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Priority-based target coverage in directional sensor networks using a genetic algorithm☆

Jian Wang *, Changyong Niu, Ruimin Shen

Department of Computer Science and Engineering, Shanghai Jiaotong University, Shanghai, 200030, China

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ABSTRACT

Sensor networks have been applied in a wide variety of situations. Recently directional sensor networks consisting of directional sensors have gained attention. As for the traditional target coverage problem, the limited sensing angle of directional sensors makes it even more challenging. Moreover, individual targets may also be associated with differentiated priorities. Considering the distance between the directional sensors and targets influences sensing quality, this paper proposes the priority-based target coverage problem and strives to choose a minimum subset of directional sensors that can monitor all targets, satisfying their prescribed priorities. Due to the NP-Complete complexity, the minimum subset of directional sensors is approximated by using a genetic algorithm. Simulation results reveal the effects of multiple factors on the size of the resulting subset.

1. Introduction

A sensor network consisting of a large number of sensors typically monitors the surrounding environment or dispersed targets of interest within a given area. For example, the sensors deployed in a battlefield monitor enemy troops. The type of information collected varies from seismic, acoustic, magnetic, to video data. Whenever data is gathered, the sensor processes it if necessary, and then forwards it towards a base station through wireless communication. Usually the base station is equipped with high computation, communication capability, as well as sufficient energy, and it is responsible for processing all information in a centralized manner according to application-specific requirements.

Recently, different directional sensors have emerged due to the constraints of manufacturing techniques, size and cost. The most distinguishing characteristic of them is the limited sensing angle. Each directional sensor can sense only a sector of the disk, centered at itself, with the radius being equal to the sensing range. Rotation, one of the common enhancements, enables directional sensors' working in distinct directions so as to facilitate cooperation between neighboring directional sensors. As far as a target coverage scenario is concerned, individual targets are usually associated with differentiated priorities, which reflects the importance of targets for specific applications. Another issue of the target coverage is monitoring quality, which typically degrades as the distance between the directional sensors and targets increases. Both priority and monitoring quality render the target coverage in directional sensor networks even more challenging.

To be clear, the following scenario is investigated in this paper. A number of targets of interest with their associated priorities are designated in the two-dimensional Euclidean field. Directional sensors are randomly and uniformly scattered within the same field. The sensing region of directional sensors is assumed to be the sector of a sensing disk, centered at the directional sensor with uniform sensing range. If the directional sensor faces in a direction, then it senses such a direction that is referred as the sensing direction. The directional sensor can monitor targets that are within its sensing region. As

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* Corresponding author.
E-mail addresses: jwang@sjtu.edu.cn (J. Wang), cyniu@sjtu.edu.cn (C. Niu), rmshen@sjtu.edu.cn (R. Shen).

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the distance between the directional sensors and targets varies, the quality of monitoring (i.e. utility) alters, too. Hence, the targets with high priority are required to be monitored by two or more directional sensors simultaneously. Realistically, the directional sensor network is made up of abundant directional sensors. The problem now being studied is to minimize the subset of directional sensors covering each target with the sufficiently aggregate quality.

Assuming that the position information of targets and directional sensors, the uniform sensing range, the uniform sensing angle, and the priorities of targets are available, the base station conducts the computation in a centralized manner and finds the minimum subset of directional sensors. Afterwards, it informs each sensor of whether or not to operate, and the sensing direction if it is chosen to operate. This paper proposes a *priority augmented graph* based on the position of directional sensors and targets, the uniform sensing range, and the uniform sensing angle. Due to NP-Complexity, the genetic algorithm is used to approximate the minimum subset of directional sensors. The remainder is organized as follows: Section 2 discusses related works. The formulation of the priority-based target coverage problem and applying the genetic algorithm to approximate the minimum subset are presented in Section 3. In Section 4, the effects of varied factors on the minimum subset are evaluated. We conclude in Section 5 with future work.

