ISSUES OF CONNECTIVITY AND 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). Wireless sensor networks are a rapidly growing area for research and commercial development.

One important criterion for being able to deploy an efficient sensor network is to find optimal node placement strategies. Deploying nodes in large sensing fields requires efficient topology control. Nodes can either be placed manually at predetermined locations or be dropped from an aircraft. However, since the sensors are randomly scattered in most practical situations, it is difficult to find a random deployment strategy that minimizes cost, reduces computation and communication, is resilient to node failures, and provides a high degree of area coverage. The notion of area coverage can be considered as a measure of the quality of service (QoS) in a sensor network, for it means how well each point in the sensing field is covered by the sensing ranges. Once the nodes are deployed in the sensing field, they form a communication network, which can dynamically change over time, depending on the topology of the geographic region, internode separations, residual battery power, static and moving obstacles, presence of noise, and other factors. The network can be viewed as a communication graph, where sensor nodes act as the vertices and a communication path between any two nodes signifies an edge.

In this paper, we discuss primarily the node deployment issues that are related to area coverage and network connectivity in wireless sensor networks and introduce the notion of coverage and connectivity and state their importance with respect to different application scenarios.

Wireless sensor networks are used to monitor a given field of interest for changes in the environment. They are very useful for military, environmental, and scientific applications to name a few. One of the most active areas of research in wireless sensor networks is that of coverage. Coverage in wireless sensor networks is usually defined as a measure of how well and for how long the sensors are able to observe the physical space. In this paper, we take a representative survey of the current work that has been done in this area. We define several terms and concepts and then show how they are being utilized in various research works.

KEYWORDS: Connectivity, Coverage, Nodes, Energy Efficiency, Wireless Sensor Networks
INTRODUCTION

One of the most active research fields in wireless sensor networks is that of coverage. Coverage is usually interpreted as how well a sensor network will monitor a field of interest. It can be thought of as a measure of quality of service. Coverage can be measured in different ways depending on the application, we will address this later in the paper.

In addition to coverage it is important for a sensor network to maintain connectivity. Connectivity can be defined as the ability of the sensor nodes to reach the data sink. If there is no available route from a sensor node to the data sink then the data collected by that node cannot be processed. Each node has a communication range which defines the area in which another node can be located in order to receive data. This is separate from the sensing range which defines the area a node can observe. The two ranges may be equal but are often different.

Historically, three types of coverage have been defined by Gage [12]

- Blanket coverage- to achieve a static arrangement of sensor nodes that maximizes the detection rate of targets appearing in the sensing field.
- Barrier coverage- to achieve a static arrangement of sensor nodes that minimizes the probability of undetected penetration through the barrier.
- Sweep coverage- to move a number of sensor nodes across a sensing field, such that it addresses a specified balance between maximizing the detection rate and minimizing the number of missed detections per unit area.

Coverage and Connectivity

Optimal resource management and assuring reliable QoS are two of the most fundamental requirements in ad hoc wireless sensor networks. Sensor deployment strategies play a very important role in providing better QoS, which relates to the issue of how well each point in the sensing field is covered. However, due to severe resource constraints and hostile environmental conditions, it is nontrivial to design an efficient deployment strategy that would minimize cost, reduce computation, minimize node-to-node communication, and provide a high degree of area coverage, while at the same time maintaining a globally connected network is nontrivial.

Challenges also arise because topological information about a sensing field is rarely available and such information may change over time in the presence of obstacles. Many wireless sensor network applications require one to perform certain functions that can be measured in terms of area coverage.

Area coverage and connectivity in wireless sensor networks are not unrelated problems. Therefore, the goal of an optimal sensor deployment strategy is to have a globally connected network while optimizing coverage at the same time. By optimizing coverage, the deployment strategy would guarantee that optimum area in the sensing field is covered by sensors, as required by the underlying application. By ensuring that the network is connected, it is also ensured that the sensed information is transmitted to other nodes and possibly to a centralized base station that can make valuable decisions for the application.

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.

**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](image)

(a) Area Coverage  (b) Point Coverage  (c) Barrier Coverage

**MATHEMATICAL FRAMEWORK**

In this section, we introduce the basic mathematical framework for sensing models, communication models, coverage models, mobility models, and graph-theory based network connectivity models applicable to wireless sensor networks. These will be used in subsequent sections for describing and analyzing the existing algorithms on coverage and connectivity and to provide future research directions.

