of the location information in the coverage control. The proposed LDCC protocol is to utilize the hop count information in the process of triangle tessellation. Suppose that all sensor nodes have a fixed transmission power, the hop count measures how many transmissions are needed for a sensor node to deliver its packet to the base station, and then the hop count information can be concluded. Specifically, in Fig. 11, after sensor nodes 3, 4, 5, 6, and 7 receive the active message from sensor node 1 as the first active message ever received, each of them resets its timer to a randomly selected value between 1 and a maximum number. Suppose that the timer of sensor node 3 expires first; then it sets itself to an active state and sends out an active message which can be received by nodes 4 and 5. Again, nodes 4 and 5 reset their respective timer. Suppose that the timer of node 5 expires earlier than that of node 4 and sends out an active message that can also be received by node 4. Then, after receiving two active messages from nodes 3 and 5 with the same hop count as itself, node 4 sets itself to a sleep state. Furthermore, to enable the rotation between the sleep and the active state for each sensor node, the active message can also attach a time period value stating how long its active state is, which will also be used for a sleep node to set its sleep time period. Therefore, after some interval, all

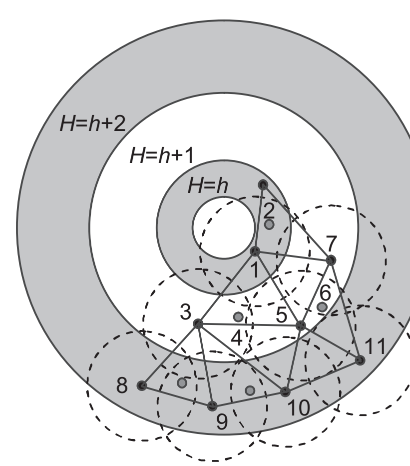

Fig. 11. An example of selecting active sensor nodes based on hop count information.

nodes become active again and the above procedure repeats for selecting the active sensor nodes for the next round.

A more practical sleep scheduling algorithm is proposed in Nath and Gibbons (2007) to prolong the whole network lifetime. This algorithm is named as Connected *K*-Neighborhood (CKN). CKN is a distributed algorithm which can turn off the redundant nodes while the network satisfies *k*-connectivity. If a node has less than *k* neighbors, none of its neighbors goes to sleep and if it has more than *k* neighbors, at least *k* of then decide to remain awake. However, CKN algorithm chooses the active nodes completely based on the ranks, which are randomly given at the beginning of executing the CKN algorithm in each epoch, and the set of awake nodes changes from epoch to epoch. As a matter of fact, it's the reasons of CKN algorithm that why CKN cannot ensure the energy consumption uniformly. For the more, in Yuan et al. (2011), a new sleep scheduling algorithm based on CKN, Energy Consumed Uniformly Connected *K*-Neighborhood (EC-CKN) algorithm, is described. In EC-CKN algorithm, the nodes' residual energy information as the parameter is considered to decide whether a node to be active or sleep aim to reduce energy consumption further. Meanwhile, EC-CKN achieves all challenges of the algorithm CKN. Hence, how to reduce energy consumption while to maintain the current coverage and connecting is a very meaningful issue in WSNs.

In this section, we described several algorithms that use sleep scheduling mechanism in order to save energy and prolong the network lifetime for sensor networks. However, almost all the algorithms are proved to be an NP-hard problem, which can only achieve as close as possible to the optimal solution. In general, sleep scheduling algorithms, which are distributed and not aware of the geographic information, do well in a large scale WSN.

5. Adjustable coverage radius

Many existing networks assume that the sensing range of a sensor is fixed. However, adjusting the transmission or sensing range of the wireless senor nodes is another power saving techniques. To the best of our knowledge, such a radius adaptive mechanism is mainly used for solving target coverage problems. The main idea of radius adaptive mechanism is reducing the overlaps among sensing ranges while maintain the QoS of coverage above a predefined detection level. How to extend the mechanism to solve more extensive coverage problems remains to be a valuable research.