2. Related work

Coverage is one of the fundamental functionalities of sensor networks. Realistically, the sensors are deployed densely in the field of interest. A high level of redundancy benefits for prolonging the network lifetime, as well as for improving the resilience of coverage and network connectivity. The coverage is basically categorized into two types: (i) field coverage, where the overall field is covered by sensors and no coverage hole can be tolerated at any time; and (ii) target coverage, where each target is monitored continuously by at least one sensor.

The coverage is often studied together with the network lifetime in existing works. In the field coverage category, MDS [1] proposes a graph theoretical approach based on minimum dominating set without using GPS/location information. It finds many subsets of sensors, each of which guarantees a high level of field coverage, with the aim to extend the overall network lifetime. Similarly, ESSC [2] makes use of the *Sponsored Sector Coverage* concept. It prolongs the network lifetime and provides a high degree of field coverage. LDAS [3] analyzes the redundancy among the sensing areas of neighboring sensors, and estimates it even without location or direction information. It prolongs the network lifetime by turning off redundant sensors alternately. [4] enhances the effectiveness of sensor networks by applying fuzzy logic system to optimize the sensor placement after initial random deployment. It maximizes the sensor coverage with relatively less energy consumption. Directional sensors recently have gained attention of researchers. For instance, [5] analyzes the probability of field coverage when each sensor is assumed to be fixed in one direction.

Work [6] investigates the field coverage and network connectivity simultaneously based on the sensors with directional antennas. It derives the condition of the field coverage and connectivity that is a function of sensor active probability. Depending only on local topology information, [7] addresses coverage enhancement in a directional sensor network through minimizing the overlapped sensing area among directional sensors.

In the target coverage category, *k-barrier coverage* [8] is used to detect an object that penetrates the protected region. In this case, the sensor network would detect each penetrating object by at least k distinct sensors before it crosses the barrier of wireless sensors. Its optimized objective is to minimize the number of sensors that form such functionality. Given the assumption that directional sensors can rotate arbitrarily, work [9] strives to find the minimum subset of directional sensors that can cover the maximum number of targets. Since the subsets are disjoint overlap, the authors are to find the maximum number of these subsets. In contrast, [10] permits non-disjointness among the subsets of directional sensors. Although increasing problem complexity, the relaxation of non-disjointness significantly prolongs the network lifetime.

As far as the utility is concerned, work [11] develops a model for a wide variety of applications, where the global objective is defined based on utility functions and a cost model for energy consumption in sensing and data delivery. In addition, aggregation utility for a specific set of sensors is a function of the size of the set as well as positions of individual sensors. [12] even defines the generic framework, given the utility value of individual sensors, to find the sequence of subsets of sensors maximizing total utility, while not exceeding the available energy. Yet, both work discuss the utility in context of omnidirectional sensor networks.

This paper considers the priority-based target coverage problem in directional sensor networks, and strives to find the minimum subset of sensors while satisfying all the targets. It differs from existing work because of the priorities of the targets as well as the distance-dependent monitoring quality. For the sake of brevity, directional sensors henceforth can be called as sensors.

3. Priority-based target coverage formulation

The objective of the priority-based target coverage is to find a minimum subset of sensors in the sensor network that can monitor all targets satisfying their priorities. We start by describing notations. Then we formulate the problem and afterwards seek to find the minimum subset of sensors.

Table 1
The summarized notations.

a_m	the mth target, $1 \le m \le M$. M is number of targets
s_i	the ith sensor, $1 \le i \le N$. N is number of sensors
A	the set of targets, $A = \{a_1, a_2, \ldots, a_M\}$
S	the set of sensors, $S = \{s_1, s_2, \ldots, s_N\}$
$d_{i,j}$	the jth sensing direction of s_i, $1 \le i \le N$, $1 \le j < \infty$
$xy\,(node)$	coordination function that provides position for *node*
ϖ	the uniform sensing angle of sensor
r	the uniform sensing range of sensor
$f(x)$	the utility that is a function of distance x, reflecting the accuracy of sensor monitoring
$g(a)$	the priority that is associated with $a \in A$
$h(y)$	the mapping function from the priority y to the utility $h(y)$

