Optimal Travel Route Designing in Wireless Sensor Networks with Mobile Sink

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***Abstract*—In this paper, we propose a shortest travel route planning scheme that takes into account the spatial characteristics of wireless transmissions for mobile data gathering in wireless sensor networks. We formulate the shortest travel route problem (STRP) as a covering salesman problem (CSP), which is regarded as a mixed integer nonlinear programming and also as a non-convex programming problem. To solve the STRP problem, we propose a heuristic algorithm named decomposition algorithm (DA), which decomposes the STRP problem into two subproblems: access sequence problem and position determining problem. We conduct extensive simulation to verify the effectiveness of the proposed algorithm and show that the DA algorithm can plan the shortest travel route in large scale WSNs other than small scale WSNs by the classical traveling salesman problem (TSP) algorithms.**

***Index Terms*—Travel Route Designing, Mobile Data Gathering, Mobile Sink, Wireless Sensor Networks (WSNs)**

I. Introduction

In wireless sensor networks with mobile sink (WSNs-MS), planning the optimal travel route for mobile sink (MS) is critical for many applications, such as drone patrols following a specified travel route [1]–[4]. In these application, since the sensor nodes can transmit data by minimum energy through the mechanism that the MS node accesses all sensor nodes by single hop manner, it is expected that the MS node travels on the shortest travel route to save its limited energy. Therefore, how to design a shorter travel route for the MS node becomes a critical issue. In this paper, we characterize this issue as the shortest travel route problem (STRP).

In literatures, some mobile data gathering schemes are related to the STRP problem, such as Data MULEs [5] and uncontrollable mobile sink [6]. However, those travel routes are based on random walk model, and do not consider the route length of the MS node. For controllable travel route, a wireless sensor network with mobile sink (WSN-MS) can be usually represented by a directed graph, and the STRP problem can be modeled as a traveling salesman problem (TSP). Therefore, a divide and conquer approach was proposed to find the shortest moving path of the MS node in [7]. Furthermore, a spanning tree covering algorithm was proposed to find an approximately shortest travel route in [8]. And in [9], the TSP algorithm was directly used to plan the travel route. Totally, those works require that the MS node has move close to sensor nodes to gather data. In fact, it is unnecessary because the MS node can communicate with sensor nodes when it just moves on boundary of the wireless transmission range.

In this paper, the spatial feature of wireless transmission motivates us to design a shorter travel route for the MS node. The spatial feature of wireless transmission means that the MS node just move to the boundary of the wireless transmission range of sensor nodes other than the exact position of sensor nodes, so that, the travel route of the MS node can be shorter than that by moving to the exact position of sensor nodes. We define the positions attached to sensor nodes that the MS node must traverse as anchor points. Since the anchor points represent the sensor nodes, the MS node just go through the anchor points other than the sensor nodes. Without loss of generality, we give the main assumptions include: (1) The data gathering process is divided into several data gathering cycles, and in each cycle, the MS node visits the sensor nodes one by one. (2) The spatial transmission ranges both of the sensor nodes and the MS node are disk shape. Under the assumptions, the STRP problem is formulated as a mixed integer nonlinear programming (MINLP).

The contribution of this work can be summarized as follows.

- First, we formulate the STRP problem as an MINLP problem. We prove that this problem is a non-convex problem, and also an NP-hard problem.
- Second, we proposed a decomposition algorithm (DA) to achieve the approximate shortest trave route. In the DA algorithm, the STRP problem is decomposed into two sub-problems: access sequence problem (ASP) and position determining problem (PDP). We solve them by given a certain initial solution.
- Third, we conduct extensive numerical experiments to verify the effective of the DA algorithm, from which, we get valuable results.

The rest of this paper is organized as follows. Section II summarizes related work. Section III introduces the system model and formulates the STRP problem. Section IV proposes the DA algorithm. Section V presents the experimental results and analysis. Section VI makes conclusion of this paper.

