Survey on Coverage Problems in Wireless Ad Hoc Sensor Networks

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***Abstract*— Wireless sensor networks have a broad range of applications in the military, surveillance, environment monitoring, and healthcare fields. Coverage of sensor networks describes how well an area is monitored. The coverage problem has been studied extensively, especially when combined with connectivity and energy efficiency. Constructing a connected, fully covered, and energy efficient sensor network is valuable for real world applications due to the limited resources of sensor nodes. In this paper, we survey five recent research approaches on coverage of wireless sensor networks and present in some detail the algorithms, assumptions, and results. A comprehensive comparison among these approaches is given from the perspective of design objectives, assumptions, algorithm attributes, and related results. Open research problems on coverage are also discussed.**

I. INTRODUCTION

A typical wireless sensor network consists of a large number of distributed sensor nodes cooperatively monitoring the physical world. Sensor networks present a new class of computing systems consisting of small and cheap devices which scattered in the environment in order to monitor the spatial-temporal phenomena around human being. Applications of wireless sensor networks include environmental and habitat monitoring, precision agriculture, surveillance, asset tracking, and healthcare [1][5].

Each node in a wireless sensor network is typically equipped with sensors, wireless communication devices, a microprocessor, and a power source. Sensor nodes can be placed on predetermined positions or randomly deployed. Nodes in a sensor network communicate with each other by self-organizing into an ad hoc wireless network. Compared to wireless ad hoc networks, wireless ad hoc *sensor* networks usually have limited resources (such as energy, bandwidth, and computation), and large and dense deployments. Because of the wide range of applications as well as significant challenges that arise due to the limited resources, a great deal of research has been conducted in this area.

An important research issue in wireless ad hoc sensor network is the coverage problem. Network coverage measures how well an area is monitored by a sensor network. If each position in the area is monitored by at least K ($K \geq 1$) sensors, the sensor network is said to be a K-coverage sensor network where K is the coverage degree. The coverage problem is essentially a Quality of Service (QoS) problem which guarantees the monitored area is covered by one or more sensor nodes. In this paper, we survey the existing researches on the coverage problem describing and comparing five algorithms that have been presented in the literature. We conclude by discussing open research problems in the area.

Energy conservation is a critical issue in sensor networks because replacement of battery is costly and even infeasible in some applications, such as battle field surveillance. A frequently used method to conserve energy is scheduling, where a minimum number of sensor nodes are activated to satisfy the K-coverage requirement and the remaining nodes are set to sleep for conserving the energy. Such scheduling schemes are used to prolong the lifetime of the sensor network. An additional advantage of this approach is that it saves energy by avoiding frequent communication collisions and redundant messages in a sensor network with dense activated nodes.

The paper continues with Section II that describes five approaches with different design objectives on the coverage problem including the scope, assumptions, and algorithms. In Section III, these approaches are compared according to different characteristics of design objectives, assumptions, algorithm attributes, and related results. Some of open research problems in the coverage problem are discussed in Section IV, followed by concluding remarks in Section V.

II. EXISTING RESEARCH ON COVERAGE PROBLEM IN WIRELESS SENSOR NETWORKS

As an important research issue, the coverage problem has been studied extensively, and many solutions have been proposed. Some solutions focus on pure coverage problems to characterize the coverage of wireless ad hoc sensor networks. Other solutions integrate network connectivity into coverage problems. Network connectivity, which indicates whether any two nodes in a sensor network can communicate with each other, is necessary for successful data transmission. Algorithms to construct a sensor network with connected coverage is valuable to real world applications. Furthermore, minimizing the energy consumption to prolong the lifetime of a sensor network is considered. Some algorithms and protocols are designed to achieve energy efficiency while maintaining a fully covered connected wireless ad hoc sensor network.

We surveyed existing methods and their contributions which address various research objectives in the coverage problem. In the following subsections, we will present in some detail the algorithms or solutions, their assumptions, and results.

A. Perimeter-area Coverage Algorithm

A Perimeter-area Coverage (PC) algorithm is presented in [7]. This algorithm determines whether every point on the monitored area of a wireless sensor network is covered by $K(K \geq 1)$ sensors. Connectivity and scheduling for preserving energy are not considered. The PC algorithm cannot be used to configure a K-coverage sensor network.

