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Multi-Objective Wireless Sensor Network Deployment Problem with Cooperative Distance-Based Sensing Coverage

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Abstract
This paper investigates the multi-objective problem of deploying wireless sensor networks with cooperative distance-based sensing coverage. This problem considers deploying a number of sensor nodes to cove multiple target points on a deployment area. Based on the locations of target points and the sensor nodes with their own inner and outer coverage radii, the distance-based sensing coverages of target nodes by sensor nodes are divided into three categories: full coverage (i.e., within the inner coverage radius), no coverage (i.e., outside the outer coverage radius), and partial coverage (i.e., between the inner and outer radii). Furthermore, this paper additionally considers the cooperative sensing coverage in which the sensing coverage of a target point is provided by more than one sensor node. The decision of sensor deployment in this paper is to select sensor nodes from potential sensor node positions so as to simultaneously maximize the collective sensing coverage of all target points and minimize the total distances between each target point and the selected sensor node(s). This paper first formulates this problem as a multi-objective optimization model, and then develops a solution procedure to determine the best non-dominated solution set for the problem model. Numerical experiments for the concerned problem by the proposed solution approach are demonstrated.

Keywords Wireless sensor network · Cooperative sensing coverage · Distance-based sensing coverage · Multi-objective optimization model · Non-dominated solution

1 Introduction

Wireless sensor network (WSN) consists of a set of sensors that are spatially distributed in the monitored region of interest (RoI) with wireless links cooperatively in order to detect and gather the information [1, 2]. Deployment of WSNs was originally motivated by military applications [3], and is currently employed in an abundant of civilian fields, such as industry, healthcare, agriculture, buildings, habitat monitoring, traffic, environment, security, and so on. [4, 5]. One of the most critical issues on WSNs is to decide the locations of wireless sensors in order to maintain the coverage and connectivity in the covered area/targets within ROI. This problem is also known as placement, coverage, and deployment in WSNs [6]. WSN deployment has significant influence on performance of WSNs based on the level of coverage and duration of connectivity. The planning strategy of WSN deployment will affect the coverage, lifetime, and transmission rate of sensors in WSNs. The work in [1] observed that an efficient sensor deployment can enhance the detection capability, increase the monitoring quality through increasing the coverage area, and reduce deployment cost. They also indicated that the coverage maximization in deployment of WSNs is always a

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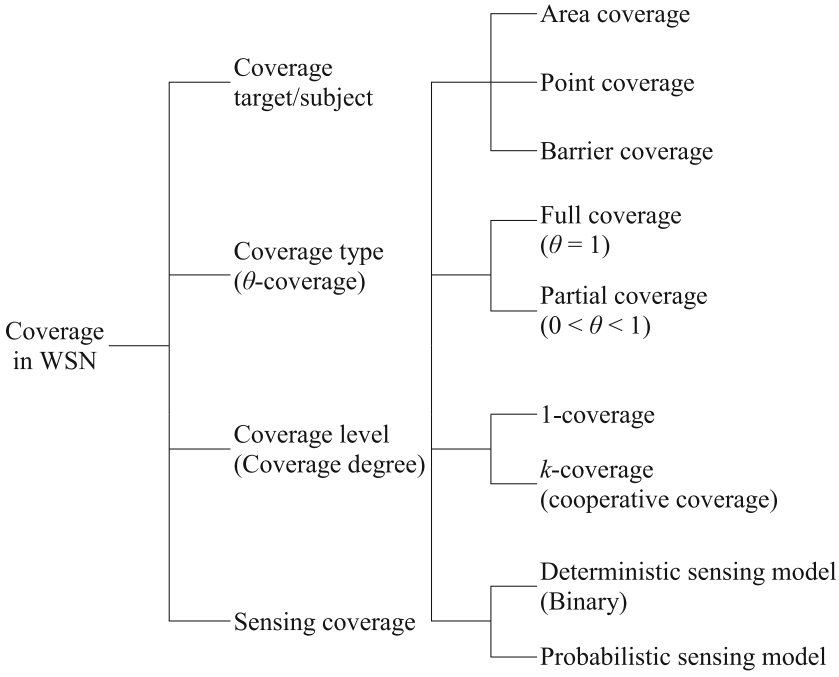
significant measurement, and has been a challenging issue because it is associated with optimization of resource sensing region supervised. Therefore, this paper focuses on the sensor coverage optimization of WSNs.

Coverage is one of the critical measurements for WSNs with regard to how adequately each point of interest (PoI) is tackled by the deployed sensor nodes, and can be considered as a measure of quality of service (QoS) [2, 7–9]. It can be divided into multiple categories, depending on various dimensions (see Fig. 1). Based on the monitored subject/target in RoI, it can be classified as *area*, *point of interest/target*, and *barrier coverage* [10–12]. The purpose of *area coverage* for WSNs is to achieve the maximal coverage in RoI by the deployed sensor nodes. *Coverage for point of interest/target* is focused on how to deploy sensor nodes to cover/control the set of discrete PoIs/targets in RoI. *Barrier coverage* is focused on the intrusion detection which penetrates the border across the sensor network. The desired coverage characteristics in barrier coverage are to detect intruders in the border and find penetration paths in order to minimize the probability of undetected penetration in WSNs. In a lot of practical applications, it is more sufficient to detect/monitor specific points or targets in RoI than that in the whole area. In addition, coverage of the whole area will require deployment of more sensor nodes, causing higher costs and less reliability [10]. Moreover, point/target coverage requires PoIs in stationary locations, and has been investigated in static WSNs. Therefore, this paper investigates monitoring stationary PoIs in static WSNs.