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II. Related Work

For mobile data gathering in WSNs, the travel route planning problem of mobile sink is a critical issue. In general, the travel route of mobile sink can be classified into three categories: random walk travel route, predictable travel route and controllable travel route. In [5], [14]–[16], a random walk travel route algorithm called Data MULEs was proposed. In this algorithm, sensors can exchange data with access points through mobile MULEs. In [17], Gao et al. studied a predictable travel route planing method. In the WSN-MS, sensors are deployed beside the travel route, like bus stops beside bus routes. The key problem of the method is how to cluster sensors to prolong network lifetime. In [7], Ma et al. proposed a controllable travel route planing strategy. The critical problem of the strategy is how to navigate the mobile robot, that is, how to design an optimal travel route.

Recently, the works on controllable travel route mainly focus on travel route planning for one or more MS nodes and multiple travel route planning. In terms of single MS node travel route planning, Ma et al. designed a controllable travel route by jointly considering the travel route designing of the MS node and the clustering of sensor nodes [7]. This is an NP-complete problem, and they proposed a divide and conquer approach to find the moving path. In [8], they further studied the travel route designing problem of single collector and multiple collectors.

For travel route planning for multiple MS nodes, Wang et al. proposed a heuristic algorithm called LoopGrowth to minimize the number of mobile nodes under the constraint of visiting intervals. In [18], Chin et al. studied the load balanced route planning problem to design the travel route of mobile sensors to balance the load, that is, the route lengths of all mobile sensor nodes should be equal. This is essentially a multiple traveling salesman problem (mTSP). They proposed a greedy algorithm to plan the travel route. As for multiple travel route planning, in [19], Zhu et al. studied the multi-path planning problem, where multiple paths are planned for a single MS node, and the MS node can follow them to access sensor nodes. They assumed that one path only covers part of sensor nodes, thus the key of the problem is how to design multiple paths to cover all sensor nodes.

Compared with previous works, in this paper we study the STRP problem by considering the spatial feature of wireless transmission. As stated in [20], the distance of 70m was regarded as a stable communication distance for the 2.4GHz in-field WSN applications, thus we should consider the spatial feature in travel route designing. In our work, the travel route designing problem is not a simple TSP problem, but a generalized TSP, which is called covering salesman problem (CSP).

III. System Model and Problem Statement

In this section, we introduce system model and formulate the STRP problem.

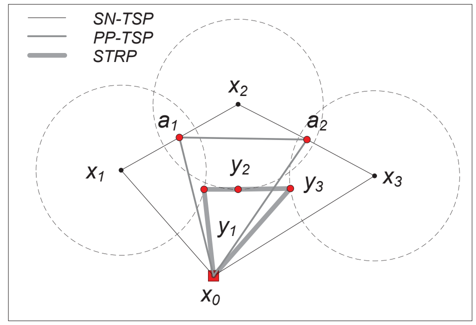

Fig. 1. Illustration of the STRP problem. The position x_0 is the original position of the MS node. The SN-TSP travel route traverses the points $\{x_1, x_2, x_3\}$, the PP-TSP travel route passes through the points $\{a_1, a_2\}$, and the STRP travel route threads the points $\{y_1, y_2, y_3\}$. The STRP travel route is the shortest one because the points $\{y_1, y_2, y_3\}$ are adjusted on the optimal positions.

A. System Model

We first give the basic assumptions as follows: (1) The WSNs is composed of only one MS node and multiple stationary sensor nodes. (2) The MS node is able to control its moving direction and speed. (3) The data gathering process is divided into several data gathering cycles, and in each cycle, the MS node visits the sensor nodes one by one. Generally, the MS node starts from the original position, visits every sensor node once, and then gets back to the original position to upload data or replenish energy. (4) The spatial transmission ranges both of the sensor nodes and the MS node are disk shape, which leads the MS node move to any position of the disk to gather data. (5) The MS node and each sensor node are equipped with only one antenna respectively, in other words, the MS node can communicate with one sensor node at a time.