The sensing range is assumed to be a disk at first; and then is relaxed to a convex polygon. For each sensor, this algorithm sorts the intersection points on the perimeter of a sensing range and then counts the intersection overlaps on the perimeter. If there are K overlaps on a perimeter segment, it will report this segment is K-covered. If all segments on the perimeter of a sensing circle are at least K-covered, this sensor is K-perimeter-covered. The paper proves that the monitored area is K-covered if and only if each sensor in the area is K-perimeter-covered. The PC algorithm has two versions, $k-UC$ version and $k-NC$ version. $k-UC$ assumes all sensors have same sensing range while $k-NC$ assumes different sensing range for different sensors.

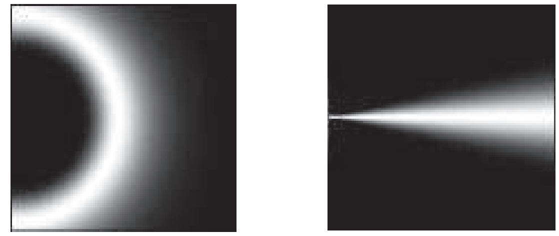
The complexity of the algorithm is $O(nd \log d)$, where n is the number of sensors in the monitored area and d is the number of nodes in the largest sensing neighbor set. Neither simulation nor experimental results are given in the paper to evaluate the algorithm.

B. Sensing Field of a Sensor Network

A single sensor can be characterized by traditional specifications such as sensing range, resolution, and accuracy. To characterize the coverage quality in a sensor network, the approach presented in [8] proposed a new sensor network specification called Sensing Field (SF). The sensing field measures how well a position in the area of sensor network is monitored. Computing the sensing field helps to deploy a sensor network with better sensing performance.

In this approach, target localization is taken as an application example to compute the sensing field. A sensing model is given for acoustic amplitude sensors and direction-of-arrival (DOA) sensors. Instead of a disk sensing range, the paper models the sensing range using an observational likelihood function as plotted in Fig. 1. The function captures the characteristic of the sensing range more accurate than a disk. For simplicity, the measurement noise is assumed to be Zero Mean Gaussian process. Based on Cramer-Rao bound (CRB), the paper derives a theoretical upper bound for the accuracy of estimating the position of a target at different positions. The paper also evaluates the model validity by using information-theoretic Kullback-Leibler (KL) divergence.

There are no experimental results presented in this paper. Only simulation results are given to illustrate the upper bound of estimation accuracy and KL divergence. Connectivity and



(a) (b)

Fig. 1. Observational model: (a) acoustic amplitude sensors and (b) DOA sensors

energy conservation are not considered in the paper. The computation of CRB is based on discretizing the sensing space (i.e. monitored area) so the computation of the sensing field is costly. It is impossible to calculate the sensing field dynamically in each sensor because of the costly computation, which limits the utilization of sensing field in a realistic application.

C. Coverage Configuration Protocol

A Coverage Configuration Protocol (CCP) is proposed in [10]. CCP can configure a sensor network to any coverage degree and maintain network connectivity at the same time. A scheduling mechanism is used in CCP to activate sensor nodes; but this mechanism does not ensure the number of activated sensor nodes to be minimum.

Assuming a disk sensing range, the work in [10] shows that coverage implies connectivity if the communication range R_c is greater or equal to twice the sensing range R_s. CCP is base on the K-coverage Eligibility algorithm which is executed by each sensor node (e.g. node A in Fig. 2) to decide whether it should become active. The coverage degree of the intersection points (e.g. $p1$, $p2$, $p3$ in Fig. 2) are computed. If any one of these intersection points is covered by less than K sensors, sensor A is eligible to activate itself. In Fig. 2, node A is ineligible for $K = 1$, but eligible for $K \geq 2$. The complexity of the K-coverage Eligibility algorithm is $O(d^3)$, where d is the number of nodes in the largest sensing neighbor set. CCP is a distributed and localized protocol, which has three modes, sleep, listen, and active. If $R_c \geq 2R_s$, CCP is sufficient to configure a sensor network with both coverage and connectivity; if $R_c < 2R_s$, CCP integrates SPAN [4] to maintain the network connectivity.