**Sensing Model**

Each node has a sensing gradient, whose radius, although ideally extending to infinity, attenuates gradually as the distance increases. The sensitivity $S$ of a sensor $s_i$ at point $P$ is usually modeled as follows [21]

$$S(s_i, P) = \frac{\lambda}{d(s_i, P)^g}$$

Where $\lambda$ and $K$ are positive sensor-dependent parameters and $d(s_i, P)$ is the Euclidean distance between the sensor and the point. Typically the value of $g$ is dependent on environmental parameters and varies between 2 and 5. Since the sensitivity rapidly decreases as the distance increases, we define a maximum sensing range for each sensor. It is customary to assume a binary sensing model, according to which a sensor is able to sense from all the points that lie within its sensing range and any point lying beyond it is outside its sensing range. Thus, according to this model the sensing range for each
sensor is confined within a circular disk of radius Rs. In a heterogeneous sensor network, the sensing radii of different types of sensors might vary, but in this chapter, to simplify the analysis of coverage algorithms, we assume that all the nodes are homogeneous and the maximum sensing radius for all of them is the same, Rs.

This binary sensing model can be extended to a more realistic one and expressed in probabilistic terms [15]. This is illustrated in Figure 2a. Let us define a quantity Ru < Rs, such that the probability that a sensor would detect an object at a distance less than or equal to (Rs – Ru) is 1, and at a distance greater than or equal to (Rs + Ru) is 0. In the interval ((Rs–Ru), (Rs + Ru)), there is a certain probability p, that an object will be detected by the sensor.

The quantity Ru is a measure of uncertainty in sensor detection. This probabilistic sensing model reflects the sensing behavior of devices such as infrared and ultrasound sensors.

![Image](image_url)

(a) Probabilistic Sensing Model                   (b) Communication Model

Figure 2

Communication Model

Similar to the sensing radius, we define a communication radius Rci (see Fig. 2b) for each sensor si. Two sensors, si and sj, are able to communicate with each other if the Euclidean distance between them is less than or equal to the minimum of their communication radii, that is, when d(si, sj) ≤ min(Rci, Rcj).

This basically means that the sensor with smaller communication radius falls within the communication radius of the other sensor. Two such nodes that are able to communicate with each other are called one-hop neighbors. The communication radii might vary depending on the residual battery power (energy) of an individual sensor. In this chapter, we assume that the communication radii for all the nodes are the same, denoted by Rc.

Coverage Model

Depending on the sensing range, an individual node will be able to sense a part of the sensing field. From the probabilistic sensing model, we define the notion of probabilistic coverage [15] of a point P(xi,yi) by a sensor si by the following equations:

\[
\text{Cov}_s(t) = \begin{cases} 
0 & \text{if } d(s_i,P) \geq d(s_i,F) \leq R_s + R_u \\
\frac{1}{1 + e^{-\gamma d(s_i,F)}} & \text{if } R_s - R_u < d(s_i,F) < R_s + R_u \\
1 & \text{if } R_s - R_u \geq d(s_i,F)
\end{cases}
\]

(2)

Here, a = d(s_i,P) – (Rs – Ru) and γ and β are parameters that measure the detection probabilities when an object is within a certain distance from the sensor. All points that lie within a distance of (Rs – Ru) from the sensor are said to be 1-covered and all points lying within the interval ((Rs – Ru), (Rs + Ru)) have a coverage value that exponentially decreases as the distance increases and is less than 1, as observed in Equation (2). Beyond the distance (Rs + Ru), all the points have
0 coverage by this sensor. However, a point might be covered by multiple sensors at the same time, each contributing a certain value of coverage.

**Graph Connectivity**

In the previous sections, we introduced the concept of degree of coverage and connectivity; here we provide formal definitions for those concepts in terms of node degree and connectivity in a graph [45].

**Node Degree**

Let $G(V, E)$ be an undirected graph. The degree $\deg(u)$ of a vertex $u \in V$ is defined as the number of neighbors of $u$. The minimum node degree of $G$ is defined as $\Delta(G) = \min_u \deg(u)$.

**k-Node Connectivity**

A graph is said to be connected if for every pair of nodes, there exists a single-hop or a multihop path connecting them; otherwise the graph is called disconnected. A graph is said to be $k$-connected if for any pair of nodes there are at least $k$ mutually independent (node-disjoint) paths connecting them. In other words, there is no set of $(k-1)$ nodes, whose removal would render the graph disconnected or result in a trivial graph (single vertex).

**k-Edge Connectivity**

In a similar fashion, the notion of $k$-edge connectivity is defined when there are at least $k$ edge-disjoint paths between every pair of nodes. In other words, there is no set of $(k-1)$ edges whose removal will result in a disconnected graph or a trivial graph.

**COVERAGE BASED ON EXPOSURE PATHS**

Approaches to solve the coverage problem in wireless sensor networks using exposure paths is basically a combinatorial optimization problem. Two kinds of optimization viewpoints exist in formulating the coverage problem: worst-case and best-case coverage.

