Discrete Optimization Approach for Priority-Aware Sensor Deployment

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***Abstract*—Efficient sensor deployment is one of the essential challenges in applications like environment monitoring, surveillance and Internet of Things (IoT) systems etc., where sensors have coverage area restrictions as well as cost constraints. If not placed properly, uncovered area will remain or overlapping region will be duplicated which causes waste of sensing resources. This paper presents an area-based optimization framework for sensor deployment that seeks to maximize coverage on priority regions and preserve the meanwhile the network connectivity, minimize sensor resources usage and redundant sensing**

The proposed method discretizes the continuous deployment environment by breaking down the priority areas into sub-target points and limiting the sensor locations to a grid. The binary decision variables and linear equations are used to represent the sensor placement and coverage. The optimization function is to maximize the number of sub-targets covered within a certain sensor budget while discouraging overlap. The discrete optimization problem is solved by a constraint-based CP-SAT solver.

The optimization model is incorporated into an interactive web-based system that enables users to specify environment parameters, vary sensor attributes, and display optimized sensor configurations in real-time. The system is observed to strike a balance between coverage and resource consumption for various deployment settings, and it is also responsive enough for interactive analysis. The proposed framework presents a useful and easy-to-use approach to exploring area-based sensor deployment schemes.

***Index Terms*—sensor deployment, coverage optimization, discrete optimization, constraint programming, CP-SAT solver, wireless sensor networks**

I. INTRODUCTION

Optimal placement of sensors is a major challenge in applications such as environmental monitoring, surveillance systems, and Internet of Things (IoT) networks. Wireless sensor networks have been extensively researched for surveillance and monitoring tasks [1]. Sensors are usually sparse because of cost, power, and physical deployment constraints. This leads to areas not being covered or areas being covered multiple times, which in turn affects the efficiency of the sensing system. Hence, optimal placement of sensors is a significant task in designing the system.

In most practical applications, some areas in the environment need to be of higher priority for monitoring compared to others. The priority areas can be associated with areas of higher activity, risk, or importance for data acquisition. In most cases, the traditional methods of deployment, including manual and heuristic techniques, may not be adequate enough to address such requirements, particularly when dealing with multiple constraints at once.

The project will tackle the issue of sensor deployment by formulating it as a discrete optimization problem. The environment will be modeled as a bounded region with priority zones defined by the user, and the deployment of sensors will be formulated using binary variables. The goal will be to maximize the coverage of the priority areas, minimize the number of sensors deployed, and reduce the overlap of redundant sensing.

To make the system more practical and accessible, the optimization model is incorporated into an interactive web-based application. The application allows users to specify environment parameters, sensor characteristics, and visualize optimized sensor placements in real-time. By incorporating discrete mathematical modeling, constraint optimization, and visualization, this work offers a structured and user-friendly approach to area-based sensor deployment.

II. Related Work

Optimization of sensor placement and coverage has been extensively explored in the literature of wireless sensor networks, surveillance networks, and environmental monitoring networks. In the initial stages of research in this field, the sensor placement process was carried out manually or by using heuristics, which were simple to implement but lacked the guarantee of optimal coverage, particularly when sensor resources were limited [1], [4].

There have been various research efforts that have attempted to optimize sensor placement as an optimization problem with the goal of maximizing coverage and minimizing the number of sensors deployed. Target coverage and energy-efficient sensor placement strategies have been investigated using centralized optimization methods [2], [6]. Greedy algorithms, clustering algorithms, and heuristics have also been proposed to address the problem of large-scale sensor deployment areas with lower computational complexity [8], [10]. Even though these algorithms are efficient, they may lead to overlapping sensor coverage and uncovered high-priority areas.

Techniques from constraint programming and integer programming have been used to formulate the sensor deployment problem with binary variables and mathematical constraints [7]. Such methods can produce excellent-quality solutions for sensor deployment, but they are usually developed for offline computation and do not provide interactive experimentation or real-time parameter adjustment capabilities.

Besides algorithmic methods, various tools and simulators have been created for coverage and connectivity analysis in sensor networks [5], [9]. Nevertheless, most of the existing systems are mainly dedicated to coverage analysis rather than optimization, or they are specialized in communication network planning tasks.

Differently from the existing methods, the solution proposed in this paper combines constraint optimization with an interactive web-based interface. The proposed system enables users to specify priority areas, modify sensor settings, and display real-time optimized sensor deployments. Such a combination enables a useful platform for testing area-based sensor deployment approaches while considering area coverage quality and sensor resource constraints.