Using simulation results, the performance of CCP is compared with the Coverage Preserve (CP) protocol in [9] and SPAN [4]. Regarding the coverage efficiency, CCP provides 1-coverage using a significantly smaller number of active nodes than the CP protocol in [9]. CCP can enforce different coverage degrees while the protocol in [9] only satisfies fixed coverage degree. CCP performs well in terms of packet delivery ratio, coverage, and the number of active nodes when $R_c \geq 2R_s$. $CCP+SPAN_{2HOP}$ is the most efficient approach in providing both sufficient coverage and connectivity when $R_c < 2R_s$ ($SPAN_{2HOP}$ is an extension of SPAN using 2-hop information to maintain the communication backbone in

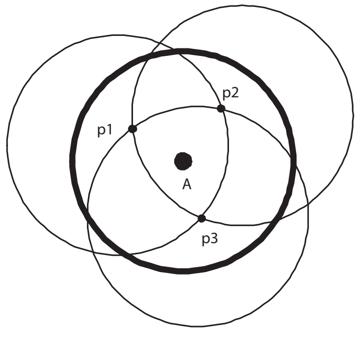


Fig. 2. An Eligibility Example

wireless network).

D. Area Dominating Set Protocol

The Area Dominating Set (ADS) in a wireless sensor network is the smallest subset of sensor nodes that fully covers the monitored area. A protocol to construct an ADS is proposed in [3]. This protocol can configure a fully covered and connected wireless sensor network while considering energy efficiency.

The ADS protocol is based on the Connected Dominating Set (CDS) constructing protocol. A CDS is a connected subset of a graph such that every vertex in the graph is either in the set or adjacent to a vertex in the set. For example, the black nodes (i.e. node 6, 7, 8, and 9) in the graph as shown in Fig. 3 form a CDS. The Marking Process proposed in [11], [12] is used to construct a CDS. The Marking Process marks any host, which has two unconnected neighbors, as a gateway. These gateways form a CDS. The CDS is further pruned by Rule k [6] which can unmark gateways covered by k other gateways. The Marking Process and Rule K are used in wireless network routing. Routing in the pruned CDS is more efficient than routing in the whole wireless network. The complexity of Marking Process and Rule K is $O(d^2)$, where d is the number of nodes in the largest communication neighbor set. The ADS protocol uses CDS constructing protocol to maintain the connectivity in wireless sensor networks.

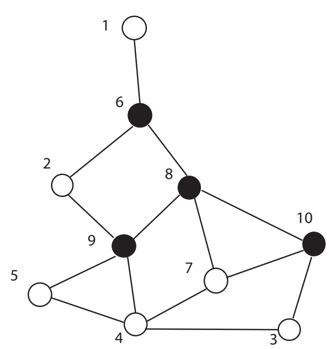


Fig. 3. A CDS Example

Coverage is not considered in CDS constructing protocols so the ADS protocol has its own algorithm to maintain coverage. The ADS protocol assumes that the sensing range of all sensors are the same and the communication range of a sensor is equal to its sensing range [3]. The ADS protocol runs on a node A as follows. First, the node A computes the area covered by each node that transmits message to it and includes the transmitting node in a subset. Second, at the end of timeout interval, node A computes a subgraph of its one-hop neighbors who sent message to it. Third, if the subgraph is connected and the subgraph nodes fully cover node A area, node A opts for sleeping status; otherwise, node A chooses active status.

There are no simulation and experimental results presented in the paper. The complexity of the ADS protocol is $O(d^3)$ because the protocol is extended from the CDS constructing protocol whose complexity is $O(d^2)$.

E. Optimal Geographical Density Control Algorithm

An Optimal Geographical Density Control (OGDC) algorithm is proposed in [13]. The OGDC algorithm can configure a sensor network with the characteristics of full-coverage, network connectivity, and maximum energy conservation. The energy is conserved by controlling the density of the active nodes. The sparser the active sensor nodes are, the less energy the sensor network consumes.

The approach assumes that the sensor density is high enough so that a sensor could be found at any desirable position and the sensing range could be different for sensors. To simplify the OGDC algorithm, it is also assumed that sensor node is aware of its own position and all nodes are time synchronized. The paper proves that complete coverage of a monitored area implies connectivity of the monitoring sensor network if and only if $R_c \geq 2R_s$. The method adopted in the OGDC algorithm is also proved to be a sensing coverage optimization. Using the OGDC algorithm, the number of activated sensor nodes is optimized to reduce energy consumption.