5.1. Target coverage

Assume that *n* sensors are randomly deployed to cover *m* targets. Each sensor has an initial energy *E* and has the capability to adjust its sensing range. In Cardei et al. (2005a), they focus on covering a set of targets while using the adjustable sensing ranges to create a maximum number of set covers.

Definition of target coverage problem (Cardei et al., 2005a): Given *m* targets with known location and an energy-constrained WSN with *n* sensors randomly deployed in the closed proximity of the targets, schedule the sensor nodes activity such that all the targets are continuously observed and network lifetime is maximized.

5.2. Radius adaptive mechanism

In Cardei et al. (2005b), the Adjustable Range Set Covers (AR-SC) problem and the mathematical model are proposed, and efficient heuristics algorithm using linear programming and greedy techniques is designed to solve the AR-SC problem.

Fig. 12(a) shows an example with four sensors s_1, s_2, s_3, s_4 and three targets t_1, t_2, t_3. Each sensor has an initial energy $E(E=2)$. Sensing range options are r_1, $r_2 (r_1 < r_2)$ corresponding to energy consumptions of $e_1(e_1=0.5)$, $e_2(e_2=1)$. The solid line represents range r_1, dotted line represents range r_2. The coverage relationships between sensors and targets are also illustrated in Fig. 12(b): $(s_1,r_1)=\{t_3\}$, $(s_1,r_2)=\{t_1,t_3\}$, $(s_2,r_1)=\{t_2\}$, $(s_2,r_2)=\{t_1,t_2\}$, $(s_3,r_1)=\{t_2\}$, $(s_3,r_2)=\{t_2,t_3\}$, $(s_4,r_1)=\{t_1,t_3\}$ and $(s_4,r_2)=\{t_1,t_2,t_3\}$. Assuming that each set cover is active for a unit time of 1, and then one solution for the AR-SC problem using the set covers has five different sets: $C_1=\{(s_1,r_1),(s_2,r_2)\}$, $C_2=\{(s_1,r_2),(s_3,r_1)\}$, $C_3=\{(s_2,r_1),(s_3,r_2)\}$, $C_4=\{(s_4,r_2)\}$, and $C_5=\{(s_1,r_1),(s_2,r_1),(s_3,r_1)\}$. This solution achieves maximum lifetime 6, obtained for example with the following sequence of set covers: C_1, C_2, C_3, C_4, C_5, and C_4. After this sequence, the residual energy of each sensor becomes zero. If sensor nodes do not have adjustable sensing ranges, then we obtain a lifetime 4 for a sensing range equal to r_2. Sensors can be organized in two distinct set covers, such as $\{(s_1,r_2),(s_2,r_2)\}$ and $\{(s_4,r_2)\}$, and each can be active twice. The number of times a set cover active depends on the residual energy values. Therefore, this example shows a 50% lifetime increase when using adjustable sensing ranges.

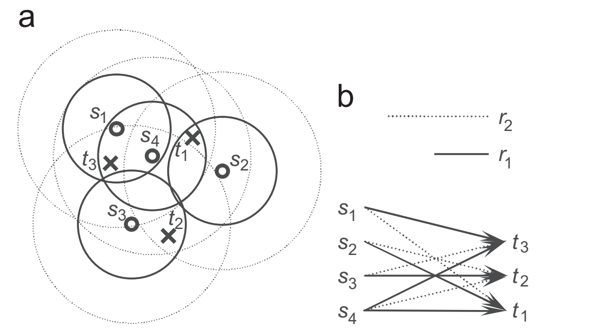

Fig. 12. An example with three targets $T=\{t_1,t_2,t_3\}$ and four sensors $S=\{s_1,s_2,s_3,s_4\}$.

In this section, coverage problems based on adjustable radius are discussed, especially, the target coverage, for lacking of such a mechanism to guarantee network connect and no coverage holes emergence in most coverage category. How to extend the adjustable radius mechanism to solve more extensive coverage problems remains to be challenging.

