Coverage in Wireless Sensor Networks

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Abstract

Recent improvements in affordable and efficient integrated electronic devices have a considerable impact on advancing the state of wireless sensor networks, which constitute the platform of a broad range of applications related to national security, surveillance, military, health care, and environmental monitoring. An important problem receiving increased consideration recently is the **sensor coverage problem***, centered around a fundamental question: How well do the sensors observe the physical space? The coverage concept is subject to a wide range of interpretations due to a variety of sensors and applications. Different coverage formulations have been proposed, based on the subject to be covered (area versus discrete points), sensor deployment mechanism (random versus deterministic) as well as other wireless sensor network properties (e.g. network connectivity and minimum energy consumption). In this article, we survey recent contributions addressing coverage problems in the context of static wireless sensor networks. We present various coverage formulations and their assumptions, as well as an overview of the solutions proposed.*

Key Words*: Connectivity, coverage, energy efficiency, wireless sensor networks.*

1 Introduction

Wireless sensor networks (WSNs) have attracted a great deal of research attention due to their wide-range of potential applications. A WSN provides a new class of computer systems and expands people's ability to remotely interact with the physical world. In a broad sense, WSNs will transform the way we manage our homes, factories, and environment. Applications of WSNs [11] include battlefield surveillance, biological detection, home appliance, smart spaces, and inventory tracking.

The purpose of deploying a WSN is to collect relevant data for processing/reporting. There are two types of reporting [4]: **event-drive** and **on-demand**. Consider a WSN with a sink (also called monitoring station) and a set of sensor nodes. In the event-driven reporting, the reporting process is triggered by one or more sensor nodes in the vicinity which detect an event and report it to the monitoring station. In the on-demand report, the reporting process is initiated from the monitoring station and sensor nodes send their data in response to an explicit request. A forest fire monitoring system is event-driven, whereas an inventory control system is on-demand. A more flexible system can be a hybrid of even-driven and on-demand.

1.1 Sensor Coverage Problem

An important problem addressed in literature is the **sensor coverage problem**. This problem is centered around a fundamental question: "*How well do the sensors observe the physical space ?*" As pointed out in [17], the coverage concept is a measure of the quality of service (QoS) of the sensing function and is subject to a wide range of interpretations due to a large variety of sensors and applications. The goal is to have each location in the physical space of interest within the sensing range of at least one sensor.

1.2 Design Choices

Sensor nodes, also called wireless transceivers, are tiny devices equipped with one or more sensors, one or more transceivers, processing, storage resources and, possibly, actuators. Sensor nodes organize in networks and collaborate to accomplish a larger sensing task. One important class of WSNs is wireless ad-hoc sensor networks (WASN), characterized by an "ad-hoc" or **random** sensor deployment method, where the sensor location is not known a priori. This feature is required when individual sensor placement is infeasible, for example battlefield or disaster areas. The characteristics of a WASN include limited resources, large and dense networks, and dynamic topology. Generally, more sensors are deployed than required (compared with the optimal placement) to perform the proposed task; this compensates for the lack of exact positioning and improves the fault tolerance. The size of a WASN may reach hundreds or even thousands of sensor nodes. If the sensors can be placed exactly where they are needed, the corresponding deployment method is **deterministic** [13].

Sensors have size, weight, and cost restrictions, which impact resource availability. They have limited battery resources, processing and communication capabilities. As replacing the battery is not feasible in many applications, low power consumption is a critical factor to be considered, not only in the hardware and architectural design, but also in the design of algorithms and network protocols at all layers of the network architecture. Therefore, an important network design objective is to maximize the network lifetime. Another clear objective, especially in a deterministic node deployment, is to use a minimum number of sensors.