As the degree of coverage for points/area in RoI, it can be considered by the proportion of covered points/area and total points/area [12]. The coverage types are categorized as full and partial/limited coverage, depending on the application requirements [2, 10, 12, 13]. *Full coverage* (or blanket coverage [11, 14]) enables every point to be monitored by sensor node(s) in WSNs [2, 6, 13]. A large number of applications on full coverage have been broadly employed, such as intrusion detection, field monitoring, household crops monitoring, 3D wireless sensor network, and so on [12–16]. However, full coverage requires a large number of sensors, and leads to high cost and complexity [2]. In addition, full coverage is not necessitated in some applications. *Partial coverage* indicates that a certain percent of points/area are covered, so that the adequate and acceptable degree of coverage is guaranteed [8, 17]. It is considered to save sensor nodes deployed and energy consumption when full coverage is not required. Applications of partial coverage include monitoring the environment, detecting potential forest fire, and so on. This degree of coverage is usually represented as θ-coverage, in which $\theta = 1$ for full coverage and $0 \le \theta < 1$ for partial coverage, respectively [12]. This paper focuses on the full coverage in which the entire points/area are covered by at least one sensor node.

In some applications, the monitoring point/area with simple coverage (or 1-coverage) (i.e., the point/area covered by at least one sensor node) is not sufficient, and may result in poor and unreliable quality for entire WSNs when some sensors are inactive. That is, 1-coverage may provide insufficient coverage to the point/area, and may lead to partial coverage. Hence, cooperative coverage [18] (i.e., sensing nodes "cooperate" to provide collective coverage to the point/area by at least k sensor nodes where $k \ge 1$) is introduced and defined as a multiple coverage or k-coverage [19, 20]. The examples include distributed detection, loss or corruption of important data, mobility tracking, critical people and facilities watching,

Fig. 1 Classification of WSN coverage



high security areas monitoring, and military intelligence in a battlefield that requires a high degree of robustness. In the *k*-coverage (or cooperative coverage), each target point is within the sensing radius of at least *k* distinct sensor nodes, and *k* is represented as coverage level (or coverage degree) [2, 10, 12, 13]. In addition, *k*-coverage can provide fault tolerance, prolong the network lifetime, and allow good decisions to be made. Therefore, this paper presents the *k*-coverage (cooperative coverage), in which each point is covered by at least *k* sensor nodes.

Sensing coverage is one of the important factors to measure the sensing ability or sensitivity of each sensor node in WSNs, and affects the energy consumption, coverage, connectivity and lifetime [2, 13, 21]. The points/area can be detected, monitored or covered *within the sensing range* of sensing node. The network coverage in WSNs can be interpreted as a *collective* sensing coverage by all active sensor nodes. The sensing coverage for each sensor node can be classified as either *deterministic (binary) sensing model*, or *probabilistic (stochastic) sensing model* [1, 2, 8, 13]. In the deterministic sensing model, if points/area can be detected/covered within the sensing range/radius of sensor nodes, then the detection probability is 1; otherwise (i.e., points/area are outside the sensing range/radius of sensor nodes), the detection probability is 0. However, uncertain factors (such as noise, interference, obstacles, etc.) will cause an imprecise sensor measurement in practical applications. Moreover, the sensing coverage of sensor nodes is not expected to collapse abruptly from 1 to 0. Accordingly, the sensing coverage should take a probabilistic form into consideration. The probabilistic sensing model estimates the sensing coverage according to the distance between sensor nodes and target points: the coverage value is 1 if the distance is less than the inner sensing radius; it is 0 when the distance larger than outer sensing radius; and it is a function with range between 0 and 1 when this distance is between those two radii. Sensing coverage can be assigned a value between 0 and 1 for each point/area by linear interpolation. The points/area can be recognized/diagnosed within the inner radius (meaning that the sensing coverage is 1), and between inner and outer radii (meaning that the sensing coverage is a certain nonzero probability value). The sensing coverage could vary as a function of distance between sensor nodes and points/area. For examples, the distance function can be a decreasing [13], exponential [8], polynomial [22] or staircase [23]. Thus, the probabilistic sensing model for each sensing node with full coverage (i.e., coverage is 1) within inner radius, none coverage (i.e., coverage is 0) outside the outer radius, and coverage depending on the decreasing function of distance (i.e., coverage is between 0 and 1) among those two radii is tackled in this paper.

In WSNs, it can be represented as an optimization problem with a single objective or multiple objectives [1, 7]. However, most of the real-world problems involves with multiple objectives which are conflicted with each other and need to be optimized simultaneously. Thus, the problems are usually formulated as a multi-objective optimization problem (MOOP), including WSNs [24]. It is expected to obtain multiple alternative solutions for MOOP, which are either dominated solutions (i.e., the solution is better than others with at least one objective) or non-dominated solutions (i.e., the solution is a tradeoff in which the preferences for all objectives are equivalent). All solution approaches to MOOPs aim to find the best tradeoff solution set among all objectives, called Pareto optimum, Pareto set, or Pareto optimal front [25]. These obtained multiple solutions from the Pareto optimal front are more desired, and can be chosen based on decision makers' preferences. In this paper, the sensor deployment problem with multi-objectives is presented.

This paper presents and investigates the multi-objective WSN deployment problem with cooperative distance-based sensing coverage. Consider a deployment area with a number of static PoIs and stationary candidate locations of sensor nodes, in which each sensor node may have various sensing coverage with different inner and outer sensing coverage radii. Sensing coverage for each sensor node is 1 within the inner coverage radius, 0 outside the outer coverage radius, and decreases from 1 to 0 by a function of distance depending on the increased distance from inner to outer radius. That is, the sensing coverage of each sensor node is a probabilistic sensing model. Each PoI must be covered by at least *k* sensor nodes with $k \geq 1$ (i.e., using the full coverage ($\theta = 1$) for all PoIs), and each PoI owns cooperative *k*-coverage. The purpose of this paper is to deploy the least number of sensor nodes in the steady candidate locations to cover all static PoIs with the maximal collective coverage provided by the deployed sensor nodes to each PoI and the minimal aggregated distances between each PoI to the selected sensor nodes, simultaneously. The problem is presented and formulated as a multi-objective optimization model with two objectives under some constraints.

The rest of the paper is as follows. Section 2 describes the proposed problem. The mathematical formulation of the proposed problem is presented in Section 3. The developed solution procedure is discussed in Section 4. Section 5 demonstrates some numerical examples. Finally, the conclusion and extension of the paper are summarized in the last section.