Under the aforementioned assumptions, we try to find out the shortest travel route for the MS node based on the spatial transmission characteristic as illustrated in Fig. 1. In the figure, there are three travel routes: the SN-TSP travel route proposed in literature [8], the PP-TSP travel route used in literature [21], and our STRP travel route based on the spatial transmission future. In literature [8], the MS node must move across the exactly positions of sensor nodes, so the SN-TSP travel route traverses the points $\{x_1, x_2, x_3\}$, which forms the tour SN-TSP=$(x_0, x_1, x_2, x_3, x_0)$. And in literature [21], the PP-TSP travel route passes through shared data gathering points, such as $\{a_1, a_2\}$, which generates the tour PP-TSP=(x_0, a_1, a_2, x_0). In this paper, however, though the selected points $\{y_1, y_2, y_3\}$ are limited in the disk shape areas, the STRP travel route STRP=$(x_0, y_1, y_2, y_3, x_0)$ is the shortest one because the positions of the points $\{y_1, y_2, y_3\}$ are chosen optimally. From the figure, we can intuitively see that the STRP travel route is the shortest one among the three travel routes.

From the example, we can see that the travel route is made of line segments, which can be defined as a sequence of anchor points or a collection of route sections. These definitions are as follows.

Definition 1 (Anchor point): An anchor point is defined as the point that is located within the transmission range of a sensor node and must be traversed by the MS node at least once in a data gathering cycle.

Definition 2 (Route section): A route section is a line segment on the travel route whose two end-points are anchor points.

The definition of anchor point is an extension of that in literatures [22] and [23]. Different from the two literatures, in this paper, an anchor point belongs to only one sensor node, and its position is a variable whose value is no more than the transmission range of the sensor node. Route section is a line segment starting from an anchor point and ending at another anchor point. As shown in Fig. 1, y_1, y_2, and y_3 are anchor points, and x_0y_1, y_1y_2, y_2y_3, and y_3x_0 are route sections.

B. Shortest Travel Route Problem

In this subsection, we first give the definition of STRP problem, and then formulate it as a MINLP problem.

Definition 3 (STRP): Given a MS node x_0 and the set of n sensor nodes $X = \{x_1, x_2, \ldots, x_n\}$, the STRP problem is defined as finding the shortest travel route by determining the positions and access sequence of anchor points.

The position of the MS node is denoted as $\overline{x_0}$, the set of positions of n sensor nodes is denoted as $\overline{X} = \{\overline{x_1}, \overline{x_2}, \ldots, \overline{x_n}\}$, and the set of positions of n anchor points is denoted as $\overline{Y} = \{\overline{y_1}, \overline{y_2}, \ldots, \overline{y_n}\}$. We first use the collection composed of the MS node and n anchor points to construct a complete directed graph $G = (A, E)$, where A is the set of vertexes that represent the collection of the MS node and n anchor points, i.e., $A = \{x_0(y_0), y_1, y_2, \ldots, y_n\}$, E is a $(n+1)\times(n+1)$ matrix whose elements represent the edges between two vertexes. And then, we formulate the STRP problem as follows.

$$\min f(\overline{Y}, C) = \sum_{i=0}^{n}\sum_{j=0}^{n} c_{ij}\|\overline{y_i} - \overline{y_j}\| \quad (1)$$

$$s.t.$$

$$\|\overline{y_i} - \overline{x_i}\| \le r, (i = 1, 2, \ldots, n) \quad (2)$$

$$\sum_{i=0}^{n} c_{ij} = 1, (j = 0, 1, \ldots, n) \quad (3)$$

$$\sum_{j=0}^{n} c_{ij} = 1, (i = 0, 1, \ldots, n) \quad (4)$$

$$c_{ij}(u_i - u_j) = c_{ij}, (i, j = 0, 1, \ldots, n-1) \quad (5)$$

$$\overline{y_i} \in [0, L] \times [0, H] \quad (6)$$

$$c_{ij} \in \{0, 1\}, (i, j = 0, 1, \ldots, n) \quad (7)$$

$$u_i, u_j \in R, (i, j = 0, 1, \ldots, n) \quad (8)$$

where $\overline{Y}$ and C are variables, r is the maximum transmission radius of sensor nodes, u_i and u_j are auxiliary variables, and R denotes the real number field. The variable $\overline{Y}$ is a vector whose elements denote the positions of vertexes in A. The variable C is a vector that is denoted by a $(n+1)\times(n+1)$ binary matrix. The elements of matrix C denote whether the edges in matrix E are selected as route sections. If the edge (y_i, y_j) is selected as a route section, then $c_{ij} = 1$, otherwise, $c_{ij} = 0$. The constraints can be explained as follows.