A sensor can be in one of the following four states: transmit, receive, idle, or sleep. The idle state is when the transceiver is neither transmitting nor receiving, and the sleep mode is when the radio is turned off. As presented in [19], the power usage for WINS Rockwell seismic sensor for transmit:receive:idle:sleep operational modes are $0.38 \div 0.7W : 0.36W : 0.34W : 0.03W$ while the sensing power is 0.02W. An interesting observation is that the receive and idle modes may require as much energy as transmitting, whereas in the traditional ad-hoc wireless networks, transmitting may use as high as twice the power of receiving. Another observation is the communication/computation power usage ratio, which can be higher than 1000 (e.g. for Rockwell WINS is $1500 \div 2700$), therefore local data processing, data fusion and data compression are highly desirable. Judiciously selecting the activity state of each sensor is accomplished through a **scheduling** mechanism. When the goal is to reduce the number of active sensors performing the coverage, this constitutes an important method for decreasing the network energy consumption. Sometimes, the scheduling mechanism has also the objective of maintaining connectivity among active sensors.

The coverage algorithms proposed are either **centralized**, or **distributed** and **localized**. In distributed algorithms, the decision process is decentralized. By distributed and localized algorithms, we refer to a distributed decision process at each node that makes use of only neighborhood information (within a constant number of hops). Because the WSN has a dynamic topology and needs to accommodate a large number of sensors, the algorithms and protocols designed should be distributed and localized, in order to better accommodate a scalable architecture.

Considering the coverage concept, different problems can be formulated, based on the subject to be covered (**area** versus **discrete points**) and on the following design choices:

- **Sensor Deployment Method**: deterministic versus random. A deterministic sensor placement may be feasible in friendly and accessible environments. Random sensor distribution is generally considered in military applications and for remote or inhospitable areas.

- **Sensing $\&$ Communication Ranges**: WASN scenarios consider sensor nodes with same or different sensing ranges. Another factor that relates to connectivity is communication range, that can be equal or not equal to the sensing range.

- **Additional Critical Requirements**: energy-efficiency and connectivity. We will refer to these as energy-efficient coverage and connected coverage.

- **Algorithm Characteristics**: centralized versus distributed/localized.

- **Objective of the Problem**: maximize network lifetime or minimum number of sensors.

Tables 1 and 2 summarize the methods covered in this chapter, according to the five choices presented above.

1.3 Coverage Problem in Other Fields

Coverage problems have been formulated in other fields, such as the Art Gallery Problem, ocean coverage, and coverage in robotic systems.

The Art Gallery Problem [20] asks to determine 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. This problem has a linear time solution for the $2D$ case. The $3D$ version is NP-hard and an approximation algorithm is presented in [16]. This visibility problem has many real world applications, such as placement of antennas for cellular telephone companies, and placement of cameras for security purposes in banks and supermarkets.

The work in [8] addresses the ocean area coverage problem. Here the authors are interested in satellite based monitoring of the ocean phytoplankton abundance. Given the orbit and sensor characteristics of each mission, numerical analysis results show that merging data from three satellites can increase ocean coverage by 58% for one day and 45% for four days. Still additional satellites produce diminishing returns.

The coverage concept with regard to the many-robot systems was introduced by Gage [7]. He defined three types of coverage: blanket coverage, barrier coverage, and sweep coverage. In the blanket coverage, the goal is to achieve a static arrangement of sensors that maximizes the total detection area. In barrier coverage the goal is to achieve a static arrangement of nodes that minimizes the probability of undetected penetration through the barrier, whereas the sweep coverage is more or less equivalent to a moving barrier. New applications arise in the context of mobile