6. Relationship between coverage and connectivity

6.1. Overview

The above mentioned are mainly deal with coverage sensing, however, it is connectivity which determines the effective transmission of data. In Wang et al. (2003), it's clear that connectivity only requires that the location of any active node be within the communication range of one or more active nodes such that all active nodes can form a connected communication backbone, while coverage requires all locations in the coverage region be within the sensing range of at least one active node. Once sensor configuration is finished, nodes shall be comprised of connected networks to send information collected back to the control center. Hence, how to combine consideration of coverage and connectivity maintenance in a single activity scheduling is essential. The target of research on relationship between coverage and connectivity is to select the least number of active nodes, while preserve coverage and maintain connectivity.

6.2. Sufficient condition for 1-coverage to imply connectivity when $R_C \geq 2R_S$

To the best of our knowledge, Zhang (2003) and Wang et al. (2003) are the earliest papers discussing how to integrate activity scheduling in both domains: communication and sensing. Both of them independently proved the same conclusion: if a convex region is completely covered by a set of nodes, the communication graph consisting of these nodes is connected when $R_C \geq 2R_S$. In other words, under the condition that $R_C \geq 2R_S$, a sensor network only needs to be configured to guarantee coverage in order to satisfy both coverage and connectivity.

6.3. Relationship between the degree of coverage and connectivity

Based on the sufficient condition for coverage to imply connectivity when $R_C \geq 2R_S$, the relationship between the degree of coverage and connectivity is quantified in Tian and Georganas (2004). In Tian and Georganas (2004), a boundary sensor is defined as a sensor whose sensing circle intersects with the boundary of the convex sensor deployment region, while all the other sensors in the region are interior sensors. Then three valuable theorems are proved, given as follows:

Lemma 1. *For a K-covered convex region A, it is possible to disconnect a boundary node from the rest of the nodes in the communication graph by removing K sensors if* $R_C \geq 2R_S$.

Theorem 2. *A set of nodes that K-cover a convex region A forms a K connected communication graph if* $R_C \geq 2R_S$.

Theorem 3. *For a set of sensors that K-cover a convex region A, the interior connectivity is*2*K if* $R_C \geq 2R_S$.

The research study is important for applications which require degrees of coverage or connectivity larger than one.

6.4. Algorithms based on connectivity maintenance and coverage preservation

In Sahoo et al. (2007), algorithms are proposed to maintain the coverage and connectivity of the WSNs, where a node has to calculate the required and available moving distance before deciding the magnitude and direction of the mobility. Based on the available mobility distance of a node, it can move to recover the coverage hole of the network.

As discussed earlier, the issue of connectivity is just as important as coverage. A WSN only needs to guarantee coverage because connectivity will be implied when $R_C \geq 2R_S$. The authors of Zhang (2003) present CCP which attempts to provide both connectivity and coverage. The protocol needs to be combined with SPAN (Chen et al., 2002) if that condition is not met. One limitation of this approach is that it assumes uniform sensing ranges instead of probabilistic sensing ranges. If the $R_C \geq 2R_S$ condition is not met then you will need to use two protocols instead of one. This adds complexity which may not be necessary since SPAN alone could be used.

The authors of Chang and Wang (2008) also explore the issue of connected coverage and introduce the Optimal Geographical Density Control (OGDC) protocol. This is similar in many respects to CCP but differs in that it tries to minimize the overlap of sensing areas of all sensor nodes for cases when $R_C \geq 2R_S$. The algorithm starts with all the nodes initially in "UNDECIDED" state. A node with sufficient power is randomly chosen to start the process of node selection. This starting node broadcasts a power-on message. Nodes, on reception of this power-on message, check their power level and the existing coverage of area under their sensing range. If sufficient power is available, and the area is not fully covered, the node adds the starting node as the neighbor, sets its state to "ON", and broadcasts the power-on message again. This process continues with slightly different behavior for power-on messages received from starting and non-starting nodes.