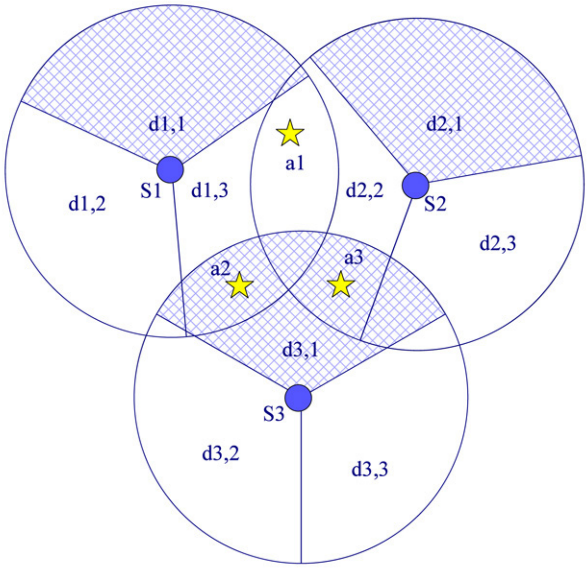

Fig. 1. An illustrative example for a directional sensor network with three targets of interest.

3.1. Notations

In Table 1, most notations are summarized. In particular, since each directional sensor is assumed to rotate arbitrarily, the number of $d_{i,j}$ is infinite. The exact definition of functions $f(x)$, $g(a)$, $h(y)$ are highly dependent on the context or requirements of applications. Without loss of generality, this paper employs the three functions as defined as follows:

$$f(x) = 1 - x^2, x \in [0, 1], \qquad g(a) = z, z \text{ is randomly and uniformly chosen within } (0, 1], \qquad h(y) = \alpha y + \beta \quad (3.1)$$

where $h(y)$ demonstrates the linear relationship between the priority and the utility, although other relationships definitely exist, and α, β are configuring parameters.

3.2. Problem formulation

Before formally formulating the priority-based target coverage problem, we show an example of a directional sensor network. In Fig. 1, $a_m (1 \le m \le 3)$ is the target and s_i $(1 \le i \le 3)$ is the directional sensor. $d_{i,j}$ $(1 \le i, j \le 3)$ represents the sensing direction of s_i. Also, $d_{1,1}$, $d_{2,1}$, $d_{3,1}$ denote the current sensing direction of s_1, s_2, s_3, respectively. The target can be sensed or monitored only when it is within the current sensing region of at least one directional sensor. Therefore, a_2, a_3 are monitored simultaneously by s_3. If a high level of priority is associated with a_2, then two sensors s_1, s_3 are required to cooperatively operate in $d_{1,3}$, $d_{3,1}$, respectively.

In order to represent individual directions of each sensor conveniently, we introduce a variable x_{ij}:

$$x_{ij} = \begin{cases} 1 & \text{the sensor } s_i \text{ operates in } j\text{th sensing direction} \\ 0 & \text{otherwise.} \end{cases} \quad (3.2)$$

The priority-based target coverage in a directional sensor network is defined as follows: given a target set A, sensor set S, coordination function $xy\,(node)$, sensing range r, sensing angle ϖ, utility function $f(x)$, priority function $g(a)$, mapping

Table 2
Algorithm 1: direction partition algorithm.

```
Input: sensor s, target set A, sensing range r, sensing angle ϖ, coordinate function xy (node)
Output: subsets collection: cs = {cs_1, ..., cs_j, ...}, cs_j ≠ Ø, cs_j ⊆ A

Let B = Ø, cs = Ø
FOR each a ∈ A
  IF |xy (a) − xy (s) | ≤ r THEN B = B ∪ {a} END
END
IF B is Ø THEN RETURN Ø END
Let V = Ø
FOR each a ∈ B
  Compute offsetting angle θ with respect to positive axis X, and V = V ∪ {θ}
END
FOR each θ ∈ V
  cs_j represents the subset of targets in B who are located between the angle θ and θ − ϖ
  cs = cs ∪ {cs_j}
END
RETURN cs
```