Coverage Approach	Coverage Type	Problem Objectives
Most Constrained-Minimally Constraining Heuristic [21]	Area Coverage	Energy-Efficiency Maximize network lifetime by reducing the number of working nodes
Disjoint Dominating Sets Heuristic [2]	Area Coverage	- // -
Node Self-Scheduling Algorithm [22]	Area Coverage	- // -
Probing-based Density Control Algorithm [26]	Area Coverage	Energy-Efficiency Maximize network lifetime by controlling working nodes density
Optimal Geographical Density Control (OGDC) Algorithm [27]	Area Coverage	Energy-Efficiency, Connectivity Maximize network lifetime by reducing the number of working nodes
Coverage Configuration Protocol (CCP) [23]	Area Coverage	- // -
Connected Dominating Set based Coverage [24]	Area Coverage	- // -
Node Placement Algorithms [13]	Area Coverage Point Coverage	Energy-Efficiency, Connectivity Deployment of a minimum number of sensors
Disjoint Set Cover Heuristic [3]	Point Coverage	Energy-Efficiency Maximize network lifetime by reducing the number of working nodes
Maximal Breach Path and Maximal Support Path Algorithms [17]	Barrier Coverage	Worst and best case coverage paths
Maximal Support Path Algorithm[14]	Barrier Coverage	Best case coverage path
Node Density -based Coverage [15]	Barrier Coverage	Find the critical node density, above which a penetrating path will be detected almost surely
Minimum Exposure Path Algorithm [18]	Barrier Coverage	Find the path of minimum exposure
Critical Node Density for Complete Coverage in the Exposure Model [1]	Barrier Coverage	Find the critical density for a high probability of target detection

Table 1. Coverage approaches.

Coverage Approach	Sensor Deployment Method	Sensing Range R_s, Comm. Range R_c		Algorithm Characteristics
		Same R_s for all sensors ?	Is $R_s == R_c$ for each sensor ?	
[21]	Random	YES	NA	Centralized
[2]	Random	YES	NA	Centralized
[22]	Random	YES + NO (both)	NA	Distributed, localized
[26]	Random	YES	NA	Distributed, localized
[27]	Random	YES	NO	Distributed, localized
[23]	Random	YES	NO	Distributed, localized
[24]	Random	YES	YES	Distributed, localized
[13]	Deterministic	YES	YES	Centralized
[3]	Random	YES	NA	Centralized
[17]	Random	NA	NA	Centralized
[14]	Random	NA	NA	Distributed, localized
[15]	Random	NA	NA	Centralized
[18]	Random	NA	NA	Centralized
[1]	Random	NA	NA	Centralized

Table 2. Characteristics of approaches listed in Table 1.

WSNs, where sensors have locomotion capabilities. Thus, the nodes can spread out such that the area covered by the network is maximized (e.g. [10]) and can relocate to handle sensor failures.

1.4 Overview

In this chapter we survey recent contributions addressing coverage problems in the context of static WSNs, that is, the sensor nodes do not move once they are deployed. Sensors have omnidirectional antennae, and can monitor a disk whose radius is referred to as sensing range. We present various coverage formulations, their assumptions, as well as an overview of the solutions proposed. The most discussed problems from the literature can be classified in the following types: area coverage, point coverage, and barrier coverage. This article continues with a discussion of these coverage problems, followed by conclusions.

2 Area Coverage

The most studied coverage problem is the area coverage problem, where the main objective of the sensor network is to cover (monitor) an area (also referred sometimes as region). Figure 1 (a) shows an example of a random deployment of sensors to cover a given square-shaped area.