- The Eq. (1) is the objective function that minimize the length of the travel route.
- Constraint Eq. (2) indicates that the anchor point must be located within the transmission range of corresponding sensor node.
- Constraint Eq. (3) denotes that each anchor point has one and only one leaving edge.
- Constraint Eq. (4) represents that each anchor point has one and only one entering edge.
- Constraint Eq. (5) avoids sub-tours. If there are sub-tours, the Eq. (5) has no solutions.
- Constraint Eq. (6) denotes that the domain of elements in $\overline{Y}$ is restricted in a rectangle area.

From the formulation, we can see that the STRP problem is an MINLP problem. we derive some properties as follows.

Lemma 1 (Non-Convexity of the Objective Function): The objective function (1) is a non-convex function.

Proof: We first construct a function $g(c_{ij}, \overline{y_i}, \overline{y_j}) = c_{ij}\|\overline{y_i} - \overline{y_j}\|$, and then show that the function is a non-convex function. We let

$$\begin{aligned}
g_1 &= g(\lambda c_{ij}^1 + (1-\lambda)c_{ij}^2, \lambda\overline{y_i^1} + (1-\lambda)\overline{y_i^2}, \lambda\overline{y_j^1} + (1-\lambda)\overline{y_j^2}) \\
&= (\lambda c_{ij}^1 + (1-\lambda)c_{ij}^2)\|\lambda\overline{y_i^1} + (1-\lambda)\overline{y_i^2} - \lambda\overline{y_j^1} - (1-\lambda)\overline{y_j^2}\| \\
&= (\lambda c_{ij}^1 + (1-\lambda)c_{ij}^2)\|\lambda(\overline{y_i^1} - \overline{y_j^1}) + (1-\lambda)(\overline{y_i^2} - \overline{y_j^2})\| \\
g_2 &= \lambda g(c_{ij}^1, \overline{y_i^1}, \overline{y_j^1}) = \lambda c_{ij}^1\|\overline{y_i^1} - \overline{y_j^1}\| \\
g_3 &= (1-\lambda)g(c_{ij}^2, \overline{y_i^2}, \overline{y_j^2}) = (1-\lambda)c_{ij}^2\|\overline{y_i^2} - \overline{y_j^2}\|
\end{aligned}$$

Note that $c_{ij} \in \{0, 1\}$ and $\lambda \in (0, 1)$. We have the following inequality:

$$g_1 \le (\lambda c_{ij}^1 + (1-\lambda)c_{ij}^2)(\lambda\|(\overline{y_i^1} - \overline{y_j^1})\| + (1-\lambda)\|(\overline{y_i^2} - \overline{y_j^2})\|)$$

Furthermore, we can obtain the following result:

$$\begin{aligned}
&g_1 \le g_2 + g_3, if(c_{ij}^1 = 1, c_{ij}^2 = 1) \\
&g_1 = g_2 = g_3 = 0, if(c_{ij}^1 = 0, c_{ij}^2 = 0)
\end{aligned}$$

However, if $(c_{ij}^1 = 1, c_{ij}^2 = 0)$ or $(c_{ij}^1 = 0, c_{ij}^2 = 1)$, the relationship between g_1 and $g_2 + g_3$ cannot be determined, which implies that g is a non-convex function. Furthermore, it is not difficult to obtain that the object function is a non-convex function. ■

We can observe from Lemma 1 that the STRP problem is a non-convex minimization problem. In the following, we prove the hardness of solving the STRP problem.

Theorem 1 (NP-complete of the STRP Problem): The STRP problem is an NP-complete problem.

Proof: We know that the object function (1) is non-convex, which implies that the STRP problem is an NP-hard problem [24]. All TSP problem can be deduced as a STRP problem when $r = 0$ in Eq. (2). Since the TSP problem is an NP-complete problem, the STRP problem is an NP-complete problem. ■

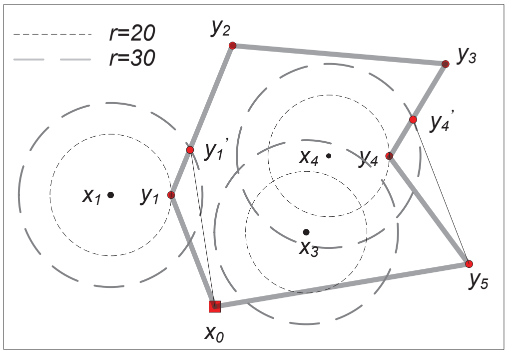

Fig. 2. Illustration of radius and route length.