function $h(y)$, as well as the constraint that each target is monitored according to the prescribed priority, the minimum subset of directional sensors as well as their corresponding sensing directions is formulated:

$$\text{minimize } |S'| \tag{3.3}$$

Subject to

$$a \prec S', \forall a \in A, S' \subseteq S \tag{3.4}$$

$$\sum_{j=1}^{\infty} x_{ij} \leq 1, \forall s_i \in S' \tag{3.5}$$

$$a \prec S' \text{ means } \sum_{s_i \in S', x_{ij}=1} f\left(\frac{distance(s_i, a)}{r}\right) * I\left(a \text{ belongs to } y_{ij}\right) \geq h\left(g\left(a\right)\right) \tag{3.6}$$

$$I\left(X\right) = \begin{cases} 1 & X \text{ is true} \\ 0 & \text{otherwise} \end{cases} \tag{3.7}$$

$$y_{ij} \text{ denotes the subset of targets falling in } j\text{th sensing region of } s_i\,. \tag{3.8}$$

The objective function (3.3) is to minimize the subset of directional sensors covering all targets. Constraint (3.4) guarantees that each target is satisfied with a subset of sensors denoted by S'. Constraint (3.5) guarantees that each sensor $s_i \in S'$ operates in at most one direction at any time. Expressions in (3.6)–(3.8) provide assistant definitions.

3.3. NP-complete

The priority-based target coverage problem is proved to be NP-Complete by simple reduction to a classical Set-Cover problem, which is NP-Complete. Given a priority-based target coverage problem as defined in the previous subsection, let

$$\forall x \in [0, 1], \quad f(x) = 1 \qquad \forall a \in A, \quad h(a) = 1 \qquad \forall \text{ priority } y, \quad h(y) = y, \quad \text{i.e. } \alpha = 1, \beta = 0. \tag{3.9}$$

Moreover, each directional sensor is assumed to be fixed in one direction. Therefore, each of individual directional sensors covers a subset of targets. Finding a minimum subset of sensors covering all the targets with satisfying their priorities is obviously a Set-Cover Problem. Consequently, the priority-based target coverage is NP-Complete. For more sophisticated proof without fixing the sensing direction, please refer to [10].

3.4. Direction partition algorithm

Typically, a directional sensor monitors distinct subsets of targets in different directions. Theoretically, there is an infinite number of directions when the sensor rotates continuously. Here the *Direction Partition* algorithm as shown in Table 2 is proposed to find all *basic* directions of the directional sensor, each of which corresponds to a distinct subset of targets.

This algorithm iteratively searches all potential *basic* directions of the directional sensor s. Usually the number of the basic directions is small, thereby significantly reducing the computation complexity of the problem using the above formulation.

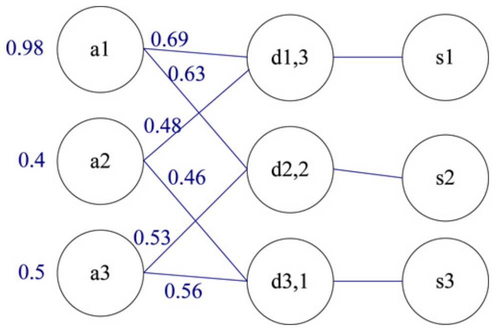

Fig. 2. Priority augmented graph for Fig. 1.

Table 3
Algorithm 2: randomized algorithm for a feasible session.

Input: priority augmented graph G
Output: subset of basic directions
Randomly select one basic direction for each sensor, denoted by W
Let $W' = \emptyset$
WHILE (each target $a \in A$ is covered under W satisfying the associated priority $g(a)$)
Randomly choose one direction $x \in W$
$W' = W, W = W - \{x\}$
END
RETURN W'

Table 4
Algorithm 3: genetic algorithm for priority-based target coverage.

