Area Coverage with Heterogeneous Sensors in the Presence of Jammers in a Wireless Sensor Network Environment

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Master of Technology
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Certificate

This is to certify that the thesis titled *Area Coverage with Heterogeneous Sensors in the Presence of Jammers in a Wireless Sensor Network Environment*, submitted by *Major Jaydeep Bodwadkar*, Roll no: *14CS60D01*, in the *Department of Computer Science and Engineering, Indian Institute of Technology, Kharagpur*, for the award of the degree of *Master of Technology*, is a record of research work carried out by him under my supervision and guidance.

The thesis fulfils all the requirements as per the regulations of this institute. Neither this thesis nor any part of it has been submitted for any degree or academic award elsewhere.

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Abstract

The area coverage problem is a fundamental problem in Wireless Sensor Network (WSN). In this thesis the use of WSN technology for ground surveillance for military applications will be investigated.

A solution to the area coverage problem in WSN provides the total number of sensors that are required to cover a given area of deployment. While previous work in this field has proposed many solutions, these studies have not addressed the issues concerning coverage in the presence of jammers.

The goal of the project is to develop an algorithm for optimal placement of heterogeneous sensors at locations which are from a given set of feasible locations and in the presence of adversary jammers.

Chapter 1

Introduction

Wireless Sensor Network (WSN) are spatially distributed autonomous sensors which are used to monitor environmental or physical such as temperature, sound, pressure, etc. The sensor placement could be pre-planned or totally random depending on the application. Once deployed these sensors cooperate to pass their data through the network to a central location. The more modern networks are bi-directional, also enabling control of sensor activity. Use of wireless sensor networks was first mostly for military applications such as battlefield surveillance [1] , but, today such networks are used in many industrial and consumer applications, such as machine health monitoring [2], industrial process monitoring and control, disaster management and so on [2] [3].

The easiest way to deploy these sensors is at fixed locations by manually placing them or can be deployed randomly (e.g., via aerial deployment), and are expected to self-organize to form a multi-hop network. A sensor node is capable of sensing some physical phenomenon (e.g., detect tank vibrations or sniper gun noise), processing the sensed data and communicating the observed measurements to other nodes [4] [5] [6]. The sensor nodes may also have the capability to compress the data before communicating it to other nodes.

Applications of WSN are varied and in different fields ranging from agriculture [7], environmental monitoring [8] [9] to military applications [10]. In this thesis, military application of WSN pertaining to border surveillance is being investigated.

1.1 Coverage in Wireless Sensor Networks

A very important problem in many wireless sensor network applications involving surveillance or monitoring of an area is the coverage problem. Coverage in WSN has been defined in different ways depending on the target applications. There are methods which try to cover all points in a given region by a set of sensors. For example, in area coverage [11] [12], it is mandatory that each point in a given region is within the sensing range of at least one sensor. k-coverage of an area [11] is a more generalised version of the problem of area coverage, where every point in the region needs to be within the sensing range of at least k sensors.

Some other coverage measures, instead of covering all points in the given region, try to cover only a given set of targets or points. In the target k-coverage problem [13], a set of points in the plane are marked as target points and the goal is to place the sensors in such a way that every target point is covered by at least k sensors. Sweep coverage [14] is used in those applications where a certain points are visited after a fixed interval of time. Perimeter coverage [15], which aims to cover all points in the perimeter of an object by a set of sensors. This helps in monitoring large targets for which a multiple sensors are needed to cover the whole perimeter of the object.

Given a set of sensors and a bounded region, several algorithms have been proposed to compute the coverage provided by the sensors as discussed above. These include algorithms for measuring k-coverage [11], path coverage [16], breach coverage [17], and barrier coverage [18]. There has been lot of work to address the problem of sensor deployment to achieve various levels of coverage desired like point coverage in a given area [19] [20] and perimeter coverage of a region [21] [18].

Though, there is extensive work on the coverage aspect in WSNs, there has been limited work on the threat by jammers and counter-measures in WSNs. Some of the important work has been at reference [22] [23]. It is useful to introduce the threat by jammers to WSN to understand the goal of the thesis.

1.2 Threat by Jammers to WSN

WSNs are susceptible to attacks by jammers. Jammers try to interfere with the transmission and reception of wireless signals by emitting high power RF signals. There can be two categories of jamming attacks. The first one targets the inter-node communication channel and the other one targets the sensors sensing capability.