2 Problem description

This section introduces the multi-objective WSN problem with cooperative sensing coverage. This problem has the following features:

- The target points and candidate sensor locations are all static on the RoI.
- All sensor nodes are homogeneous to emit/propagate their signals/coverage physically (e.g., infrared and ultrasound) or non-physically (e.g., service time) [18–20].
- The signal strength of each sensor node depends on its inner and outer sensing coverage radii. The coverage is *full* if the target node is within the inner sensing radius; *none* if the target node is outside the outer sensing radius; and *partial* if the target node is between those two radii. The sensing coverage radii of each sensor node may depend on its capacity, whether it is blocked by surrounding buildings, and so on.
- Each target point receives the combined signals/coverage from the sum of individual signals/coverage provided by each assigned sensor [18, 19].
- The purpose of this paper is to deploy the minimal number of sensor nodes in the steady candidate locations to cover all static target points. The objectives of the concerned problem are simultaneously to maximize the sum of the combined coverage of each target point provided by the assigned sensor nodes and to minimize the aggregated distances between each target point to the assigned sensor node(s).
- The problem can be presented and formulated as an MOOP with two objectives under some constraints.
- In order to simplify the problem, the costs for sensor nodes deployment are neglected in this paper.

The sensor coverage of the concerned problem has the following assumptions:

- Coverage target/subject: **point coverage**.

  The concerned problem is to deploy sensor nodes to cover target points on RoI.
- Coverage type: **full coverage**.

  All target points on RoI must be covered by the deployed sensor nodes.
- Coverage level/degree: ***k*-coverage**.

  In the concerned problem, each point has cooperative coverage, i.e., it is covered by at least *k* sensor nodes in order to achieve satisfied coverage.
- Sensing coverage: **probabilistic sensing model**.

  The sensing coverage of each sensor node is denoted by 1 if the concerned target node is within inner sensing radius, 0 if it is outside outer sensing radius, and a decreasing function of distance between 1 and 0 if it is between both radii.

Therefore, the concerned problem in this paper is defined as follows.

Definition 1 *Multi-objective WSN deployment problem with cooperative distance-based sensing coverage* is to deploy the minimal number of sensor nodes on the candidate locations to cover all target points on RoI with the objectives of simultaneously maximizing the collective coverage of each target point received from selected sensor nodes and minimizing the aggregated distances between each target point and selected sensor nodes where each target point is covered by at least *k* deployed sensor nodes. Each sensor node has its own sensing coverage (with an inner radius and an outer radius), and the provided coverage is denoted as 1 within inner sensing coverage radius, 0 outside the outer sensing coverage radius, and a function of distance decreased from 1 to 0 by the increased distance among both radii.

3 Problem formulation

In the previous section, the concerned problem is formulated as a multi-objective optimization model with two objectives and related constraints. This section presents the mathematical formulation of the problem.

Consider that two subsets *I* and *J* are the sets of target points and candidate locations of sensor nodes, respectively. Both *i* and *j* are denoted as the indices of target points and potential locations, respectively, where $i \in I$, $i = 1, 2, , |I| = n$ and $j \in J$, $j = 1, 2, , |J| = m$. The inner and outer sensing coverage radii for sensor node *j* are shown as r_j^{in} and r_j^{out}, where $0 \le r_j^{in} \le r_j^{out}$. The distance and coverage between target point *i* and sensor node *j* are d_{ij} and C_{ij}, respectively. As mentioned above, the sensing coverage of the sensing sensor node is presented as 1 within inner sensing radius, 0 outside the outer radius, and a decreasing function of distance between two radii. Let the distance decreasing function of sensing coverage for sensor node *j* to target point *i* is denoted as $f\left(d_{ij}\right)$, where 0 and $r_j^{in} < d_{ij} < r_j^{out}$. The piecewise form of C_{ij} is presented as:

$$C_{ij} = \begin{cases} 1, & \text{if} 0 \le \mathrm{d_{ij}} \le \mathrm{r_j^{in}}; \\ f\left(d_{ij}\right), & \text{if} \mathrm{r_j^{in}} < \mathrm{d_{ij}} < \mathrm{r_j^{out}}; \\ 0, & \text{if} \mathrm{d_{ij}} \ge \mathrm{r_j^{out}}. \end{cases}$$

The type of the distance decreasing function $f\left(d_{ij}\right)$ depends on the application requirement mentioned above. Furthermore, such a sensing coverage was formulated as a mathematical form by [26]. Thus, the mathematical formulation of sensing coverage C_{ij}, provided by sensing sensor node *j* to target point *i*, can be represented as:

$$C_{ij} = \min\left\{ \max\left\{ \frac{\max\left\{r_j^{in} - d_{ij}, 0\right\}}{\max\left\{r_j^{in} - d_{ij}, \epsilon\right\}}, f\left(d_{ij}\right) \right\}, \frac{\max\left\{r_j^{out} - d_{ij}, 0\right\}}{\max\left\{r_j^{out} - d_{ij}, \epsilon\right\}} \right\}$$

where ϵ is a positive small real number.

It is worth mentioned that the strength of sensing coverage depends on not only the proximity but also the feature of sensor node. It means that the coverage strength provided by the closer sensor node to the target point cannot be guaranteed to be larger than that provided by the farther one. For example, consider that there are two sensor nodes with $r_1^{in} = 15$, $r_1^{out} = 20$ and $r_2^{in} = 5$, $r_2^{out} = 15$, respectively. The distances between target point 1 and both sensor nodes are $d_{11} = 13$ and $d_{12} = 10$. Target point 1 receives the coverage from both sensor nodes are $C_{11} = 1$ and C_{12}, respectively. It is obvious that sensor node 1 provides the larger coverage to target point 1 than sensor node 2, although the distance between target point 1 to sensor node 1 is larger than that from sensor node 2.