Input: priority augmented graph G
Output: minimum sensor subset
Initialize the genetic algorithm
Run *Algorithm* 2 to get a sufficient large set of feasible sessions denoted by W
WHILE W does not satisfy the stopping condition (i.e. no improvement in last 10 iterations)
Evaluate each feasible session in W
Assign probability to each session accordingly
Select feasible sessions with respect to the probability and preserves those elites
Apply the crossover operation on multiple pairs of feasible sessions in W
Choose some feasible sessions and impose mutation on them
END
RETURN the minimum subset of feasible sessions within W

3.5. Priority augmented graph

Fig. 2 is an instance of a priority augmented graph constructed based on Fig. 1, whose vertexes consist of targets, sensing directions, and sensors. The left column of vertexes represents the set of targets A. The middle column is a collection of basic directions $\{d_{i,j}\}$ of different sensors. The last column denotes the set of sensors S. Each target a_m links to all basic directions it belongs to $d_{i,j}$, with the accompanying utility labeled along the edges. Each sensor s_i connects to all of its own basic directions $\{d_{i,j}\}$. Since s_i can only work in one direction at any time, at most one edge can be selected among the ones arising from the directional sensor itself. In addition, the value next to the target a_m is the result mapped from the priority.

3.6. Randomized algorithm for initial population

Feasible session is defined as the minimal subset of basic directions, monitoring all the targets satisfying the corresponding priority requirement. In a densely deployed sensor network, it is possible to have multiple feasible sessions for the same set of targets. We resort to a randomized algorithm as shown in Table 3 to find feasible sessions. Although the returned result may be an empty set, by repeatedly executing this randomized algorithm, a large set of feasible sessions can be found, which is used as the initial population of the genetic algorithm.

3.7. Genetic algorithm

By feeding the set of feasible sessions to the genetic algorithm, we approximate the minimum subset of sensors by executing the genetic algorithm as outlined in Table 4.

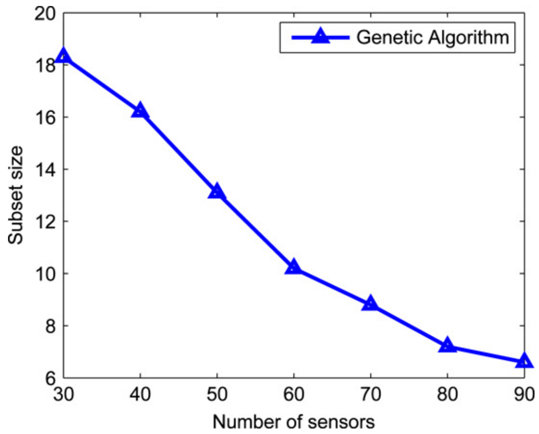

Fig. 3. Size vs. number of sensors.

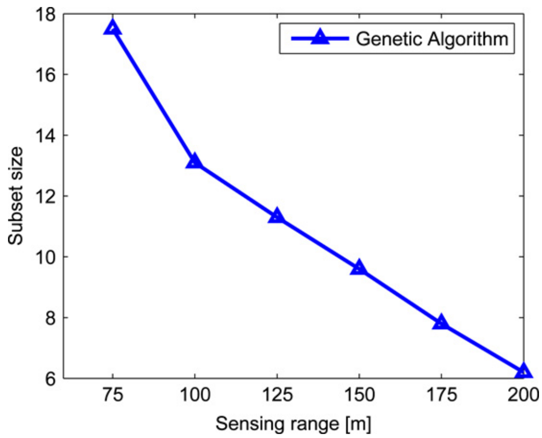

Fig. 4. Size vs. sensing range.

Specifically, the quality of the feasible session $x \in W$ depends on the difference between the sums of the utilities of individual sensors $s \in x$ and of the utilities of all targets mapped from their priorities. The feasible sessions with a small difference are treated as good ones. Consequently, a high probability is assigned. Next, those good feasible sessions are preserved for the next generation. Some of feasible sessions joining into the next generation are constructed by the mutation operation. Most of candidate feasible sessions are generated by the crossover operation upon two feasible sessions selected according to their probabilities.