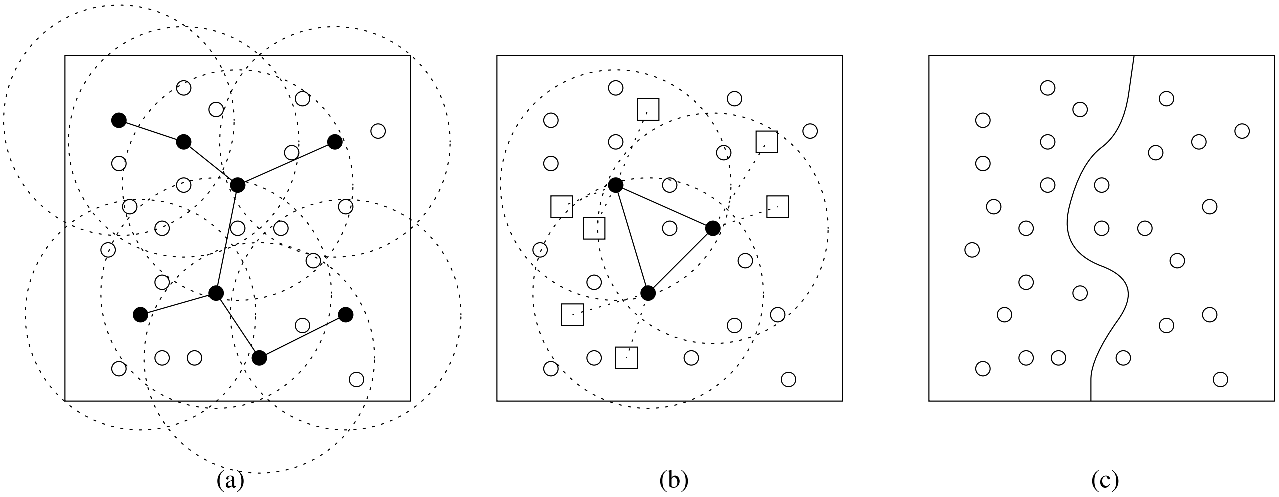

Figure 1. (a) area coverage, (b) point coverage, and (c) barrier coverage.

The connected black nodes form the set of active sensors, as the result of a scheduling mechanism. Next, we survey recent area coverage problem formulations, their models and assumptions, as well as solutions proposed.

2.1 Energy-Efficient Random Coverage

In this section we present several energy-efficient coverage mechanisms. Energy-efficiency is an important issue in WASN, caused by limited battery resources. Mechanisms that conserve energy resources are highly desirable, as they have a direct impact on network lifetime. Network lifetime is in general defined as the time interval that the network can perform the sensing functions and transmit data to the sink. During the network lifetime, some nodes may become unavailable (e.g. physical damage, lack of power resources) or additional nodes might be deployed. An efficient frequently used mechanism is scheduling the sensor node activity and allowing redundant nodes to enter the *sleep* mode as often and for as long as possible. To design such a mechanism, we need to answer the following questions:

1. Which is the rule that each node should follow to determine whether to enter sleep mode?
2. When should nodes make such a decision?
3. How long should a sensor remain in the sleep mode?

Such node scheduling mechanisms are illustrated next.

The works in [21] and [2] consider a large population of sensors, deployed randomly for area monitoring. The goal is to achieve an energy-efficient design that maintains area coverage. As 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 every set can individually perform the area monitoring tasks. These set areas are then activated successively, and while the current sensor set is active, all other nodes are in a low-energy sleep mode. The goal of this approach is to determine a maximum number of disjoint sets, as this has a direct impact on the network lifetime. The solutions proposed are centralized. Slijepcevic and Potkonjak [21] 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 algorithm [21] computes the disjoint covers successively, selecting sensors that cover the critical element (field covered by a minimal number of sensors), giving priority to sensors that: cover a high number of uncovered fields, cover sparsely covered fields and do not cover fields redundantly. Cardei et al [2] model the disjoint sets as disjoint dominating sets. The maximum disjoint dominating sets computation is NP-complete, and a graph-coloring based algorithm is proposed. Simulations have shown that the number of sets computed is between 1.5 and 2 times greater than using the algorithm in [21], with lapses in area coverage less than 5%, on average.

Another energy-efficient node-scheduling-based coverage mechanism is proposed in [22]. The protocol proposed is distributed and localized. The off-duty eligibility rule determines whether a node's sensing area is included in its neighbors' sensing area. Solutions for determining whether a node's coverage can be sponsored by its neighbors (sponsored coverage calculation) is provided for several cases: when nodes have the same sensing range and know their location, when nodes have the same sensing range and can obtain neighboring node's directional information, or in particular scenarios when nodes have different sensing ranges. The node scheduling scheme is divided into rounds, where each round has a self-scheduling phase followed by a sensing phase. 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, containing 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 T_w time to listen for neighboring nodes update. This work does not specify synchronization mechanisms in detail. It is implemented as an extension of the data gathering LEACH protocol [9], and simulation results show an increase of 1.7 on average in system lifetime.