The work in [26] introduced the multi-objective competitive location problem (MOCLP) with distance-based attractiveness, in which potential facilities are selected to cover all demand points on a plane in order to maximize the sum of coverage of each demand point and minimize the aggregated distances of each demand point to the selected facility, simultaneously. Comparing the proposed problem with the previous MOCLP, the major difference between them is that this paper additionally considers the cooperative coverage. Let $y_j = 1$ be the sensor node once deployed at the candidate location j, and $y_j = 0$ otherwise. Let $x_{ij} = 1$ be the target point i covered by sensor node deployed at location j, and $x_{ij} = 0$ otherwise. Each target point must be covered by k sensor nodes, where $k \geq 1$. Therefore, the mathematical model of the concerned problem is formulated as follows [26]:

$$\text{Max} \sum_{\mathrm{i}\in\mathrm{I}} \sum_{\mathrm{j}\in\mathrm{J}} \mathrm{C_{ij}x_{ij}} \tag{1}$$

$$\text{Min} \sum_{\mathrm{i}\in\mathrm{I}} \sum_{\mathrm{j}\in\mathrm{J}} \mathrm{d_{ij}x_{ij}} \tag{2}$$

subject to

$$\sum_{j\in J} y_j = m \tag{3}$$

$$y_j \geq x_{ij} \qquad \forall i \in I, j \in J \tag{4}$$

$$\sum_{j\in J} x_{ij} = k \tag{5}$$

$$y_j \in \{0, 1\} \qquad \forall j \in J \tag{6}$$

$$x_{ij} \in \{0, 1\} \qquad \forall i \in I, j \in J \tag{7}$$

In the above model, the first objective is to maximize the sum of the combined coverage for each target point received. The second objective is to minimize the aggregated distances between each target point to the assigned sensor nodes. Constraint (3) ensures that m sensor nodes must be deployed. Constraint (4) ensures each target point to be covered by the deployed sensor node. Constraint (5) indicates that each target point must be covered by k sensor nodes for cooperative coverage consideration. Constraints (6) and (7) enforce the decision variables to be binary.

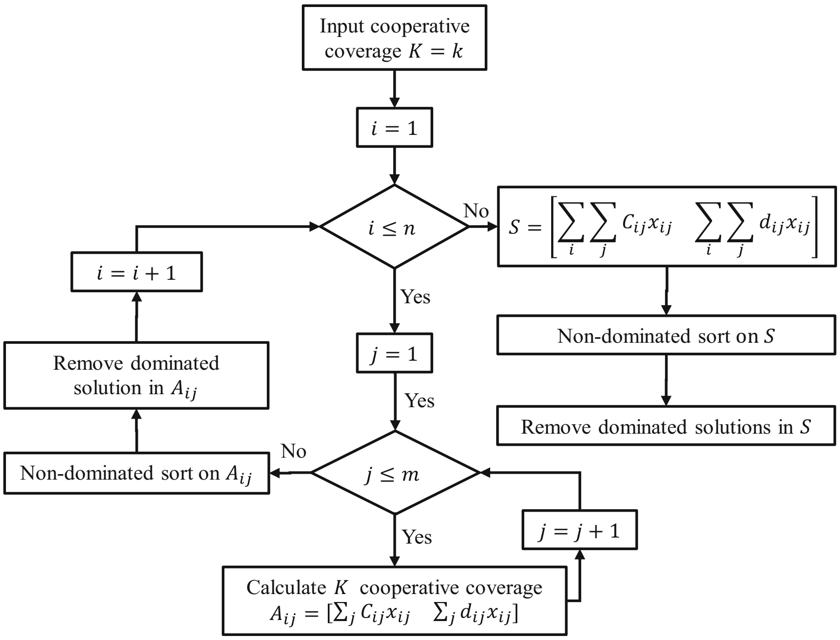
4 Solution procedure

In previous section, the proposed problem is proposed as an MOOP with two objectives that may be in conflict with each other. When simultaneously optimizing multiple objectives, there is usually no single global optimal solution; and inherently, a set of alternative solutions to satisfy the optimal conditions are expected to be obtained [24, 27]. The Pareto optimal solutions, or Pareto frontier, consist of a set of solutions which are non-dominated by each other and are not dominated by any other solutions. In addition, the propose problem considering maximizing coverage and minimizing the number of sensors installation in WSNs has been shown as an NP-hard [28] or NP-complete problem [28, 29]. The multi-objective evolutionary algorithms (MOEAs) have been developed to tackle multiple objectives simultaneously, e.g., SPEA2 [30], PESA-II [31], and NSGA- II [32]. Although the recently MOEAs can solve multi-objective WSN problems efficiently and effectively, they still consume highly computational resources, and obtain only approximately near-optimality.

The work in [26] introduced an algorithm to find the Pareto optimality of the MOCLP. The best non-dominated solution set of simultaneously maximizing the collective coverage and minimizing the aggregated distances for n demand points corresponding to m facilities can be obtained by combining all of non-dominated solutions of each demand point corresponding to m facilities. The algorithm starts to find the non-dominated solution set of each individual demand point corresponding to m facilities for two objectives. After that, non-dominated solution sets for all individuals are combined with each other to obtain all collective solutions. Finally, non-dominated-sorting all combinational solutions can reach Pareto optimality of the problem. In their work, 36 instances have been implemented to achieve each best non-dominated solution set with well performance, comparing the exhaustive search which can find best Pareto optimal solution set but usually with poor efficient ability.

The proposed problem in this paper is simultaneously to find the maximal collective coverage for all of each target point from every selected sensor node and the minimal aggregated distances between each target point and every assigned sensor node where

Fig. 2 The proposed solution procedure



the cooperative sensing coverage is considered. For the sake of computational effectiveness and efficiency, the solution procedure is introduced to find the best non-dominated solution set of the proposed problem referring to [26]. The developed algorithm is detailed as the following steps:

1) Input parameters.
2) Find the best non-dominated solution set for each target point with maximal collective coverage from selected sensor node, or sensor nodes for cooperative coverage, and the minimal aggregated distance(s) between the target point and assigned sensor node(s).
3) Combine each best non-dominated solution set corresponding to each objective for each target point.
4) Non-dominated-sort all combined pairs of solutions by maximizing the collective coverage and minimizing the aggregated distances, simultaneously.
5) The best non-dominated solution set is found by removing dominated pairs of solutions.

The above procedure is also illustrated in Fig. 2.