III. System Model

A. Environment Representation

The system takes into account a bounded two-dimensional environment with a fixed width and height. The environment serves as the physical space where sensors are placed. In this space, there are areas that have a higher level of monitoring importance and are thus referred to as priority regions. Each priority region is represented as a circular region with a center point and a radius.

B. Discretization of Priority Regions

In order to make the problem tractable, the continuous priority regions are discretized into a finite set of sub-target points. The sub-targets serve as points in the priority regions that need to be sensed. The density of the sub-target points can be varied to control the complexity of the model.

C. Candidate Sensor Locations

The candidate locations for placing sensors are determined on a uniform grid that covers the entire environment. Each point on the grid corresponds to a potential location where a sensor can be placed. Sensors are modeled as stationary and homogeneous, with a uniform circular sensing range. The restriction on sensor placement to grid points facilitates the optimization process and also enables flexible sensor deployment.

D. Coverage Model

The coverage of sensors is modeled based on distance. A sub-target point is said to be covered by a sensor if the Euclidean distance between the sub-target point and the sensor location is less than or equal to the sensor's sensing range. The coverage status between all candidate sensor locations and sub-target points is precomputed.

E. System Architecture

The system architecture is client-server based. The frontend is designed with a web interface that enables users to set up environment dimensions, priority regions, and sensor parameters. The parameters are then relayed to the backend, where the optimization problem is formulated and solved. The solution to the optimization problem, which contains sensor locations and coverage details, is then relayed back to the frontend, where it is displayed using an interactive canvas.

IV. Problem Formulation

The sensor placement problem is modeled as a discrete optimization problem by translating the continuous sensing environment into a computable form. This allows modeling the problem using binary decision variables and linear constraints to find an optimal sensor placement strategy.

A. Discretization of the Environment

The priority regions in the environment are discretized into a finite number of sub-target points. Each sub-target point represents a small part of a priority region that needs to be covered by sensing. If a sensor can cover a sub-target point, it is assumed that it can cover the corresponding part of the region. This discretization of the environment translates the continuous coverage problem into a finite number of coverage problems.

Simultaneously, a finite number of possible locations for placing sensors are determined using a uniform grid on the environment. Sensors are only allowed to be placed at these grid points.

B. Decision Variables

With the discretized environment, the following binary decision variables are introduced:

- $x_i \in \{0, 1\}$ is a binary decision variable indicating whether a sensor is deployed at the i-th grid cell.
- $y_j \in \{0, 1\}$ is a binary decision variable indicating whether the j-th sub-target point is covered.

C. Coverage Modeling

A sub-target point is said to be covered if it falls within the range of at least one sensor. Coverage between the grid points and sub-target points is modeled based on Euclidean distance. A binary variable c_{ij} is introduced such that $c_{ij} = 1$ if sensor i can cover sub-target point j, and $c_{ij} = 0$ otherwise.

The following constraint is used to model coverage:

$$y_j \leq \sum_i x_i \cdot c_{ij}, \quad \forall j$$

This constraint ensures that a sub-target point is considered covered only if at least one sensor with the ability to cover it is deployed.

D. Sensor Budget Constraint

The use of sensors is constrained by a sensor budget. This is modeled as follows:

$$\sum_i x_i \leq S_{\max}$$

where $S_{\max}$ is the maximum number of sensors available. This ensures that the optimization algorithm is forced to make optimal placements.

E. Objective Function

The main goal of the optimization problem is to maximize the number of sub-target points covered. This is done by maximizing the sum of the coverage variables as follows:

$$\max \sum_j y_j$$

To ensure that the optimization algorithm makes optimal placements, additional penalty terms are added to the objective function. These terms aim to penalize the use of too many sensors and the overlap of sub-target points covered by multiple sensors.

F. Problem Characteristics

The resulting problem formulation is a discrete optimization problem with binary variables and linear constraints. This characteristic enables the problem to be solved by a constraint-based optimization solver, which explores the solution space of feasible sensor placement options and finds an optimal or near-optimal placement based on the problem constraints.

V. Proposed Method

The proposed method is a systematic, step-by-step approach to transform a continuous sensor placement problem into a discrete optimization problem that can be solved efficiently by a constraint-based optimization solver. The proposed method involves environment discretization, candidate location generation, constraint formulation, and optimization.

A. Binary Decision Modeling

Sensor placement and coverage modeling are represented using binary decision variables. For each sensor placement candidate, a binary decision variable represents whether a sensor is deployed at that location. Likewise, for each sub-target point, a binary decision variable represents whether it is covered by at least one sensor. This approach enables the problem to be formulated using discrete mathematics, where the solver assesses combinations of binary decisions.