A probing-based, node-scheduling solution for the energy-efficient coverage problem is proposed in [26]. Here all sensors are characterized by the same sensing range and coverage is seen as the ratio between the area under monitoring and total size of the network field. The off-duty eligibility rule is based on a probing mechanism. Basically, a sensor broadcasts a probing message PRB within a probing range r. Any working node that hears this message responds with a PRB_RPY. If at least one reply is received, the node enters the sleep mode. Probing range is selected based on the desired working node density (number of sensors per unit area) or based on the desired coverage redundancy, whereas the wake-up time is based on the tolerable sensing intermittence. This protocol is distributed, localized, and has low complexity but still does not preserve the original coverage area.

2.2 Connected Random Coverage

An important issue in WSNs is connectivity. A network is connected if any active node can communicate with any other active node, possibly using intermediate nodes as relays. Once the sensors are deployed, they organize into a network that must be connected so that the information collected by sensor nodes can be relayed back to data sinks or controllers. An important frequently addressed objective is to determine a minimal number of working sensors required to maintain the initial coverage area as well as connectivity. Selecting a minimal set of working nodes reduces power consumption and prolongs network lifetime. Next we will present several connected coverage mechanisms.

An important, but intuitive result was proved by Zhang and Hou [27], which states that if the communication range R_c is at least twice the sensing range R_s, a complete coverage of a convex area implies connectivity of the working nodes. If the communication range is set up too large, radio communication may be subject to excessive interference. Therefore, if the communication range can be adjusted, a good approach to assure connectivity is to set transmission range as twice the sensing range.

Based on this result, Zhang and Hou [27] further discussed the case for $R_c \geq R_s$. An important observation is that an area is completely covered if there are at least two disks that intersect and all crossings are covered. Here a disk refers to a node's sensing area and a crossing is an intersection point of the circle boundaries of two disks. In the ideal case, in which node density is sufficiently high, the subset of working nodes can be optimally chosen for full coverage. Based on these results, authors proposed a distributed, localized algorithm, called optimal geographical density control (OGDC). At any time, a node can be in one of the tree states: UNDECIDED, ON and OFF.

The algorithm runs in rounds, and at the beginning of each round a set of one or more starting nodes are selected as working nodes. After a back-off time, a starting node broadcasts a power-on message and changes its state to ON. The power-on message contains: (1) the position of the sender and (2) the direction along which a working node should be located. The direction indicated by the power-on message of a starting node is randomly distributed. Having starting nodes randomly selected at the beginning of each round ensures uniform power consumption across the network. Also, the backoff mechanism avoids packet collisions. At the beginning of each round, all nodes are UNDECIDED and will change either to ON or OFF state until the beginning of the next round. This decision is based on the power-on messages received. Every node keeps a list with neighbor information. When a node receives a power-on message, it checks whether its neighbors cover its sensing area, and if so, it will change to OFF state. A node decides to change into the ON state if it is the closest node to the optimal location of an ideal working node selected to cover the crossing points of the coverage areas of two working neighbors. NS-2 based simulation shows good results in terms of percentage of coverage, number of working nodes and system lifetime.