In this section, we discussed relationship between coverage and connectivity, giving some typical examples based on connectivity maintenance and coverage preservation.

7. Simulation tools

Nowadays simulation tools of WSNs have been widely used, due to two serious limitations of the physics experimental platform (Shu et al., 2008). The first one is large scale, for what it is very expensive to buy a large number of sensor nodes until today. Especially, the cost for building a large scale platform of WSNs is also not acceptable for most academic researchers. The second one is non-replicable environment, for some specific applications, e.g., monitoring an erupting volcano, deploying a test-bed may cause serious damage. Fortunately, using simulation tools, researchers can study the WSNs in the environment which can be controlled, and observe the nodes mutual function caused by the disturbance and the noise. Researchers can gain nodes detail to improve the network success ratio and reduce network maintenance works. Although there are many simulators for WSN, our focus is on coverage and connectivity. Typical simulation tools used in the field of coverage and connectivity are described as follows.

7.1. Matlab

In Ghosh (2004), Matlab and the GNU "R" package are used for simulating the coverage algorithm. Several software platforms, e.g., Matlab, are excellent in handling large amount of data with high efficiency. To date, among the data processing platforms, Matlab has been mostly used in WSNs researches due to its high ability in mathematical calculation and results visualization. However, the existing applications that use Matlab in WSNs are mainly in the area of data analysis, calculation, algorithm evaluation and simulation.

7.2. Network simulator

In Shirmohammadi et al. (2009), CHEFC (Cluster Head Election with Full Coverage) was simulated through using NS-2.27 software. Network simulator is a discrete-event network simulator for Internet systems, targeted primarily for research and educational use. NS-2 is developed in C++, while NS-3 is written in C++ and Python. Users can configure the parameters of network and set up network by themselves and have a deeper sight into the entire network operation process by the animation demonstration process and the performance analysis graphics. This design simplifies the trouble of studying NS, and makes researchers to speed up the process of research and development. NS-2 has been widely used in network simulations, but does not perform well for WSNs. NS-3 is not a simple expansion of NS-2, it is a new simulator integrating Python and C++ programming feature. It is worth well looking forward to the performance of NS-3.

7.3. OPNET

A square-based WSNs with the topologies and routing protocol for simplicity is simulated to compare the performance of protocols, which are put forward in Tian et al. (2005). OPNET is a large and powerful software with a wide variety of possibilities. OPNET can be used as a research tool and also as a network design/analysis tool. OPNET was originally built for the simulation of fixed networks, and therefore, it contains extensive libraries of accurate models from commercially available fixed network hardware and protocols.

7.4. OMNET++

OMNET++ (Omnet; Xian et al., 2008; van Hoesel and Havinga, 2009) (Objective Modular Network Testbed in C++) is a public source component-based discrete event network simulator. OMNET++ provides two user interfaces: TKENV and CMDENV. TKENV is OMNET++'s GUI. It provides three methods: automatic animation, module output windows and object inspectors. CMDENV is a pure command-line interface. This feature is useful for batched simulation runs.

Besides, NetTopo has not formed a complete version, but it has considered integrating with real WSNs test-bed, from which NetTopo can be clearly distinguished. The simulation framework in NetTopo does well in algorithm oriented.

In simulation environments, WSNs system can be represent by four main parts including: WSNs applications, communication network protocol stack, properties of the communication channel and mobility of sensor nodes. All these simulators have their own advantages and limitations. Table 1 shows the comparison of typical simulation tools.

Usually, Matlab is good at data analysis, calculation, and algorithm evaluation. OMNET++, NS2 and OPNET all have strong programmability. OPNET is so expensive and NS2's protocol mode is excessively unitary, so OMNET++ has the big advantage in the model library and the available model aspects. TOSSIM (Levis et al., 2003) is an emulator rather than a simulator, as it runs actual application code. One drawback in TOSSIM is a lack of energy consumption modeling which is quite important in WSNs.