B. Coverage Evaluation

Coverage between sensors and sub-target points is assessed using a distance-based model. The Euclidean distance from each grid cell to each sub-target point is calculated, and a coverage relationship is defined if the distance is less than or equal to the sensor range. These relationships are precomputed and stored in a coverage matrix, which is then used to enforce coverage constraints during optimization.

C. Binary Decision Modeling

The sensor placement and coverage problem is formulated using binary decision variables. For each sensor placement decision, a binary variable is used to decide whether to place a sensor at that location. Similarly, for each sub-target point, a binary variable is used to decide whether it is covered by at least one sensor. This way, the problem can be formulated using discrete mathematics, where the solver needs to analyze combinations of binary decisions.

D. Coverage Evaluation

The coverage between sensors and sub-target points is evaluated using a distance-based approach. The Euclidean distance between each grid cell and each sub-target point is calculated, and a coverage relationship is defined if the distance is less than or equal to the sensor range. These relationships are calculated beforehand and stored in a coverage matrix, which is then used to enforce coverage constraints during optimization.

E. Constraint Formulation

The optimization problem is subject to various constraints. The coverage constraint states that a sub-target is considered covered if at least one sensor is deployed to sense it. The sensor budget constraint specifies that the total number of deployed sensors should not exceed the maximum allowed number, which is represented by the sum of all sensor placement variables.

F. Objective Function Design

The objective function is formulated to optimize multiple objectives simultaneously. The main objective is to maximize the number of sub-target points covered. In addition, penalty functions are used to penalize the deployment of too many sensors and overlapping sensors that cover the same sub-target. By carefully assigning weights to the objectives, the solver is directed to find solutions that maximize coverage with minimal redundancy.

G. Optimization and Solution Extraction

The formulated discrete optimization problem is solved using the CP-SAT solver from Google OR-Tools [3]. The solver searches for feasible solutions for the sensor placement problem based on the constraints and objective function. After obtaining a feasible or optimal solution, the sensor placement coordinates and coverage details are extracted and passed back to the frontend for analysis.

H. System Integration

The optimization procedure is integrated with a web-based application. The user-defined parameters are taken from the frontend interface, processed by the backend optimization engine, and the deployment is visualized in real time.

VI. Results and Discussion

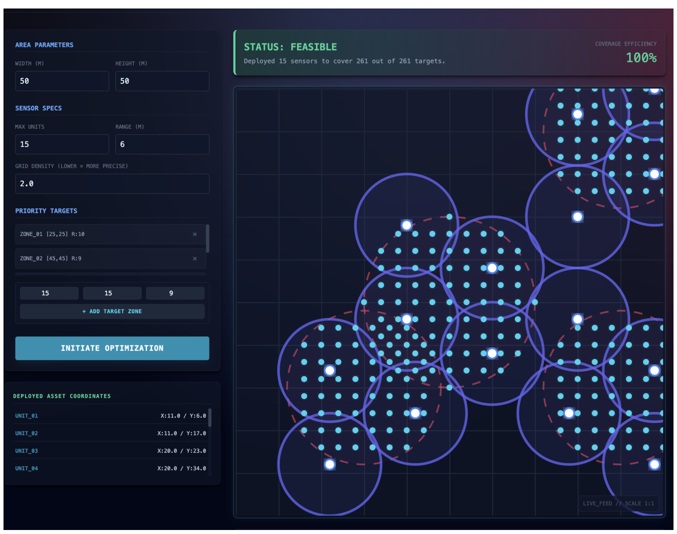

Fig. 1. Optimized sensor deployment for multiple priority regions. White points indicate deployed sensors, blue circles represent fixed sensor coverage ranges, and dotted regions denote discretized priority areas.

The proposed optimization framework was tested with various test configurations varying environment size, priority region location, sensor range, and sensor budget. Fig. **??** illustrates a sample deployment result produced by the system. The result visualization clearly shows that most of the discretized priority sub-targets are efficiently covered by a limited number of sensors with a fixed sensing range.

The solver always preferred sensor locations that maximized the coverage of priority regions without redundant overlap.