Some applications may require different degrees of coverage while still maintaining working node connectivity. We say that a network has a coverage degree k (k-coverage) if every location is within the sensing range of at least k sensors. Networks with a higher coverage degree can obtain higher sensing accuracy and be more robust to sensor failure. Wang et al [23] generalized the result in [27] by showing that, when the communication range R_c is at least twice the sensing range R_s, a k-covered network will result in a k-connected network. A k-connected network has the property that removing any $k-1$ nodes will still maintain the network connectivity. The following discussion addresses the case when $R_c \geq 2R_s$. To define the k-coverage eligibility mechanism, the problem of determining the coverage degree of a region is reduced to a simpler problem of determining the coverage degrees of all the intersection points. Given a coverage region A, a point p is called an *intersection point* if: (1) p is an intersection point of the sensing cycles of any two nodes u and v, e.g. $p \in u \cup v$, and (2) for any node v, $p \in v \cap A$ and $|pv| = R_s$, where R_s is the sensing range. The authors proved that a convex region is k-covered if it contains intersection points and all these intersection points are k-covered. Based on this, a sensor is ineligible to turn active if all the intersection points inside its sensing circle are at least k-covered.

The work in [23] introduces coverage configuration protocol (CCP) that can dynamically configure the network to provide different coverage degrees requested by applications. To facilitate the computation of intersection points, every node maintains a table with neighbor information (location, status: active/inactive) and periodically broadcasts a HELLO beacon with its current location and status. A node can be in one of the three states: SLEEP, LISTEN and ACTIVE. All nodes start in the SLEEP state for a random time. When a node wakes up, it enters LISTEN state, and based on the outcome of the eligibility rule over a time interval, it will enter either SLEEP or ACTIVE state. Once a node is in the ACTIVE state, it will re-evaluate the coverage eligibility every time it receives a HELLO message and decide whether to go into the SLEEP state or remain in the ACTIVE state.

For the case when $R_c < 2R_s$, CCP does not guarantee network connectivity. The solution adopted in [23] is to integrate CCP with SPAN [5] to provide both sensing coverage and network connectivity. SPAN is a distributed algorithm that conserves energy by turning off unnecessary nodes while maintaining connectivity. The combined eligibility rule is as follows: (1) an inactive node goes into the active state if it satisfies the eligibility rules of SPAN and CCP, and (2) an active node withdraws if it satisfies neither the eligibility rule of SPAN or CCP. With this combined mechanism we can obtain k-coverage through CCP and 1-connectivity through SPAN. The algorithm was implemented and tested using NS-2 and showed good performance results in terms of coverage, active nodes and system lifetime.

2.3 Deterministic Coverage

Kar and Banerjee [13] consider the problem of deterministically placing a minimum number of sensor nodes to cover a given region. The sensing area is a disk with radius r called r-$disk$, and the sensing and communication radii are equal. The basic pattern is an r-$strip$, a string of r-disks placed along a line such that the distance between two adjacent disks is r. This forms a connected component. To cover a given area, it is first filled with horizontal r-$strips$ with distance $r(1 + \sqrt{3}/2)$ between them. Then another strip is added so as to intersect all other parallel r-$strips$. This results in a connected sensor network that covers the given area. For covering of the two dimensional plane, the performance ratio is 1.026, while for a bounded convex region with perimeter L and area A the performance ratio is $2.693(1 + 2.243Lr/A)$.

2.4 Node Coverage as Approximation

When a large and dense sensor network is randomly deployed for area monitoring, the area coverage can be approximated by the coverage of the sensor locations. One method to assure coverage and connectivity is to design the set of active sensors as a connected dominating set (CDS). A distributed and localized protocol for constructing the CDS was proposed by Wu and Li, using the *marking process* in [24]: A node is a coverage node if there are two neighbors that are not connected (i.e., not within the transmission range of each other). Coverage nodes (also called gateway nodes) form a CDS. A pruning process can be used to reduce the size of coverage node set while keep the CDS property. Dai and Wu [6] provide a generalized pruning rule called *pruning Rule k*. Basically, a coverage node can be withdrawn if its neighbor set can be collectively covered by those of k coverage nodes. In addition, these k coverage nodes have higher priority and are connected. Pruning Rule k ensures a constant approximation ratio. The CDS derived from the marking process with Rule k can be locally maintained, when sensors switch-on/off.