The jammers that regress the sensors' sensing capability have to be very specific type of jammers. If a sensor uses RF to sense then the jammer against it should be a RF jammer using the same frequency as the sensor e.g. a camera sensor will not be affected by a RF jammer. Hence, if the WSN consists of heterogeneous sensors, the adversary would require different types of jammers to deteriorate the WSN.

The jammers which attack the inter-node network are of different types of that try to intentionally inject false data during the inter-node communication which affects the data transmission and also the performance of WSN reduces as it causes the overutilization of the scarce resources like battery power, memory etc.

1.3 Motivation and Objective

In the military context, there is an ongoing threat of infiltration and adverse border activity on our western frontier. Specifically, the region in Rajasthan which is a vast barren piece of desert between us and the enemy has very less defensive positions. Placing & maintaining troops there would be very difficult and risky. Moreover, due to the vastness of the land it is impossible to guard every inch of it. Generally troops will be placed on most likely approaches of the enemy. But, there is always a good chance that unguarded stretches are used for infiltration. Thus, it is required to have an effective surveillance cover on such stretches of land.

For surveillance, the military has many sensors all of which have different capabilities. Table 1 shows some of the sensors with their capabilities

Ser	Name	Type	Range
1.	Unattended Ground Sensor	Audio Sensor	50m human detection 5km Tank detection
2.	Hand Held Thermal Imagers	Infrared light sensor	3.5 km
3.	Radar Type 1	Radio Frequency	5 km
4.	Radar Type 2	Radio Frequency	40 km
5.	Radar Type 3	Radio Frequency	60 km
6.	Laser Range Finders	Day camera, Thermal Imager, Goniometer	10 km
7.	Long Range Reconnaissance Camera	Optical sensor	16 km
8.	Weapon Locating Radar	Radio Frequency	50 km
9.	UAV	Camera, Thermal Imager	350 km

Table 1: Sensors available with the military for surveillance

The use of WSN for surveillance will be known to the adversary and methods to disable the sensors, the network or inject false information into it will be used by the adversary. For the purpose of disabling the sensors the use of jammers by the adversary cannot be ruled out. The jammers available with the enemy is a confidential information and publicly available information suggests that the enemy has RF jammers for HF, VHF, UHF and microwave ranges.

Hence, to use the WSN effectively, it is required to place the sensors at locations such that there is no effect of jammers and administrative requirements of the sensors is minimised.

In thesis, we explore and investigate the use of wireless sensor network to create a surveillance grid consisting of a number of heterogeneous sensors like cameras, audio sensors, ground sensors, radars, etc. for providing effective and continuous border surveillance in the presence of adversary Jamming activity to disable the sensors' sensing capability.

1.4 Organisation of the Thesis

The thesis has been divided into various chapters. These chapters have been organised as follows:

a. **Chapter 2** discusses about the previous work related to Area Coverage in Wireless Sensor Networks

b. **Chapter 3** discusses the problem statement as a whole and brings out the approach used to solve the problem. It then presents some experimental results.

Chapter 2

Background & Literature Survey

Coverage is an important problem in WSN which aims to find out how well a sensor field is monitored. It is an important performance metrics to measure QoS of sensor networks. Sensor coverage model, like many other sensor characteristics such as transfer function, sensitivity, dynamic range, accuracy, etc., can be used to measure the sensing capability and quality of a single sensor.

Coverage metrics can form part of QoS measurements in all network stages and can be formulated in various ways with different assumptions, objectives and scenarios. In the design stage, the question could be to know how many sensor nodes are needed such that every point in a sensor field is covered. In the deployment stage, sensors could be deterministically placed at the desired locations, or simply scattered within the area of interest from an aircraft. In the operation stage, the problem is to schedule different sensor nodes so as to prolong network operational time at the same time preserving the network coverage.