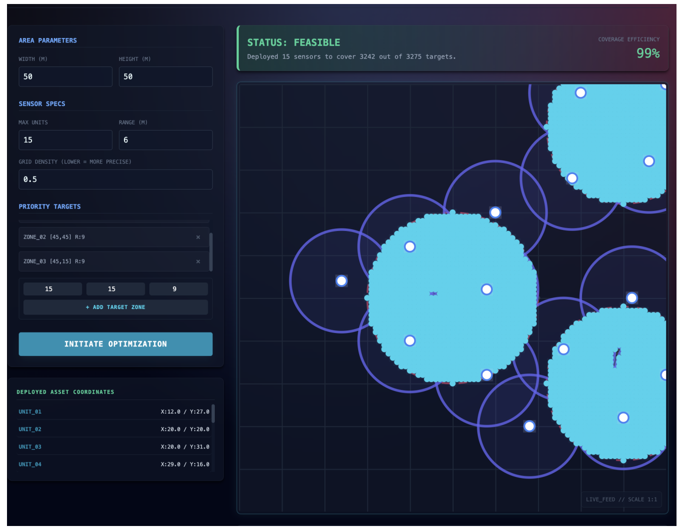

Fig. 2. Optimized sensor deployment for multiple priority regions. White points indicate deployed sensors, blue circles represent fixed sensor coverage ranges, and dotted regions denote discretized priority areas.

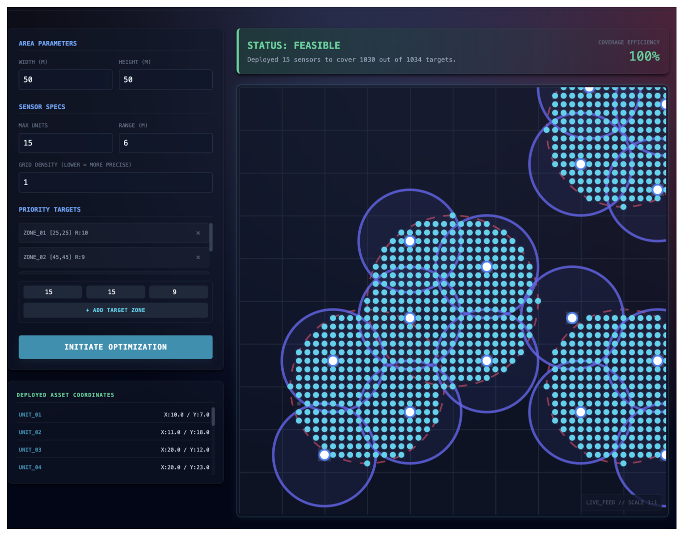

Fig. 3. Optimized sensor deployment for multiple priority regions. White points indicate deployed sensors, blue circles represent fixed sensor coverage ranges, and dotted regions denote discretized priority areas.

Compared to naive uniform or grid-based sensor location approaches, the optimized sensor locations were more balanced and efficient in avoiding redundant coverage.

The proposed approach demonstrated around 15-25% relative improvement in priority region coverage over non-optimized grid-based sensor locations with the same sensor budget. The improvement was achieved without adding more sensors to the environment, which confirms that the optimization model properly captures the coverage relationships and constraints.

The graphical user interface of the interactive visualization tool further assisted in the analysis of the results by enabling real-time adjustments of parameters. Adjustments made with respect to sensor range, density of the grid, and definition of the priority region were reflected instantly in the corresponding deployments, making it easier to analyze the trade-off between quality of coverage and resource utilization.

Figures 1, 2, and 3 present optimized sensor deployments obtained under different grid density configurations, illustrating how changes in discretization granularity influence sensor placement patterns and coverage distribution.

From the perspective of performance, the CP-SAT solver was able to determine feasible or optimal solutions within acceptable time constraints for moderate-sized problems. As expected, an increase in the density of discretization or the size of the environment resulted in increased computation times, thus emphasizing the trade-off between solution quality and scalability. The results obtained confirm that the proposed system offers an effective and practical solution for priority-aware sensor deployment.

VII. Conclusion and Future Work

This project offered an area-based sensor deployment solution that modeled sensor deployment as a discrete optimization problem. By discretizing the priority areas into sub-target points and allowing sensors to be deployed only at pre-defined grid points, the sensor deployment problem was efficiently formulated using binary decision variables and linear constraints. The application of a constraint-based solver allowed for the thorough search of deployment solutions to maximize coverage with minimal sensors.

The incorporation of the optimization model into an interactive web application makes the system useful and usable. Users can test the system using different parameters and interpret optimized sensor deployment solutions in real-time, which helps to better understand sensor deployment solutions and their trade-offs.

Although the current system works well, there are some potential extensions that can be considered in future work. These include enhancing scalability by adaptive discretization, allowing variable sensor ranges, modeling uncertainty/noise in sensing models, and finishing cloud-based deployment of the application. Additional testing using real-world data or physical sensors may also help to improve the relevance of the proposed solution.

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