The node coverage problem can be related to the broadcasting problem, where a small set of forwarding nodes is selected [25]. Forwarding set selection in broadcasting is similar to the point coverage problem, where both try to find a small coverage set. Note that directed diffusion [12] also uses this platform to collect information through broadcasting. As the interest is propagated through the network, sensor nodes set up reverse gradients to the sink in a decentralized way. The difference is that in directly diffusion, all sensors forward the data. One difference between node coverage and area coverage is that neighbor set information is sufficient for node coverage, while in area coverage, geometric/directional information is needed.

3 Point Coverage

In the point coverage problem, the objective is to cover a set of points. Figure 1 (b) shows an example of a set of sensors randomly deployed to cover a set of points (small square nodes). The connected black nodes form the set of active sensors, the result of a scheduling mechanism.

Next, we present a coverage approach for each sensor deployment method: random and deterministic.

3.1 Random Point Coverage

The point coverage scenario addressed in [3] has military applicability. It considers a limited number of points (targets) with known location that need to be monitored. A large number of sensors are dispersed randomly in close proximity to the targets; the sensors send the monitored information to a central processing node. The requirement is that every target must be monitored at all times by at least one sensor, assuming that every sensor is able to monitor all targets within its sensing range.

One method for extending the sensor network lifetime through energy resource preservation, is the division of the set of sensors into disjoint sets such that every set completely covers all targets. These disjoint sets are activated successively, such that at any moment in time only one set is active. As all targets are monitored by every sensor set, the goal of this approach is to determine a maximum number of disjoint sets, so that the time interval between two activations for any given sensor is longer. By decreasing the fraction of time a sensor is active, the overall time until power runs out for all sensors is increased and the application lifetime is extended proportionally by a factor equal to the number of disjoint sets. A solution for this application is proposed in [3], where the disjoint sets are modelled as disjoint set covers, such that every cover completely monitors all the target points. The authors prove that the disjoint set coverage problem is NP-complete and and propose an efficient heuristic for set covers computation using a mixed integer programming formulation.

3.2 Deterministic Point Coverage

In [13], Kar and Banerjee consider the scenario where it is possible to explicitly place a set of sensor nodes. This is feasible in friendly and accessible environments. Given a set of n points, the objective is to determine a minimum number of sensor nodes and their location such that the given points are covered and the sensors deployed are connected. For the case when all sensors have the same sensing range and the sensing range equals the communication range, the authors propose an approximation algorithm with performance ratio 7.256. The algorithm begins by constructing the minimum spanning tree over the targeted points, and then successively selects sensor node locations on the tree (vertices or along the edges) such that the coverage and connectivity is maintained at every step.

4 Barrier Coverage

Inspired from Gage's classification, we consider the barrier coverage as the coverage with the goal of minimizing the probability of undetected penetration through the barrier (sensor network). Figure 1 (c) shows a general barrier coverage problem where start and end points of the path are selected from bottom and top boundary lines of the area. The selection of the path depends on the objective, as we discuss next. There are two types of barrier coverage models proposed in literature.

4.1 Barrier Coverage Model 1

The first model is proposed by Meguerdichian et al [17], where the following problem is addressed: given a field instrumented with sensors and the initial and final locations of an agent that needs to move through the field, determine a maximal breach path (MBP) and the maximal support path (MSP) of the agent. The MBP (MSP) corresponds to the worst (best) case coverage and has the property that for any point on the path, the distance to the closest sensor is maximized (minimized). The model assumes homogeneous sensor nodes, known sensor locations (e.g.

through GPS), with sensing effectiveness decreasing as the distance increases. The authors proposed a centralized solution, based on the observation that MBP lies on the Voronoi diagram lines and MSP lies on Delaunay triangulation lines. The proposed algorithm starts by generating the Voronoi diagram (or Delaunay triangulation diagram), assigns every segment a weight equal with the distance to the closest sensor (or equal with the segment length) and then uses binary-search and Breadth-First-Search for path computation.