5 Experimental examples

The concerned problem, the corresponding formulation, and the developed solution procedure have been introduced in the former sections. In this section, some experimental examples are implemented. Before the numerical tests, the partial sensor coverage needs to be defined. Assume that the partial sensor coverage $f(d_{ij})$ follows a gradual covering with decreasing linear distance function between inner and outer sensing coverage radii. That is, the distance decreasing function of sensing coverage for sensor node j to target point i is denoted and represented as:

$$f^{GC}(d_{ij}) = \frac{r_j^{out} - d_{ij}}{r_j^{out} - r_j^{in}} \qquad (8)$$

In addition, the sensing coverage C_{ij} can be reformulated as follows [26]:

$$C_{ij}^{GC} = \frac{\max\left\{r_j^{out} - d_{ij}, 0\right\}}{\max\left\{r_j^{out} - r_j^{in}, r_j^{out} - d_{ij}, \epsilon\right\}} \qquad (9)$$

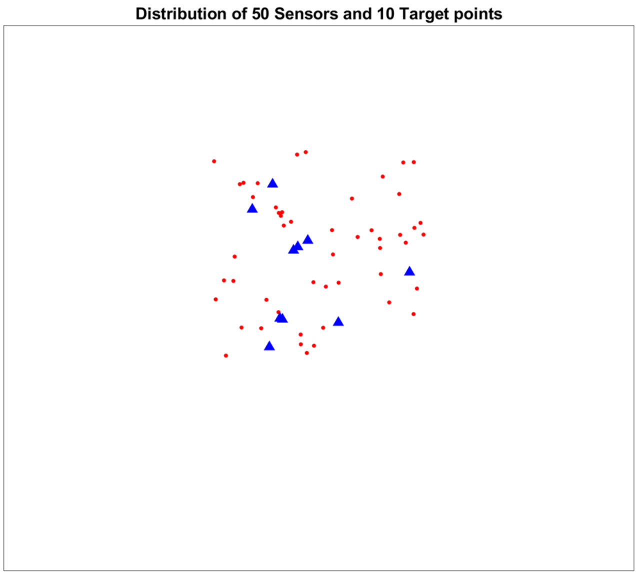
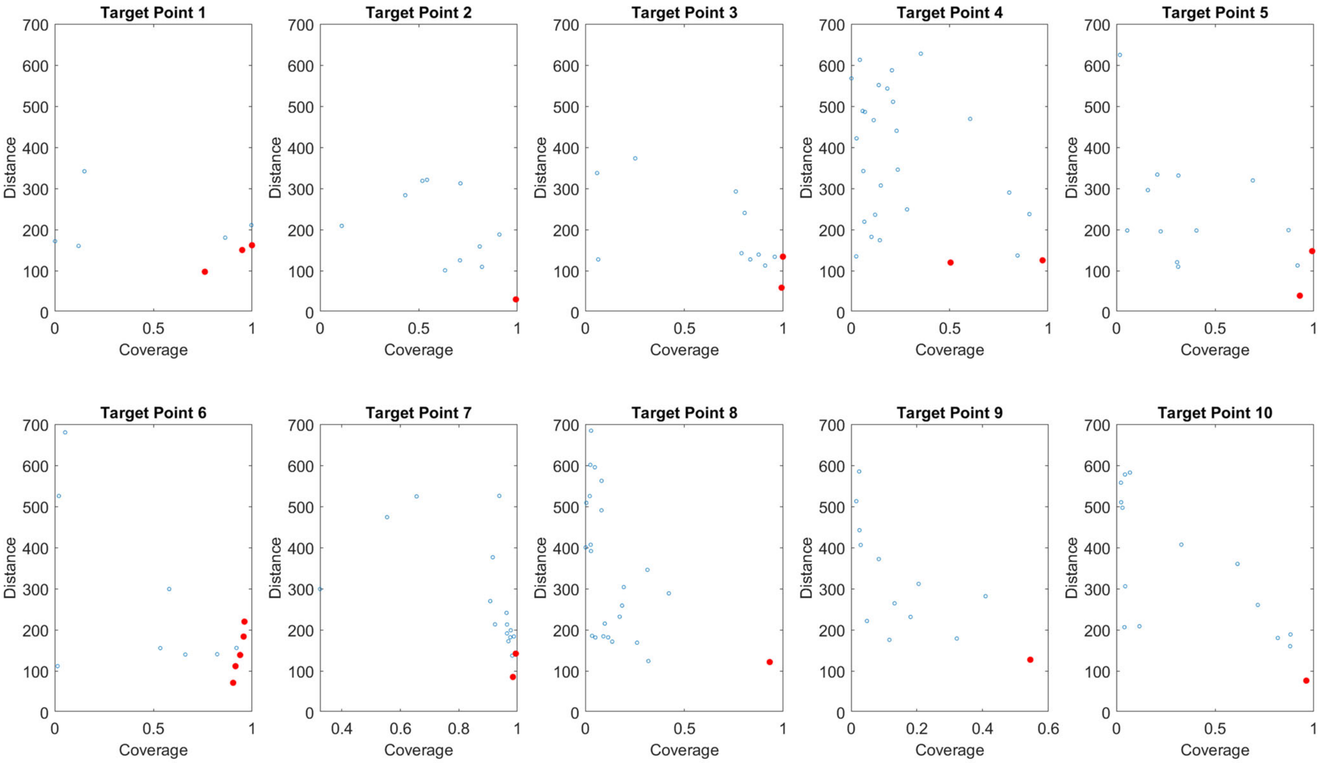
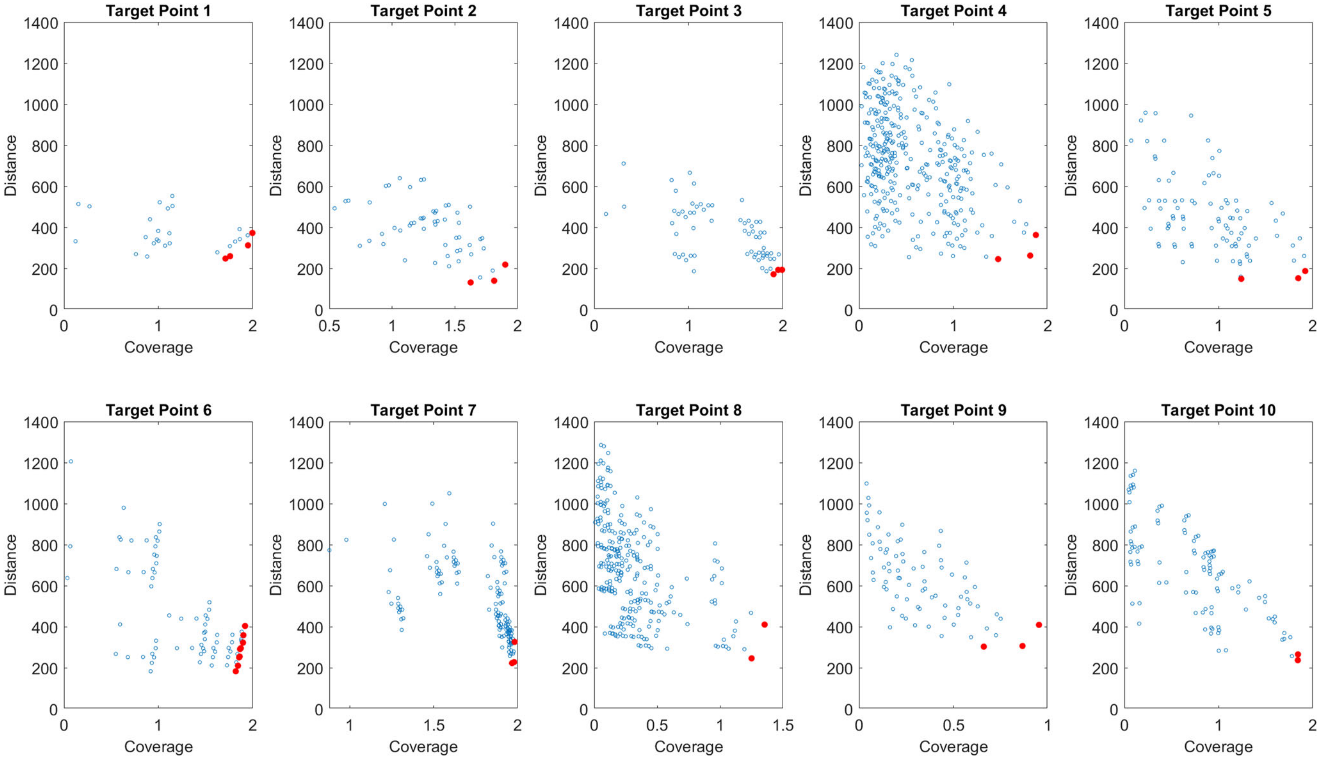