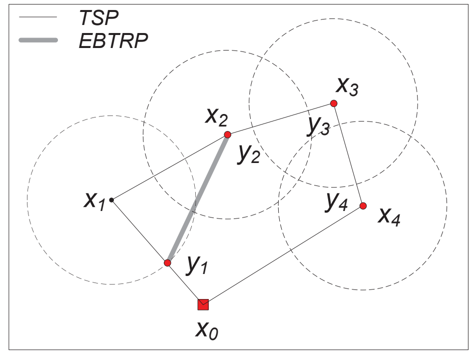

Fig. 3. Illustration of longest travel route.

Theorem 2 (Variable Radius Principle): In the STRP problem, if transmission radius r becomes larger, then the shortest travel route becomes shorter.

Proof: The travel route of the MS node may be two overlapped line segments or the border of a closed polygon. If the travel route is two overlapped line segments, we can shorten the travel route by moving the endpoints of line segments to the MS node as the transmission radius is enlarged. If it is the border of a closed polygon, we can shorten the travel route by moving the vertexes of the closed polygon to the border of the transmission radius as it increases. As shown in Fig. 2, we assume that the border of the polygon $x_0 - y_1 - y_2 - y_3 - y_4 - y_5 - x_0$ is a travel route in the WSN-MS when the transmission radius $r = 20$. If the transmission radius is increased to 30, i.e., $r = 30$, we can construct a shorter travel route by moving anchor point y_1 to $y_1^{'}$. In addition, we can also construct another shorter travel route by moving anchor point y_4 to $y_4^{'}$. Therefore, in the STRP problem, as the transmission radius increases, the shortest route length becomes shorter. ■

According to the result of Theorem 2, we can derive two corollaries about the longest travel route and the shortest travel route.

Corollary 1 (Longest Travel Route): In the STRP problem, if the transmission radius equals to zero, i.e., $r = 0$, then the travel route is the longest.

Proof: The basic idea of the proof is that we can construct a shorter travel route by putting an anchor point near the MS node at the border of transmission disk. As shown in Fig. 3, we assume that the travel route $x_0 - x_1 - x_2 - x_3 - x_4 - x_0$ is a TSP travel route when $r = 0$. If the transmission radius satisfies the condition $r > 0$, we can set the anchor point of the sensor node x_1 at the transmission border, i.e., the position of the anchor point y_1, and other anchor points remain on the positions of sensor nodes, i.e., $\overline{y_2} = \overline{x_2}, \overline{y_3} = \overline{x_3}, \overline{y_4} = \overline{x_4}$. Then, we can observe that the travel route $x_0 - y_1 - y_2 - y_3 - y_4 - x_0$ is shorter than the travel route $x_0 - x_1 - x_2 - x_3 - x_4 - x_0$. Therefore, we are always able to construct a shorter travel route when $r > 0$, which implies that the TSP travel route when $r = 0$ is the longest travel route. ■

Similarly, we can have the result about the shortest travel route.

Corollary 2 (Shortest Travel Route): In the STRP problem, if the transmission radius equals to the maximum distance between the sensor nodes and the MS node, the travel route is the shortest, i.e., equals to zero.

According to Corollary 2, we give the maximum distance between the sensor nodes and the MS node, $\overline{r}$, by

$$\overline{r} = max\{\|x_i - x_0\|\}, (i = 1, 2, \ldots, n) \tag{9}$$

IV. Solutions

Since the STRP problem is an NP-complete problem, it is hard to achieve exact solution when there are amounts of sensor nodes in the WSNs. Therefore, we proposed the DA algorithm to achieve the approximate solution.