8. Typical issues summary and research challenges

8.1. Typical issues summary

As described in Section 1, there are three categories of approaches to the issues of conserving energy in WSNs, including coverage deployment strategy, sleep scheduling mechanism, and adjustable coverage radius. Many researchers have investigated these approaches, and proposed their own solutions. We summarize the typical issues on coverage and connectivity in WSN as shown in Table 2. This summary aims to be more convenient to grasp the coverage and connectivity issues from macro.

8.2. Research challenges

A great number of related works about coverage and connectivity have done, however, there are still a lot of challenges and problems need to be solved.

Table 1
Comparison of typical simulation tools.

Characteristic	Matlab	NS	OPNET	OMNET++	NetTopo	TOSSIM
License	Commercial	GPL	Commercial	Academic free, commercial	Open source	Open source
Platform support	Universal	Linux, Unix, Windows (Cygwin)	Universal (TinyOS)	Universal	Universal (JVM)	TinyOS
Programming language	Matlab script	C++, C, Tcl, OTcl, Python	C++, C	C++, C, nesC	Java	C++, C, nesC
Code exportable (actual app. code)	No	Limited	Limited	Limited (nesC yes)	Limited	Yes
Scalability to large networks ($n>100$)	Good	Fair (some cases)	Excellent	Good	Excellent	Excellent
Protocol design/optimization	None	Possible	Possible	Possible	Possible	Possible
Mobile support	No	Yes	Yes	Yes	Yes	No
Dynamic network topology support	No	Yes	Yes	Yes	Yes	No
3D radio modeling	Yes	No	Yes	No	No	No
Involved references	Ghosh (2004)	Shirmohammadi et al. (2009)	Tian et al. (2005)	Omnet (); Xian et al. (2008); van Hoesel and Havinga (2009)	Shu et al. (2008)	Levis et al. (2003)

Table 2
A summary of typical issues on coverage and connectivity in WSNs.

Category	Approach	Proposed solution	Sensing model	Deployment strategy	Coverage radius	Characteristic	Known location
Coverage deployment strategy	Computational geometry	Seamless coverage (Wang and Zhang, 2009)	Disc	Deterministic	Fixed	Centralized energy-efficient	Yes
		k-coverage (Huang and Tseng, 2005)	Non-disk supported	Random	Any	Centralized or distributed	Yes
		Breach path	Disc	Random	Any	Geometry method centralized	Yes
		Support path (Cao et al., 1997)					
		CCP (Zhang, 2003)	Disc	Random	Fixed	Distributed	No
		OGDC (Chang and Wang, 2008)	Disc	Random	Fixed	Distributed	Yes
		VEC, VOR (Wang et al., 2004)	Disc	Random	Any	Distributed	Yes
	Virtual forces	VFA (Zou and Chakrabarty, 2003)	Disc	Random	Fixed	Distributed	No
		CPVF (Tan et al., 2009)	Disc	Random	Fixed	Distributed	No
	Mobility	C^3R, ECR (Tamboli and Younis, 2009)	Disc	Random	Fixed	Hole recovery	No
		VEC-based (Sahoo et al., 2010)	Disc	Random	Fixed	Hole recovery	Yes
Sleep scheduling mechanism	Disjoint sets	Dominating sets (Cardei et al., 2002; Slijepcevic and Potkonjak, 2001)	Disc	Random	Fixed	Centralized or distributed energy-efficient	No
		CDS (Zou and Chakrabarty, 2005)	Disc	Random	Fixed		
	Sleep scheduling	Off-duty eligibility rule (Tian and Georganas, 2002)	Disc	Random	Any	Distributed energy-efficient	Yes
		LDCC (Wang et al., 2009)	Disc	Random	Any	Distributed	No
		EC-CKN (Yuan et al., 2011)	Disc	Random	Fixed	Distributed *k*-neighborhood energy balance	Yes
Adjustable coverage radius	Computational sets	AR-SC (Cardei et al., 2005b)	Disc	Random	Adjustable	Centralized energy-efficient	No