Fig. 3 The geographical distribution of 50 target points and 10 candidate sensor nodes (blue triangle: target point; red dot: candidate sensor node)

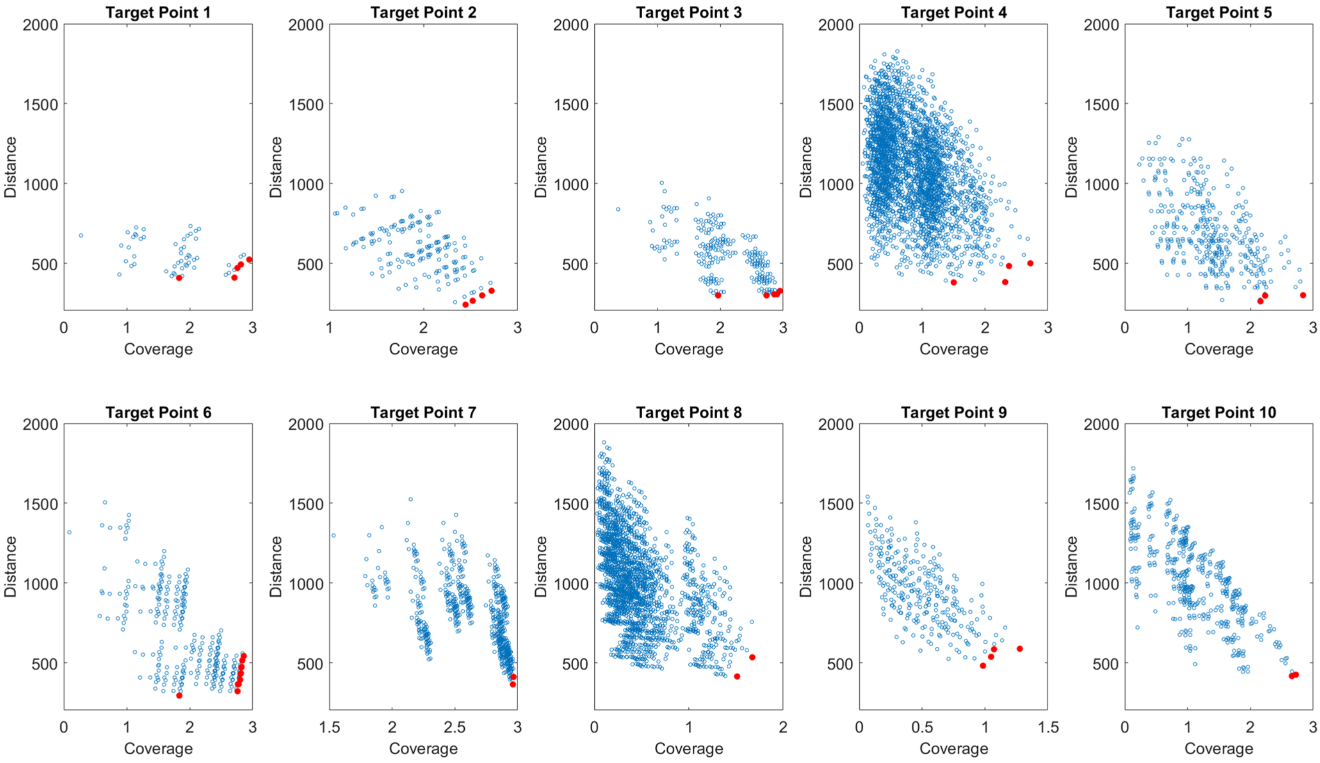


(a) $k = 1$



(b) $k = 2$

Fig. 4 Illustration of solutions for each target point (red dot: best non-dominated solutions)