The best coverage problem is further explored and formalized in [14], where Li et al proposed a distributed algorithm for MSP computation using the relative neighborhood graph. The authors also consider two extensions, namely MSP with least energy consumption and MSP with smallest path distance.

Another important is the determination of the number of sensor nodes to be randomly deployed in the field such that the probability of a penetration path is close to zero. Liu and Towsley [15] address this coverage and detectability problem in the context of grid-based sensor networks and random sensor networks. The authors propose a critical density for a given sensor networks based on percolation theory, such that for nodes deployed with a lower density a penetrating path that will not be detected almost surely exists, whereas above this critical density any crossing object is almost surely detected.

4.2 Barrier Coverage Model 2

The second barrier coverage problem is the *exposure-based model*, introduced by Meguerdichian et al. in [18]. Here, the sensing abilities of the sensors diminish as the distance increases, but another important factor is the sensing time (exposure). The longer the exposure time, the greater the sensing ability. The $2D$ sensing model is defined as $S(s,p) = \frac{\lambda}{[d(s,k)]^k}$, where $d(s,p)$ is the Euclidean distance between the sensor s and the point p, and λ and k are sensor technology-dependent parameters. Another characteristic is the intensity of the sensor field. For example, all-sensor field intensity for a point p, field F and n sensors $s_1, s_2, ..., s_n$ is defined as $I(F,p) = \sum_1^n S(S_i, p)$. The exposure of an object moving in the sensor field during the interval $[t_1, t_2]$ along the path $p(t)$ is defined as $E(p(t), t_1, t_2) = \int_{t_1}^{t_2} I(F, p(t)) |\frac{dp(t)}{dt}| dt$.

Given a field instrumented with n sensors and the initial and final points of the object, the authors consider the problem of determining the minimal exposure path. This path corresponds to the worst-case scenario. As the exposure analytical computation is intractable, the solution proposed uses a grid-based approach to transform the problem domain to a tractable discrete domain. The minimal exposure path in each grid square is then restricted to line segments connecting any two vertices. In the next step, the grid is transformed into a weighted graph, where the weight (exposure) of an edge is approximated using numerical techniques. Finally, the Dijkstra's single-source-shortest-path algorithm is used to find the minimal exposure path between any arbitrary starting and ending points on the grid. The approximation quality improves by increasing the grid divisions, at a cost of higher storage and run-time.

Another aspect of the exposure-based model is pointed out in [1]. To estimate the sensor node deployment density, one should consider both the sensor characteristics as well as target specifications. For example, detection of an enemy tank requires less nodes due to the strong the acoustic signal, compared with soldier detection that might require more sensors. This paper assumes the target moves in a straight-line path, with constant speed, between two given points. Two radii are associated for a given sensor : *radius of complete influence* defined as the distance from the sensor such that all targets originating within this radius are detected and *radius of no influence* with the property that any target originating beyond it cannot be detected. Using the sensing and exposure model described above, and knowing the threshold energy $E_{threshold}$ required to detect a target, this paper proposes solution to calculate the influence radii as well as the sensor nodes deployment density. Thus, to cover an area A, computing the number of nodes to be deployed as $O(\frac{A}{r^2})$ where r is the radius of no influence, achieves a probability of detection of 98% or above.

5 Conclusion

In this article we categorized and described recent coverage problems proposed in literature, their formulations, assumptions and proposed solution. Sensor coverage is an important element for QoS in applications with WSNs. Coverage is in general associated with energy-efficiency and network connectivity, two important properties of a WSN. To accommodate a large WSN with limited resources and a dynamic topology, coverage control algorithms and protocols perform best if they are distributed and localized. Various interesting formulations for sensor coverage have been proposed recently in literature. To meet the intended objective, these problems aim at either deterministically placing sensors nodes, determining the sensor deployment density, or more generally, at designing mechanisms that efficiently organize or schedule the sensors after deployment.

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