4. Simulation

We run the genetic algorithm for the priority-based target coverage problem on a computer with 1.5 GHz CPU and 512 MB memory. All algorithms are implemented on the *MATLAB*, which provides strong optimization toolboxes. The directional sensor network is configured as follows: N sensors with uniform sensing range r and sensing angle ϖ, and M targets are scattered randomly and uniformly in a region of 400 m $\times$ 400 m. The basic directions $\{d_{i,j}\}$ for each sensor s_i are found by the direction partition algorithm. $h(y) = 2 * y + 0.1$ is used while $f(x)$, $g(a)$ are the same as in Eq. (3.1). In addition, each result in the plots is averaged over 120 runs through random scattering sensors and targets.

First, the sensing angle ϖ is set to $\frac{2\pi}{3}$. Fig. 3 presents the relationship between the size of the subset of sensors and the set of sensors S while $M = 10$, $r = 100$ m. Intuitively, the size linearly decreases as $N = |S|$ increases, because some directional sensors can monitor more targets simultaneously and a high level of aggregate utility among neighboring sensors appears more often.

When the number of sensors is fixed to be 50 and that of targets still remains to be 10, we study the relationship between the size of the subset and the sensing range as shown in Fig. 4. The size decreases as the sensing range grows. It is reasonable since more targets could be covered when sensors have a large sensing range. Implicitly, a large sensing range also gives rise to a high utility for the same target because of the normalized distance used in the mapping function. A similar result also

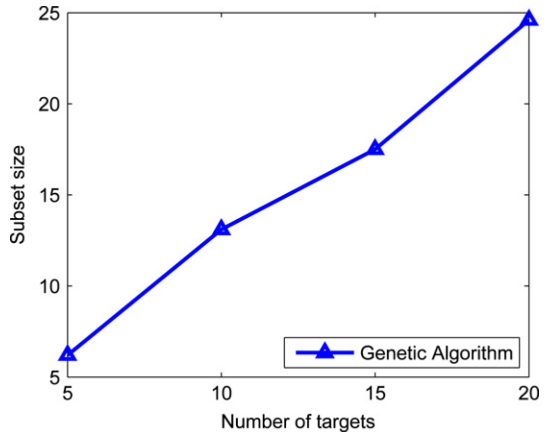

Fig. 5. Size vs. number of targets.

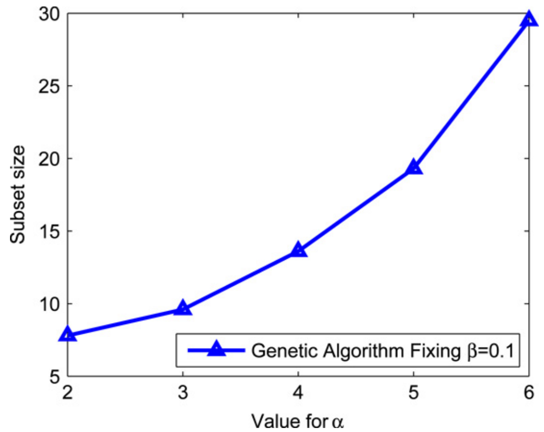

Fig. 6. Size vs. α.

arises when the sensing angle ϖ becomes large, although the improvement is relatively less surprising than prolonging the sensing range.

In Fig. 5, we reveal the relationship between the size of the subset and the number of targets when fixing $N = 50$, $r = 100$ m, $\varpi = \frac{2\pi}{3}$. As more targets are to be covered, the size consequently increases. Fig. 6, fixing $M = 10$, $N = 80$, $r = 125$ m, $\varpi = \frac{2\pi}{3}$, shows that the size is remarkably affected by α while fixing $\beta = 0.1$, because α weights more on the same priority. A similar result would be also obtained by changing β accordingly.

5. Conclusion

This paper investigates a priority-based target coverage problem in directional sensor networks, where each target is to be monitored by one or more directional sensors depending on the target's priority. This problem is proved to be NP-Complete. By proposing the direction partition algorithm, the priority augmented graph as well as leveraging the genetic algorithm, the minimum subset of sensors is well approximated. The simulation results show the effects of various factors on the subset of sensors. In future work, we will investigate other efficient algorithms and practical decentralized implementation in large scale sensor networks.

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