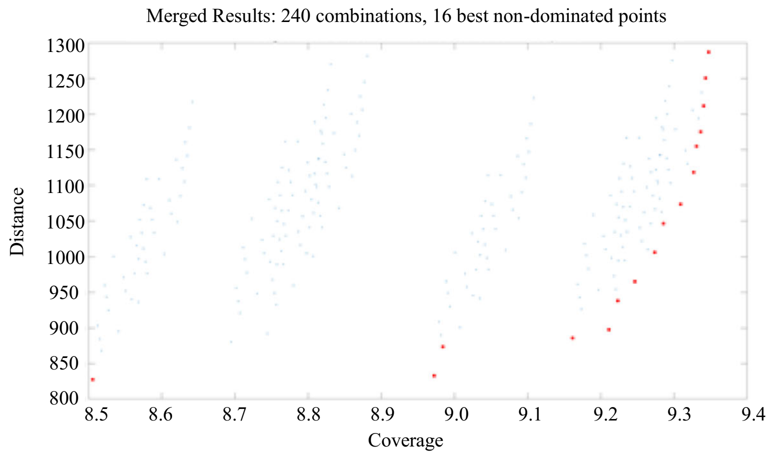
(c) $k = 3$

Fig. 4 (continued)

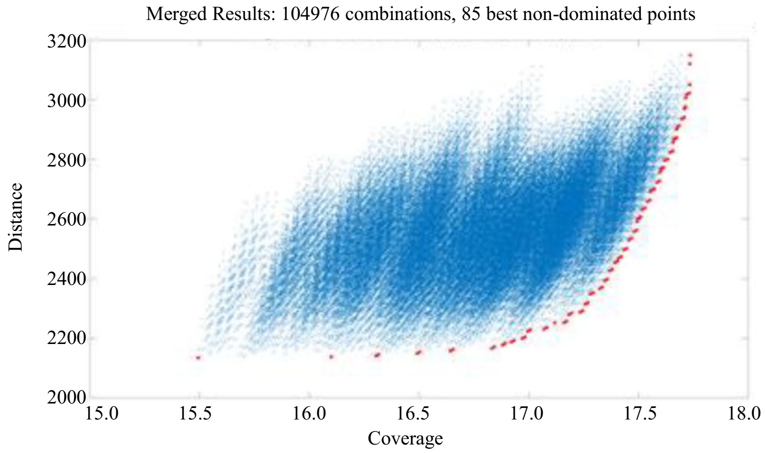
The simulated experimental instances are implemented by the developed MATLAB program on a laptop computer equipped with Intel Core i5-8250U CPU @ 1.60 GHz/ 1.80 GHz and 8.00 GB RAM. There are 10 target points and 50 candidate sensor nodes designated in the numerical tests. Figure 3 depicts the geographical distribution of all target points and candidate sensor nodes. Each candidate sensor node has its inner and outer coverage radii. Furthermore, this experiment considers the cooperative coverage in which each target point can be covered by k sensor nodes for $k = 1, 2, 3$, respectively.

Figure 4 illustrates the solutions and the best non-dominated solutions (depicted as red dots) for each of 10 target points where cooperative coverage $k = 1$ (Fig. 4a), $k = 2$ (Fig. 4b), and $k = 3$ (Fig. 4c), respectively. For example, there are three best non-dominated solutions for the target point 1 and one best non-dominated solutions for target point 2 when $k = 1$, etc. The other solution sets can be explained similarly. Figure 5 explains the merged solutions for all best non-dominated solutions of 10 target points and the corresponding best non-dominated solutions (depicted as red dots) for cooperative coverage $k = 1$ (Fig. 5a), $k = 2$ (Fig. 5b), and $k = 3$ (Fig. 5c), respectively. It also shows that the number of best non-dominated solutions is 16 in Figs. 5a and 85 in Fig. 5b, and 89 in Fig. 5c. In addition, some observations from the achieved best non-dominated solution set in Fig. 5 are as follows:

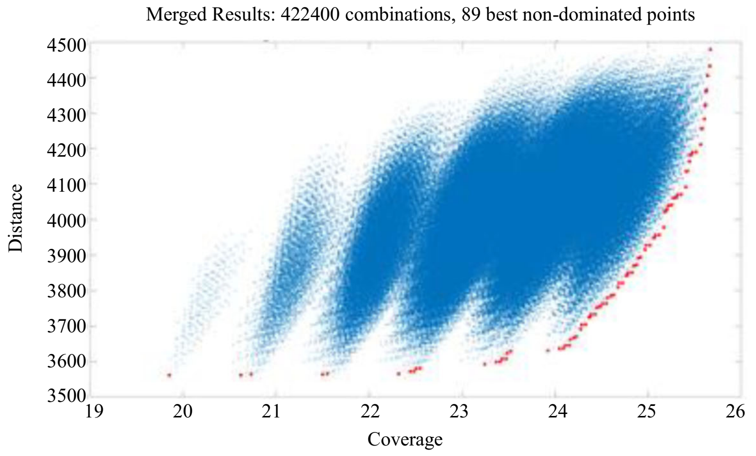
1. The bottom-left solution on the best non-dominated solution front holds the least collective sensor coverage and distances as compared to the other solutions on the front. On the contrary, the top-right solution on the best non-dominated solution front set holds the largest collective sensor coverage and distances.
2. The bottom-left solution on the best non-dominated solution front has less selected sensor nodes than the top-right solution.
3. On average, the target points are closer to the selected sensor nodes in the bottom-left solution on the best non-dominated solution front, as compared with the other solutions. The top-right solution on the best non-dominated solution front indicates that the target points are farther to the selected sensor nodes.
4. On average, the selected sensor nodes have larger inner and outer coverage radii for the top-right solution on the