Studies in the field of coverage in WSN is divided broadly into three categories – point (or target) coverage, area coverage, and barrier coverage. Before various coverage categories are discusses it is needed to define coverage and connectivity. [24] defines coverage and connectivity as follows:

Definition 1 *(Coverage & k-coverage). Given a set of sensors,* $S = s_1, s_2, \dots, s_n$ *, in a 2-D area* X*. Each sensor* $s_i, (i = 1, \dots, n)$*, 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 2 *(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.*

Following definitions from [25] will be helpful to discussing barrier coverage:

DEFINITION 3 *(Belt of Width w). If* $l1$ *and* $l2$ *are two parallel curves with separation* w*, the region between* $l1$ *and* $l2$ *is referred to as a belt region of width* w*. The two curves* $l1$ *and* $l2$ *are the belt's parallel boundaries.*

DEFINITION 4 *(Crossing Path). A path is said to be a crossing path if it crosses from one parallel boundary of a belt region to the other boundary of the belt region.*

DEFINITION 5 *(k-Barrier Coverage). A sensor network deployed over a belt region is said to provide k-barrier coverage if and only if all crossing paths through the belt intersect the sensing region of at least k distinct sensors.*

2.1 Point Coverage

Point coverage problems deal with a set of discrete points in a region. The sensor nodes can be deterministically placed or randomly deployed in the sensor field to cover these points. These points can be particular space points in the sensor field or can be used in place of physical targets in the sensor field (e.g. enemy gun positions in a battlefield).

The problem of placing the least number of sensors to cover all targets can be formulated as an Integer Linear Programming (ILP) problem as follows:-

Minimize $\sum_{i=1}^{I} x_i$

Subject to $\sum_{i=1}^{I} \delta_{ij} > 0, j = 1, \ldots, J$

$$x_i = \begin{cases} 1, & if\ a\ sensor\ is\ placed\ at\ site\ i \\ 0, & otherwise \end{cases}$$

$$\delta_{ij} = \begin{cases} 0, & \text{if target } j \text{ is covered by a sensor located at site } i \\ 1, & \text{otherwise} \end{cases}$$

[20] provide a generalization of the above ILP by trying to minimize the network cost, if different sensor nodes have different costs and

coverage capabilities. Sometimes, distance between any pair of sensor nodes can be a constraints such as two sensors should not be too close as discussed in [26].

[27] proposes an efficient method to extend the sensor network lifetime by organizing the sensors into a maximal number of disjoint sets that are activated successively. It is shown in [28] that selecting disjoint sets do not necessarily result in a larger lifetime of the network than non-disjoint sets. In this approach, the nodes are organized into maximal numbers of set covers instead of disjoint-sets. [29] addresses the target coverage issue in wireless sensor networks that have sensors with adjustable sensing range. To solve this issue, linear programming, a localized greedy algorithm, and a distributed greedy algorithm, are proposed.

2.2 Area Coverage

Most of the research in the field of sensor networks consists of area coverage. The goal of area coverage is to cover as much area as possible with the minimum number of sensors. It is shown in [30] that the problem of selecting a subset of sensors that cover the whole area is NP-Complete, and the authors proposed an efficient approximation algorithm to address area coverage. [31] proves that if the radio range is at least twice the sensing range, complete coverage of an area implies connectivity among the working set of nodes. In ACOS [32], each node computes the area which can be only covered by it. If this area is smaller than a threshold, then this node goes to active mode.

In [33] algorithms aimed at optimizing the number of sensors and determining their placement to support distributed sensor networks have been discussed. The optimization framework is inherently probabilistic due to the uncertainty associated with sensor detections. It discusses coverage optimization under the constraints of imprecise detections and varying terrain.

[11] provides a polynomial-time algorithm, in terms of the number of sensors to determine whether every point in the given region is k-covered. They have considered heterogeneous sensors with different sensing ranges while discussing their strategy. In this they prove that

if no two sensors are located in the same location then the whole network area is k-covered iff each sensor in the network is k-perimeter-covered. This result is profoundly used in the contribution to this thesis. Given heterogeneous sensors, [20] discusses algorithms for sensor deployment to achieve full coverage and [34] investigates algorithms for k-coverage on a sensor field using near-minimum cost of sensors. [35] investigates the Sensor Scheduling for k-Coverage problem and provide a heuristic algorithm to schedule the sensors in such a way that the monitored region can be k-covered throughout the whole network lifetime and maximize the network lifetime. The following results from [11] and [35] are relevant to this work:-

DEFINITION 6 *(Perimeter-covered). Consider any two sensors* s_i *and* s_j*. A point on the perimeter of* s_i *is perimeter-covered by* s_j *if this point is within the sensing range of* s_j*.*