The DA algorithm is motivated by the fact that the constraints of the variable $\overline{Y}$ and the variable C are independent, that is, $\overline{Y}$ is only constrained by Eq. (2), and the variable C is only constrained by Eqs. (3)-(5), which means that the nonlinear constraint (2) and the integer linear constraints (3) - (6) are independent. So, we decompose the STRP problem into two sub-problems: the ASP problem and the PDP problem. In the ASP problem, the nonlinear constraint (2) is replaced by a solution $\overline{Y^\sharp}$, and in the PDP problem, the integer linear constrains are replaced by a solution $C^\sharp$. The ASP problem and the PDP problem can be formulated as follows, respectively.

$$ASP: \ \min f(\overline{Y^\sharp}, C) = \sum_{i=0}^{n}\sum_{j=0}^{n} c_{ij}\|\overline{y_i^\sharp} - \overline{y_j^\sharp}\| \tag{10}$$

$s.t.$

$$\sum_{i=0}^{n} c_{ij} = 1, (j = 0, 1, \ldots, n) \tag{11}$$

$$\sum_{j=0}^{n} c_{ij} = 1, (i = 0, 1, \ldots, n) \tag{12}$$

$$c_{ij}(u_i - u_j) = c_{ij}, (i, j = 0, 1, \ldots, n-1) \tag{13}$$

$$c_{ij} \in \{0, 1\}, (i, j = 0, 1, \ldots, n) \tag{14}$$

$$u_i, u_j \in R, (i, j = 0, 1, \ldots, n) \tag{15}$$

where $\overline{Y^\sharp}$ satisfies the constraint (2). We can observe from Eqs. (10) - (15) that the ASP problem is an integer linear programming problem (ILP) as well as a classical TSP problem.

$$PDP: \ \min f(\overline{Y}, C^\sharp) = \sum_{i=0}^{n}\sum_{j=0}^{n} c_{ij}^\sharp \|\overline{y_i} - \overline{y_j}\| \tag{16}$$

$$s.t.$$

$$\|\overline{y_i} - \overline{x_i}\| \le r, (i = 1, 2, \ldots, n) \tag{17}$$

$$\overline{y_i} \in [0, L] \times [0, H] \tag{18}$$

where $C^\sharp$ satisfies the constraints Eqs. (3) - (5). It is not difficult to observe from Eqs. (17) - (18) that the PDP problem is a convex nonlinear programming problem (NLP).

The process of the DA algorithm is presented in Algorithm 1, which includes the following steps: setting a certain initial solution $\overline{Y^\sharp}$ by manual, solving the ASP problem with $\overline{Y^\sharp}$ and achieving $C^\sharp$ in line 1, and solving the PDP problem with $C^\sharp$ and achieving the final results in lines 2-3.

Algorithm 1 Decomposition Algorithm (DA)

Input:

$\overline{X}$: the positions of the sensor nodes.
r: the disk communication radius.
$\overline{Y^\sharp}$: a seed solution defined by manual.
ILP_{asp}: an integer linear solver for Eqs. (10)-(15).
NLP_{pdp}: a nonlinear solver for Eqs. (16)-(18).

Output:

f^*: the programmed length of travel route.
$\overline{Y^*}$: the programmed position of anchor points.
C^*: the programmed selected tour sections.

1: $C^\sharp \leftarrow ILP_{asp}(\overline{Y^\sharp}, C_0)$
2: $[f^*, \overline{Y^*}] \leftarrow NLP_{pdp}(\overline{Y_0}, C^\sharp)$
3: $C^* \leftarrow C^\sharp$
4: **return** $[f^*, \overline{Y^*}, C^*]$

The time complexity of the DA algorithm is mainly determined by the solver NLP_{pdp} and the solver ILP_{asp}. Generally, the solver NLP_{pdp} is a typical convex nonlinear programming solver, such as the solver of gradient descent method, the solver of Newton's method, and the solver of interior point method, and so on. The time complexity of the solver NLP_{pdp} is usually directly determined by the method, the precision and the number of iterations. However, the ASP problem is a classical TSP problem, which is difficult to solve in polynomial time. To accelerate its solver ILP_{asp}, we further decompose the ASP problem as a flow conservation problem (FCP), which is formulated as

$$FCP: \ \min f(\overline{Y^\sharp}, C) = \sum_{i=0}^{n}\sum_{j=0}^{n} c_{ij} \|\overline{y_i^\sharp} - \overline{y_j^\sharp}\| \tag{19}$$

$$s.t.$$

$$\sum_{i=0}^{n} c_{ij} = 1, (j = 0, 1, \ldots, n) \tag{20}$$

$$\sum_{j=0}^{n} c_{ij} = 1, (i = 0, 1, \ldots, n) \tag{21}$$

$$c_{ij} \in \{0, 1\}, (i, j = 0, 1, \ldots, n) \tag{22}$$

where the FCP problem is that the ASP problem deletes the constraint Eq. (13).