The OGDC algorithm is round-based. Each round includes a node selection phase and a stable state phase. In the situation where $R_c < 2R_s$, the OGDC runs as follows. In the node selection phase, every node volunteers itself to be a starting node. If a node is selected to be a starting node, it turns itself on and broadcasts an "On" message to the nodes in its communication range. When a node receives an "On" message, it will set up a timer whose length is proportional to the distance between the sender and the receiver. If it doesn't receive any more messages from other nodes before the timer expires, it turns itself on. The mapping from the distance to the timer controls the working nodes density. After finishing node selection, all nodes enter stable states being active or sleeping and wait for the next round. In the situation where $R_c < 2R_s$, OGDC uses a group-merging process to select the active nodes in the first phase. The OGDC algorithm is distributed and localized. There is no complexity analysis in the paper and the details of the OGDC algorithm given are not sufficient for a complexity analysis.

The simulation results indicate that the OGDC algorithm is better than CCP, PEAS, and GAF-like algorithm in terms of the percentage of coverage, the number of working nodes required to provide the percentage of coverage, and the α-lifetime (α-lifetime is defined as the total time during which at least α portion of the total area is covered by at least one node).

III. Comparison and Taxonomy of Existing Research

The coverage problem solutions presented in section II are compared with respect to design objectives, assumptions, attributes, and experimental results.

A. Comparison of Design Objectives

There are three types of design objectives in coverage problems. The essential design objective is to solve the pure coverage problem for characterizing or improving the coverage of the wireless sensor networks. Another design objective is to maintain the network connectivity in a fully covered sensor network for successful communication. Besides the connectivity and coverage, the energy efficiency is an important design objective which has been studied together with the coverage problem.

The PC algorithm and the SF characterization focus on pure area coverage. Connectivity and energy efficiency are not studied in these two approaches. CCP, ADS, and OGDC are designed for the connected-coverage problem. These three algorithms use a scheduling mechanism to conserve energy. OGDC has a better scheduling strategy and maximizes energy conservation. The CDS constructing protocol is used in wireless networks instead of sensor networks; however, its solution for network connectivity is used by the ADS protocol. We presented the CDS constructing protocol for a better understanding of the ADS protocol. The objectives of the algorithms are shown in Table I.

TABLE I
Comparison of design objectives

	Area Coverage	Connectivity	Energy
PC	Yes	No	No
SF	Yes	No	No
CCP	Yes	Yes	Yes
OGDC	Yes	Yes	Yes
ADS	Yes	Yes	Yes

B. Comparison of Assumptions

All work mentioned above assumes a static sensor network application scenario where sensors do not move after deployment and also assumes the sensors are aware of their positions through localization techniques.

Most algorithms, such as the PC algorithm, CCP, OGDC algorithm, and ADS protocol, model the sensing range as a disk. CCP and ADS assume all sensor nodes have the same size of sensing range. Different sensing range is allowed in the PC algorithm and the OGDC algorithm. On SF calculation, the sensing range is modeled by an observational likelihood function which is a more accurate method to model a real sensor than a disk. However, the function increases the complexity of the algorithm.

The relationship between connectivity and coverage has been studied in [10] and [13]. Coverage implies connectivity if and only if $R_c \geq 2R_s$. When the ratio between the communication range and the sensing range is less than 2, an additional method needs to be used to maintain connectivity and coverage. In CCP, SPAN is used; while in OGDC, a Group Merging Process (GMP) is used. ADS assumes that the communication range equals the sensing range. The ratio of communication range and sensing range is not used to the PC algorithm and SF method because they are not designed for network connectivity.

The OGDC algorithm has special assumptions on the sensor node density and time synchronization which have been discussed in section II.E. Table II shows the comparisons on the assumptions made by these algorithms.

TABLE II
Comparison of assumptions

	Sensing Range	R_c/R_s
PC	arbitrary	N/A
SF	likelihood function	N/A
CCP	same size disks	CCP if ≥ 2; +SPAN if < 2
OGDC	same/different size of disks	OGDC if ≥ 2; +GMP if < 2
ADS	same size disks	1

C. Comparison of Algorithm Attributes

The attributes of each algorithm are discussed from the following perspectives: distribution, localization, and coverage degree. A distributed algorithm implements the scheduling mechanism in a decentralized way. There is no center node which decides the status of other nodes; instead, the decision is made by every node. Most protocols use distributed algorithms, such as CCP, OGDC, CDS construction algorithm, and ADS. In a localized algorithm, the scheduling decision can be made based on one hop neighborhood information. The OGDC algorithm, CDS construction algorithm, and ADS are localized.