DEFINITION 7 *(k-Perimeter covered). Consider any sensor* s_i*. We say that* s_i *is k-perimeter covered if all points on the perimeter of* s_i *are perimeter covered by at least k sensors other than* s_i *itself. Similarly, a segment of* $s_i's$ *perimeter is k-perimeter covered if all points on the segment are perimeter covered by at least k sensors other than* s_i *itself.*

DEFINITION 8 *(Perimeter Coverage Level). The Perimeter Coverage Level (PCL) of a sensor A is the number of the sensors in the same set that cover any point on A's perimeter of the sensing area.*

THEOREM 1. *If no two sensors are located in the same location then the whole network area A is k-covered iff each sensor in the network is k-perimeter-covered.*

In WSNs that consist of a large number of low power, short-lived, unreliable sensors, one of the main design challenges is to obtain long system lifetime, as well as maintain sufficient sensing coverage and reliability. A lot of research work on sensor node-scheduling schemes has resulted into algorithms which can reduce overall energy consumption of the system, therefore increasing its lifetime, by turning off some redundant nodes.

In [35] the authors provide an algorithm for finding disjoint sets of sensors which provide k-coverage while maximizing the network lifetime. They show that the Sensor Scheduling Problem is NP-hard and provide a heuristic algorithm for it.

This idea presented in [35] has been used in thesis to find the near optimal set of sensors which fully cover the Area of Interest. The advantage of using their algorithm is that 1) the algorithm provide solutions to k-cover the monitored area; 2) k-coverage is guaranteed; 3) sensors can have different sensing ranges; 4) there is no limitation on the number of sensors and the sensor positions.

The idea is to assume that all sensors from the given set of sensors types are already deployed at each of their respective feasible locations. With this arrangement if the Area of Responsibility is not covered, then no subset of the sensors can cover the region. If the region is covered by deploying all sensors, then we can find disjoint subsets which can cover the region fully. The algorithm proceeds by greedily construct subsets C_i by choosing sensors from the area with the lowest sensor density. When an individual subset C_i is being made, at each step the sensor with a smaller PCL value will be added to C_i. This way we ensure that sensors are widely distributed in the area and fewest number of sensors are included in C_i.

2.3 Barrier Coverage

The aim, in barrier coverage problems, is to identify the desired coverage characteristics, if it exists, for a sensor network. A typical application of WSNs is intrusion detection. Mobile objects should be detected by the deployed sensors when they enter a sensor field or are passing through one. It may not be required to detect the object at every point on its path. Instead, it might suffice if the object is detected at least by k distinct sensors before it crosses the sensor field. This requires a sensor network to provide k-barrier coverage over a sensor field.

[18] proposes an efficient algorithm for testing whether a barrier is k-covered or not. Sensors are represented as vertices and two vertices are connected by an edge if their sensing regions intersect with each other. Using a modified version of this graph, the authors show that verifying k-barrier coverage in an open barrier is equivalent to determining k disjoint paths in this graph. Similarly, for closed barrier, verifying k-barrier coverage is equivalent to determining k disjoint cycles which are going around in the entire closed barrier. The paper presents algorithms for measuring strong barrier coverage for both open and closed barriers. It also presents some necessary and sufficient conditions for the presence of weak barrier coverage.

Chapter 3

Problem Formulation & Experimental Results

This chapter formally gives out the problem statement and the approach used to solve it. It is divided into four sections. Section 3.1 giving out the formal problem definition, section 3.2 introduces the development approach. Section 3.3 focuses on the experimental setup and results.

3.1 Problem Statement

The area under surveillance is called as the Area of Interest, $A = \{(x_0^A, y_0^A), (x_0^A, y_1^A), (x_1^A, y_1^A), (x_1^A, y_0^A)\}$. A set of heterogenous sensor types $S = \{S_0, S_1, S_2, \dots, S_n\}$ $n \geq 1$ are available with us with and each sensor type $S_i \in S$ has the following information associated with it:-

a. Range of operation R_i^S which determines the Area of Influence of the sensor A_i^S
b. Set of feasible locations $L_i^S = \{(x, y) |\ x_0^A \leq x \leq x_1^A,\ y_0^A \leq y \leq y_1^A\}$
c. Cost C_i^s

For every sensor s will have a tuple associated with it as

$$(s.type, s.range, s.location, s.cost)$$

where,

$s.type \in S$

$s.range = R_{s.type}^s$

$s.location \in L_{s.type}^S$ (the current location of the sensor)