8.2.1. Optimal node deployment

Optimal node deployment is a very challenging problem that has been proven to be NP-hard for most of the formulations of sensor deployment (Cheng et al., 2008b; Poduri et al., 2006). To tackle such complexity, several heuristics have been proposed to find sub-optimal solutions (Efrat et al., 2005; Pan et al., 2005; Dhillon and Chakrabarty, 2003b; Clouqueur et al., 2002). However, the context of these optimization strategies is mainly static in the sense that assessing the quality of candidate positions is based on a structural quality metric such as distance, network connectivity and/or basing the analysis on a fixed topology. How to optimize dynamic or hybrid networks remains to be a hot research.

8.2.2. Innovate and improve coverage control algorithms

Once a network is deployed completely, and the algorithms run all over the lifetime of WSNs. However, similar to optimal node deployment, almost all the algorithms also can be taken as NP-hard problems, which can only do their best to close to the optimal solution. A typical example has mentioned in Section 5. ‘‘How to extend the adjustable radius mechanism to solve more extensive coverage problems’’ was put forward. Such factors have hence simply become the most challenge in the filed of WSNs. An excellent algorithm could provide WSNs with higher quality of coverage and longer life cycle.

8.2.3. Effective design of sensing models: form the lab to the real world

Since most of the existing works on coverage and connectivity issues based on the disc sensing model or the probabilistic sensing model, nobody could have failed to notice the fact that the sensing range can be influenced by real geography environment and communication jamming. It is likely that the theoretical design based on the disc sensing model or the probabilistic sensing model near perfect, but using in the actual, the results will vary greatly. Hence, the design of sensing models form the lab or theory to the real world is essential.

8.2.4. Coverage hole's detection and repair mechanism

Although the coverage and connectivity issues have been interpreted in a variety of ways in the existing literature, only a few researches focus on coverage holes. Coverage holes (Ahmed et al., 2005) may cause by random deployment or energy exhaustion, one of the challenges is how to detect such holes, another one is how to repair these holes. Some protocols have been discussed in Section 3.2, such as VEC, VOR and Minimax algorithm. However, approaches relies on the use of Voronoi diagrams are mainly used, and they have several problems in practice. First and foremost, they assume that a sensor can easily detect all or most of its Voronoi neighbors through local communication, but communication range may not be enough to cover all Voronoi neighbors. Besides, significant sensing overlaps or voids among sensors may be ignored leading to poor network coverage. Hence, coverage hole is a hot research direction.

8.2.5. Three-dimensional (3D) coverage

The 2D coverage problem has been solved efficiently in Zhang et al. (2010) with a polynomial time algorithm in terms of the number of sensors. However, the spatial of 3D networks is much more complex than that of 2D networks. The random structure assumption which is adopted by most of the current researchers cannot satisfy all demands of 3D WSNs in real life. Besides, compared with 2D coverage, complexity of 3D coverage control algorithms exponentially increase.

9. Conclusion

Coverage and connectivity are two of the most fundamental issues in WSNs, which have a great impact on QoS of WSNs. Many algorithms, strategies and mechanisms have been proposed by researchers around the world to solve these problems. First, a brief introduction to the basic knowledge of coverage concepts is given in this paper. Second, we take energy efficient factors into consideration, and describe the coverage and connectivity issues from three aspects: coverage deployment strategy, sleep scheduling mechanism and adjustable coverage radius. In each section, we described recent research results proposed in literature, their formulations and assumptions as well as proposed solutions. Then, we introduce and compare most popular and typical simulation tools used in coverage and connectivity area. Finally, typical issues on coverage and connectivity in WSNs are summarized, and existing problems and challenges are discussed. We hope that our efforts can be used as a starting point of what has been done in such field so far or even do some help to future research.

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