In the worst-case coverage, usually the problem is tackled by trying to find a path through the sensing region, such that an object moving along that path will have the least observability by the nodes. Hence, the probability of detecting the moving object would be minimum. Two well-known methods of approaching the worst-case coverage problem are minimal exposure path [26] and maximal breach path [24,27]. On the other hand, in the best-case coverage, the goal is to find a path that has the highest observability, and hence an object moving along that path will be most probable to be detected by the nodes. Finding such a path can be useful for certain applications, including those that require the best coverage path in regions where security is of highest concern, or those that would like to maximize some predefined benefit function from the nodes while traversing the sensor field.
Minimal Exposure Path: Worst-Case Coverage

Exposure is directly related to the area coverage problem in sensor networks. It is a measure of how well a sensing field is covered with sensors. Informally stated, it can be defined as the expected average ability of observing a target moving in the sensing field. The minimal exposure path provides valuable information about the worst-case coverage in sensor networks. Let us first explain the notion of exposure, which is defined as an integral of a sensing function that is inversely proportional to the distance from the sensors, along a path between two specified points during a certain time interval [21,24].

Maximal Breach Path: Worst-Case Coverage

We observed that finding a minimal exposure path is equivalent to finding a worst-case coverage path, which provides valuable information about node deployment density in the sensing field. A concept very similar to finding the worst-case coverage paths is the notion of maximal breach paths [22]. A maximal breach path through a sensing field starting at A and ending at B is a path such that, for any point P on the path, the distance from P to the closest sensor is maximum. The concept of the Voronoi diagram [24], a well-known construct from computational geometry, is used to find a maximal breach path in a sensing field. In two dimensions, the Voronoi diagram of a set of discrete points (also called sites) divides the plane into a set of convex polygons, such that all points inside a polygon are closest to only one point. In Figure 4a, 10 randomly placed nodes divide the bounded rectangular region into 10 convex polygons, referred to as Voronoi polygons. Any two nodes si and sj are called Voronoi neighbors of each other if their polygons share a common edge. The edges of a Voronoi polygon for node si are the perpendicular bisectors of the lines connecting si and its Voronoi neighbors. Since by construction, the line segments in a Voronoi diagram maximizes the distance from the closest sites, the maximal breach path must lie along the Voronoi edges. If it does not, then any other path that deviates from the Voronoi edges would be closer to at least one sensor, thus providing more exposure. Having said that the maximal breach path between two endpoints A and B will lie along the Voronoi edges, we now describe an algorithm that finds such a path. First a geolocation based approach is used to determine node locations, and a Voronoi diagram based on that information is constructed. Then a weighted, undirected graph G is constructed by creating a node for each vertex and an edge corresponding to each line segment in the Voronoi diagram. Each edge is given a weight equal to the minimum distance from the closest sensor. The algorithm then checks the existence of a path from A to B using breadth-first search (BFS) and then uses binary search between the smallest and largest edge weights in G to find the maximal breach path. It should be noted that the maximal breach path is not unique. It can be proved that the worst-case time complexity of the algorithm is given by \(O(n \log n)\), and for sparse networks it is \(O(n)\).

Figure 4
Figure 4 (a) Voronoi diagram of 10 randomly deployed nodes; (b) Voronoi polygon for node S, constructed by drawing perpendicular bisectors of the lines connecting S and its neighbors; (c) Delaunay triangulation for the same set of nodes.

Maximal Support Path: Best-Case Coverage

A maximal support path through a sensing field starting at A and ending at B is a path such that for any point P on that path, the distance from P to the closest sensor is minimized. This is similar to the concept of maximal exposure path. However, the difference lies in the fact that a maximal support path algorithm finds a path at any given time instant, such that the exposure on the path is no less than some particular value that should be maximized. In contrast, the maximal exposure path does not focus on any particular time; rather, it considers all the time spent during an object’s traversal.

A maximal support path in a sensing field can be found by replacing the Voronoi diagram by its dual, Delaunay triangulation as shown in Figure 4b, where the edges of the underlying graph are assigned weights equal to the length of the corresponding line segments in the Delaunay triangulation. (A Delaunay triangulation [21] is a triangulation of graph vertices such that the circumcircle of each Delaunay triangle does not contain any other vertices.) Similar to the maximal breach path approach described earlier, this algorithm also checks for the existence of a path using breadth-first search and applies binary search to find the maximal support path. Assuming the probabilistic sensing model as described earlier, typical values are calculated for the quantities \( (R_s - R_u) \) and \( (R_s + R_u) \), which are termed as radius of complete influence (denoted by \( R_{ci} \)) and radius of no influence (denoted by \( R_{ni} \)), respectively. It can be proved that for a typical threshold exposure \( E_{th} \), the values for radius of complete influence and no influence are given by the following equations [1]

\[
E_{th} = \frac{\lambda}{\pi R_{ci}^2} \left( \frac{6}{\pi + 2} \right)
\]

(3)

\[
E_{th} = \frac{21}{2 \pi R_{ni}^2} \tan^{-1} \left( \frac{6}{\pi R_{ni}^2} \right)
\]

(4)

and that to cover an area \( A \) with random deployment, the number of nodes required is of the order of \( O(A/R_{ni}^2) \).