However, the FCP problem may exist sub-tours. To avoid the sub-tours, we iteratively use the sub-tour constraint Eq. (13) (STC). The core idea of the STC constraint is to check whether the obtained travel route contains the sub-tour route, in other words, whether the constraint Eq. (13) is satisfied. If yes, the sub-tour route cannot be added into the travel route list. The integer linear programming algorithm for ASP is shown in Algorithm 2.

Algorithm 2 Integer Linear Programming for ASP (ILP_{asp})

Input:

$\overline{Y^\sharp}$: a seed solution from the DA algorithm.
ILP_{fcp}: an integer linear solver for Eqs. (19)-(22).
$CheckTour$: checks sub-tours and generates the number of sub-tours k and the set of sub-tours ST.

Output:

C^*: the obtained access sequence.

$STC \leftarrow \emptyset$, $k \leftarrow 0$
while $k \neq 1$ **do**
  $C^* \leftarrow ILP_{fcp}(\overline{Y^\sharp}, C_0)$
  $[k, ST] \leftarrow CheckTour(C^*)$
  $ILP_{fcp}(\overline{Y^\sharp}, C_0) \leftarrow ST$
end while
return C^*

V. Numerical Results

In this section, we provide numerical results to verify the performance of the DA algorithm. We first give the metrics of performance evaluation and the parameter settings, and then give the experiment results.

A. Metrics and Settings

In the experiments, we mainly consider the route length and the transmission radius as metrics for algorithm verification and performance analysis, which are defined as follows.

- Route length(RL): Given $\overline{Y}$ and C, the metric RL is defined as

$$RL = \sum_{i=0}^{n}\sum_{j=0}^{n} c_{ij} \|\overline{y_i} - \overline{y_j}\|$$

TABLE I
DEFAULT SIMULATION PARAMETERS

Parameter	Value	Comments
Ω_1	$L: 200, H: 200, n < 10$	Small plane.
Ω_2	$L: 1000, H: 1000, n < 100$	Large plane.
r_{max}	70m	Maximum transmission radius.

- Transmission radius (TR): We consider the WSNs whose sensor nodes have the same transmission radius, i.e., $r = r_{max}$.

The parameters of the numerical simulation are shown in Table I, where we give two application scenarios: one is a small plane with a few sensor nodes, and the other is a large plane with more sensor nodes.

B. Experiment Results

In the experiments, we first randomly make a WSN-MS with almost 100 sensor nodes on the large plane Ω_2, and then program two travel routes through the DA algorithm and a classical TSP algorithm to verify the effectiveness of the DA algorithm, where the results are shown in Fig. 4. We then randomly create a WSN-MS with almost 10 sensor nodes on the small plane Ω_1, and program several travel routes by changing the transmission radius to show the relationship between the metric of transmission radius and the metric of travel route, where the results are shown in Fig. 5 and Fig. 6.

The travel routes that are programmed by the DA algorithm and the classical TSP algorithm mentioned in the literature [8] are shown in Fig. 4. In the figure, the length of the travel route programmed the DA algorithm is 4842m, and that programmed by the TSP algorithm is 7999.5m, respectively. From this experiment, we can see that the length of the travel route programmed by the TSP algorithm is longer than that programmed by the DA algorithm, which verifies Corollary 1 that the travel route is the longest one when the transmission radius equals to zero, in other words, the travel route of the MS node can be shorter by considering the spatial transmission range.