The coverage degree achieved by different algorithm varies. For example, CCP can configure the sensor network with K-coverage ($K \geq 1$) while OGDC only configures 1-covered sensor network due to its minimum density control strategy. The comparisons about the attributes are summarized in Table III.

D. Comparison of Results

Simulation instead of experiments is used to evaluate the protocols by most papers. If the network connectivity is one of the design objectives, the NS-2 simulator is used. The commonly used performance metrics are the percentage of coverage, the number of active nodes, and the sensor network

TABLE III

COMPARISON OF ATTRIBUTES

	Distributed	Localized	Degree
PC	N/A	N/A	$K \geq 1$
SF	No	No	N/A
CCP	Yes	No	$K \geq 1$
OGDC	Yes	Yes	$K = 1$
ADS	Yes	Yes	$K \geq 1$

lifetime. The percentage of coverage presents the ratio of covered area to the total area to be monitored. The higher is better. The number of active nodes is the number of nodes activated for covering the monitored area. Fewer active nodes means better algorithm performance. The lifetime is the time during which a sensor network can function properly after deployment. The longer lifetime indicates that energy is better conserved by the algorithm.

Because CCP and OGDC have the same design objectives, paper [13] compares the performance of these two solutions. The paper shows that OGDC takes less time to configure the sensor network than CCP. The number of working nodes is less by using OGDC. When the number of deployed nodes increases, the performance of CCP as measured by the coverage percentage and number of working nodes decreases. OGDC configures the senor network with longer lifetime than CCP. During the lifetime, a higher coverage percentage can be maintained by OGDC.

Regarding the algorithm complexity, there is no complexity analysis for the SF characterization and the OGDC algorithm. The complexity of the PC, CCP, and ADS algorithms is shown in Table IV.

TABLE IV

COMPARISON OF RESULTS

(n: number of sensors in the monitored area; d: number of sensors in the largest sensing neighbor set)

	Simulation	Complexity
PC	No	$O(nd \log(d))$
SF	Yes	No
CCP	Yes	$O(d^3)$
OGDC	Yes	No
ADS	No	$O(d^2)$

IV. OPEN RESEARCH PROBLEMS

Most recent works on the sensor network coverage problem are still limited to theoretical studies [2]. Future research focusing on solutions which accelerates practical deployment could be conducted. There are several additional research problems listed below.

A. Coverage solutions for sensors with irregular sensing/communication range

In realistic sensor networks, the sensing and communication range are irregular. For example, the directional antenna, which is used broadly in surveillance, has a sector sensing range. The communication range of the sensor is not an ideal circle. The solutions for the coverage of a sensor network whose sensor node has an irregular sensing or communication range is necessary in real world applications.

B. Coverage solutions for mobile sensor networks

In a mobile sensor network, the sensor nodes are mobile and they move after deployment. The movement of sensors might be caused by the environment they are in (such as winds, currents, and etc.) or by the actuator they have. The coverage solution in this type of sensor network could be studied.

C. Coverage solutions with fault tolerance

Fault tolerance is the ability to sustain sensor network functionalities without any interruption due to sensor node failures [1]. Fault tolerance should be considered while configuring a connected and fully covered sensor network. The failure of sensor nodes should not affect the coverage and connectivity of a sensor network.

D. Other energy conservation methods beside scheduling

In order to conserve energy in a sensor network, scheduling is a frequently used method. Besides scheduling, reducing communication range also conserves energy. We need to study how to maintain the connectivity and coverage when communication rang is reduced and how much should be reduced.

E. Coverage solutions for specific applications

Some applications, such as tracking and detection, may use specific coverage solutions. The solutions should dynamically determine which sensor should sense and what needs to be sensed while considering the energy conservation.

V. CONCLUSIONS

Five recent research approaches on the sensor network coverage problem wrer surveyed in this paper. Their assumptions, algorithms, and performance were presented. A comparison was also conducted. Coverage with connectivity is important for characterizing the QoS of wireless sensor networks. A scheduling mechanism is frequently used to configure an energy efficient, fully covered, and connected wireless sensor network. The principle of these algorithms is scheduling a minimum number of sensor nodes to cover the monitored area. In addition, a distributed and localized algorithm outperforms a centralized algorithm in energy conservation due to less message transmissions. The OGDC algorithm that integrates optimization into scheduling has achieved significant energy conservation. We plan to compare the performance of these algorithms based on a common platform using simulations. More research could be conducted for the practical deployment of a sensor network.

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