COVERAGE BASED ON SENSOR DEPLOYMENT STRATEGIES

The second approach to the coverage problem is to seek sensor deployment strategies that would maximize coverage as well as maintain a globally connected network graph. Several deployment strategies have been studied for achieving an optimal sensor network architecture that would minimize cost, provide high sensing coverage, be resilient to random node failures, and so on. In certain applications, the locations of the nodes can be predetermined and hence can be hand-placed or deployed using mobile robots, while in other cases we need to resort to random deployment methods, such as sprinkling nodes from an aircraft. However, random placement does not guarantee full coverage because it is stochastic in nature, hence often resulting in accumulation of nodes at certain areas in the sensing field but leaving other areas deprived of nodes.

As mentioned in the introduction, the problem of sensor deployment is related to the traditional art gallery problem (AGP) [23] in computational geometry. The AGP seeks to determine the minimum number of cameras that can be placed in a polygonal environment, such that the entire environment is monitored. In a similar way, an optimal deployment strategy tries to deploy nodes at optimal locations, such that the area covered by the sensors is maximized. In the following, we briefly describe several sensor deployment algorithms targeted for static, mobile, and mixed-sensor networks that aim to provide optimum sensing field architecture.
CONCLUSIONS

We have seen that exposure paths can be viewed as a measure of goodness of detectability of a moving target in a sensing field. The notions of min–max exposure paths, breach paths, and support paths provide critical information to the application in terms of identifying sparsely and densely covered areas. We also discussed and compared several node deployment algorithms for static and mobile as well as for mixed-sensor networks, and observed that, depending on the coverage requirements, topological information, presence of obstacles, and other variables, the algorithms vary with respect to their goals, assumptions, and complexities.

The deployment of nodes in mixed-sensor networks, which require one to strike a balance between the number of static and mobile sensors, involves the optimization of a cost/performance-based objective function and is therefore challenging. We discussed one approach [25] that initially deploys a fixed number of static and mobile nodes in a sensing field, after which the static nodes are required to find local coverage holes and bid for mobile sensors to relocate to the targeted locations and reduce or eliminate those holes, thus increasing area coverage. However, this approach has a drawback because it deploys a fixed number of mobile nodes. To overcome this shortcoming, we [14] considered a mixed-sensor network, where initially a fixed number of static nodes are deployed, which deterministically find the exact amount of coverage holes existing in the entire network using the structure of Voronoi diagrams and then dynamically estimate the additional number of mobile nodes needed to be deployed and relocated to the optimal locations of the holes to maximize overall coverage. This approach of deploying a fixed number of static nodes and a varying estimated number of mobile nodes can provide optimal coverage under controlled cost. A mixed sensor approach is a very attractive one, because it allows one to choose the degree of coverage required by the underlying application as well as gives an opportunity to optimize on the number of additional mobile nodes needed to be deployed. We [15] provided distributed algorithms to find suboptimal minimum connected sensor covers, such that the whole sensing field is covered using a suboptimal number of sensors. In another study [5,7] we proposed a novel energy conserving data gathering strategy based on a tradeoff between coverage and data reporting latency with the ultimate goal of maximizing a network’s lifetime. The basic idea is to select in each data reporting round only a minimal number of k sensors as data reporters, based on a desired sensing coverage specified by the user or application. Besides conserving energy, such a selection of minimum data reporters also reduces the amount of traffic flow, thus avoiding traffic congestion and channel interference. Simulation results of our proposed schemes demonstrate that the user-specified percentage of the monitored area can be covered using only k sensors. It also shows that the sensors can conserve a significant amount of energy with a small tradeoff and that the higher the network density, the higher is the energy conservation rate without any additional computation cost. In one of our works [6] for efficient resource management in wireless sensor networks, we presented a two phase clustering scheme for energy saving and delay adaptive data gathering in order to extend a network’s lifetime.

Further research on optimization algorithms in mixed sensor networks and evaluating tradeoffs between latency and data gathering strategies can provide valuable information to optimize resources in a sensing field and help answer questions related to the theoretical bounds on coverage and connectivity.

REFERENCES