(a) $k = 1$



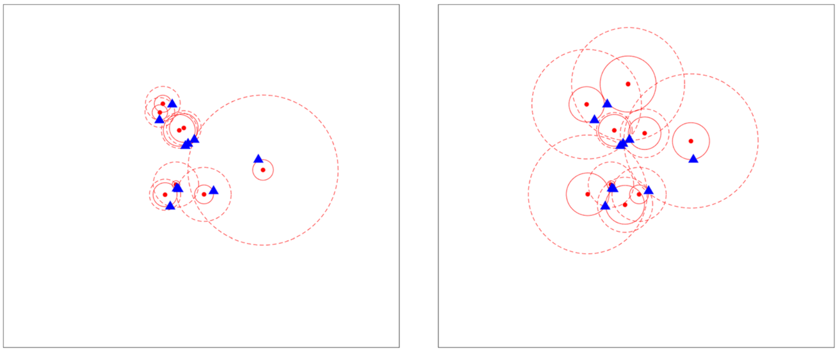
(b) $k = 2$



(c) $k = 3$

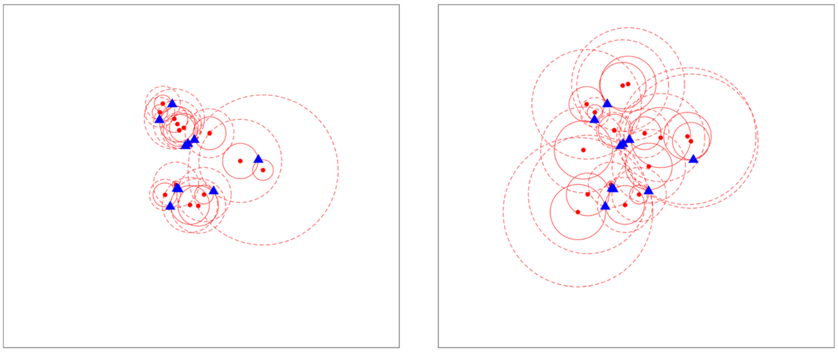
Fig. 5 Illustration of merged solutions for all target points (red dot: best non-dominated solutions). **a** $k = 1$; **b** $k = 2$; **c** $k = 3$

Fig. 6 The geographical distribution of selected sensor nodes and all target points for the bottom-left and top-right solutions on the best non-dominated solution set (Solid line: circle with inner coverage radius; Dish line: circle with outer coverage radius). **a** $k = 1$; **b** $k = 2$; **c** $k = 3$



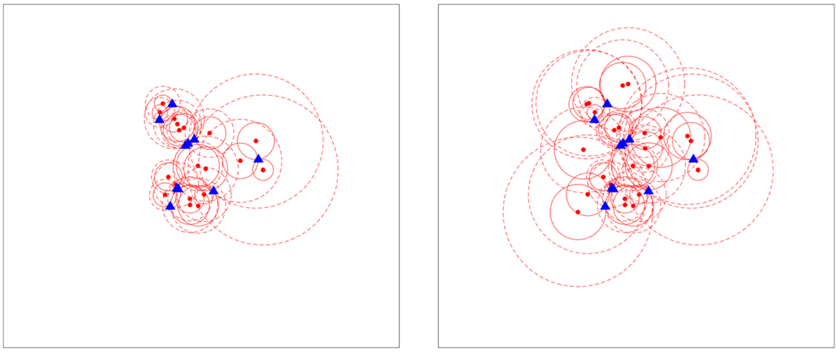
(a) Best non-dominated solution of the bottom-left point, 8 sensors (b) Best non-dominated solution of the top-right point, 9 sensors

a



(a) Best non-dominated solution of the bottom-left point, 14 sensors (b) Best non-dominated solution of the top-right point, 16 sensors

b



(a) Best non-dominated solution of the bottom-left point, 19 sensors (b) Best non-dominated solution of the top-right point, 24 sensors

c

best non-dominated solution front. The bottom-left solution on the best non-dominated solution front demonstrates that the selected sensor nodes have smaller inner and outer coverage radii.

The last three observations can be interpreted in Fig. 6. Figure 6 presents the geographical distribution of all target points and the selected sensor nodes with inner and outer coverage radii. This figure demonstrates that the sensor nodes with smaller inner and outer coverage radii which are closer to the target points tend to be selected in the bottom-left solution on the best non-dominated solution front. It also shows that there are less selected sensor nodes for the smaller collective sensor coverage and distances, as compared with the top-right solution on the best non-dominated solution front. These observations imply that the decision makers can consider other preferences in the sensor deployment issue for the provided best non-dominated solution set.

6 Conclusion

This paper has investigated the multi-objective WSN deployment problem with cooperative distance-based sensing coverage. Each candidate sensor node can provide sensing coverage based on its inner and outer coverage radii. This problem is to select a number of sensor nodes to cover all target points while simultaneously maximizing the collective coverage and minimizing the total distances between each target point and selected sensor node(s). In addition, this paper considers the cooperative sensing coverage in which each target point must be covered by *k* sensor nodes. The concerned problem is formulated as a multi-objective optimization model. The solution procedure is developed to achieve the best non-dominated solution set, referring to [26]. Some numerical experiments corresponding to cooperative sensing coverage $k = 1$ to 3 are demonstrated and illustrated.

The contribution of this paper is to introduce the sensor deployment problem considering the sensing coverage, distance, and cooperative coverage, simultaneously. The problem is formulated as a multi-objective optimization model. The sensing coverage is re-classified as coverage target/subject, coverage type, coverage level/degree, and coverage of sensing. Furthermore, the developed solution procedure referring to [26] can find the best non-dominated solution front with efficient computing time.

Some further works can be extended in the future studies. This problem should consider the cost factors such as installation, transmission costs, and so on. Various functions of partial sensing coverage can be applied in the model. In addition to the sensing coverage and distance, some other factors are encouraged to extend the proposed model. The cooperative coverage in which each target point is covered by *k* sensor nodes can be relaxed more flexibly. In addition, the proposed model can also be considered to solve complex multi-layer sensor networks.

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