$s.cost = C_{s.type}^S$

There is a set of jammers $J = \{J_0, J_1, \dots, J_m\}$ $m \geq 1$ which are used to jam the sensors in area of interest A. The jammers together may jam the area completely, partially or not jam at all. Each jammer J_i $0 \leq i \leq m$ is has a circular area of influence and is associated with the following information:-

a. Range of operation R_i^J which determines the Area of Influence of the jammer A_i^J
b. Fixed location $L_i^J = (x_i, y_i)$
c. Cost of operation C_k^J

Every sensor type S_j in presence of a jammer J_k has a probability of sensing P_{jk} defines as follows:-

$$P_{jk} = \begin{cases} 0 & if\ S_j\ can\ be\ jammed\ by\ J_k \\ 1 & if\ S_j\ cannot\ be\ jammed\ by\ J_k \end{cases} \quad 0 \leq i \leq m, \quad 0 \leq j \leq n$$

The following assumptions will be made while solving the problem at hand:-

a. Position of the enemy Jammers remain static.
b. Area of Interest A is a rectangle.
c. Infinite number of sensors of each type are available
d. Feasible locations for the sensors is within the Area of Interest.

Our goal is to find a minimum cardinality set $R = \{r_i\}$ $1 \leq i \leq q$ where r_i is a sensor such that $r_i.type \in S$ and $r_i.location \in L_{r_i.type}^S$ is the location of the sensor fixed by the algorithm. For every point $p \in A$ following should hold:-

a. If p is in the Area of Influence of a jammer $J_k \in J$ then p is in the Area of Influence of some sensor r_i with $t = r_i.type$ such that P_{tk}=1
b. If p is out of the Area of Influence of all jammers then p is in the Area of Influence of some sensor r_i

The following sections present the various helped in achieving the preliminary results:-

3.2 Development Approach

The approach is to assume that all feasible locations of each sensor types have been filled with sensors of that type, such that no location is empty. We then check if, after this deployment, the sensors covers the Area of Interest. Thereafter, we find a suitable minimum cardinality sub-set of sensors which covers the Area of Interest.

Huang et. al. in [11] consider a more general sensor coverage problem. They investigate the problem of determining if the area of interest is sufficiently k-covered by a set of sensors deployed at certain fixed locations in that area, where k is a predefined constant. The sensing range of each sensor can be same or a different. Their approach determines how the perimeter of each sensor's sensing range is covered, thus leading to an efficient polynomial time algorithm. In [11], they have proved that as long as the perimeters of sensors are sufficiently covered, the whole area is sufficiently covered. The proposed algorithm can be made more efficient by translating it to a distributed version where each sensor only needs to collect local information to make its decision.

Selecting a min set of sensors from among the given set can be modelled as a Sensor Scheduling for k-Coverage (SSC) problem. Gao et. al. in [35] show that the SSC problem is an NP-hard problem and propose a heuristic algorithm for it. The heuristic they have used is to order the sensors in non decreasing order of their PCL and select them in this order to form disjoint subsets.

Another heuristic that has been experimented with is to pick the sensors in non-increasing order of their ranges. As larger sensor ranges are selected first, the chance of covering the region with a smaller subset increases. The algorithm for this is as follows:

Algorithm 1: Get set of subsets covering the region

Input: S the set of sensors
Output: C the set of subsets covering the region

Sort S in non-increasing order of sensor ranges
while S *is not empty* **do**
    cov_i = isCoveredBy (C_i)
    if $cov_i < k$ **then**
        $node$ = the first sensor in S
        Add $node$ to C_i
        Remove $node$ from S
    else
        Add C_i to C
        i++
Output C

The input is S, the set of all the sensors. The output is a collection of subsets C, and each subset can cover the whole monitored region. To justify if a subset C_i can cover the entire monitored region, we can use the method proposed in [11] and we call it $isCoveredBy(C_i)$. Firstly, all the sensors in S are sorted in non-increasing order based on their ranges of operation. Then sensors are added to a subset in a greedy manner. If at some iteration, the current subset C_i can cover the region, a new subset C_{i+1} will be constructed in the same manner.

The algorithm stops when we can no longer construct a subset that can cover the whole monitored region.

3.3 Experimental Results

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