There are 4 travel routes programmed by the DA algorithm when the transmission radius changes, which is shown in Fig. 5. In the figure, the radii are 0m, 30m, 60m, and 90m, and the route lengthes are 627m, 431m, 319m, and 216m, respectively. From the figure, we can see that the length of travel route is related to the transmission radius. Specifically speaking, larger transmission radius makes the travel route shorter, and further more, if the radius varies from 0 to r_{max}, the length of travel route will vary from RL_{tsp} to 0. Fig. 6 further verifies the relationship. From the figure, we can observe that the relationship between the transmission radius and the route length is approximately linear, i.e., $RL \approx \overline{RL} - \alpha r, (r \in [0, \overline{r}])$. The observation is consistent with the principle in Theorem 2.

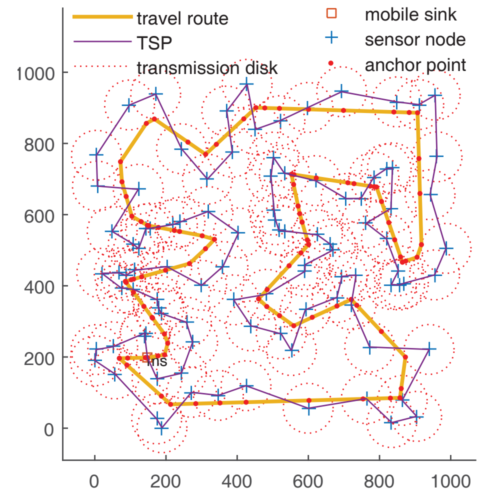

Fig. 4. The travel routes programmed by the DA algorithm and the TSP algorithm, respectively. The WSN-MS is with 99 sensors and one mobile sink on the large plane Ω_2. The length of the travel route programmed the DA algorithm is 4842m, and that programmed by the TSP algorithm is 7999.5m, respectively.

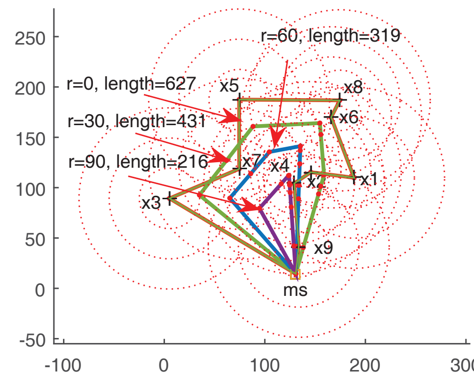

Fig. 5. The travel routes programmed by DA algorithm when the transmission radius changing. The WSN-MS is with 9 sensors and 1 mobile sink on the small plane Ω_1. The radii are 0m, 30m, 60m, and 90m, and the length of the corresponding routes is 627m, 431m, 319m, and 216m, respectively.

VI. CONCLUSIONS

In this paper, we study the shortest travel route problem (STRP) in wireless sensor networks with mobile sink. We formulate the STRP problem as a mixed integer nonlinear programming problem. We prove that this problem is a non-convex and NP-complete problem. To solve the problem, we propose a heuristic algorithm named decomposition algorithm (DA). The DA algorithm decomposes the STRP problem into two sub-problems, i.e., access sequence problem (ASP) and position determining problem (PDP), and solve them independently. In the experiments, we verify the effectiveness of the DA algorithm by test the metric of route length and the metric of transmission radius. From the experiments, we can see that the DA algorithm can achieve shorter travel route than the classical TSP algorithm does, so it can be applied in large scale STRP problem.

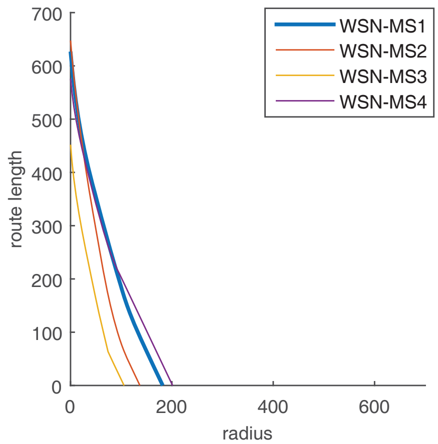

Fig. 6. The relationship between the route length and the transmission radius in 4 different WSNs-MS with 9 sensors node and 1 mobile sink on the small plane Ω_1. Among the 4 WSNs-MS, the network WSN-MS1 is the network shown in Fig. 5.

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