Delivery Latency Minimization in Wireless Sensor Networks with Mobile Sink

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***Abstract*—Adopting mobile data gathering in wireless sensor networks (WSNs) can reduce the energy consumption on data forwarding thus achieve more uniform energy consumption among sensor nodes. However, the data delivery latency inevitable increases in mobile data gathering due to the travel of the mobile sink. In this paper, we consider a delivery latency minimization problem (DLMP) in a randomly deployed WSN. To solve this problem, we first select the traversed anchor points on the border of the communication range of sensor nodes to shorten the travel route, and then let the mobile sink move and collect data at the same time to reduce the travel time. In addition, we also employ the time division approach to traverse the sensor nodes whose signals cover the same travel segments. We formulate the DLMP as an integer programming problem which subjects to the direct access constraint, the data transmission constraint and the route traverse constraint. We prove that the DLMP is an NP-Complete (NPC) problem. To solve the NPC problem, we propose a substitution heuristic algorithm, a traveling salesman problem (TSP) heuristic algorithm and a random heuristic algorithm. We conduct extensive simulations to evaluate the performance of the proposed algorithms, and the results show that all the three algorithms can shorten the data delivery latency in mobile data gathering, with the substitution heuristic algorithm being the most effective one.**

***Index Terms*—Wireless sensor networks, mobile sink, delivery latency minimization, substitution heuristic algorithm.**

I. Introduction

A wireless sensor network with mobile sink (WSN-MS) provides an effective method to collect data, where one or more mobile sinks take responsibility of forwarding data from sensor nodes to the base station while sensor nodes are responsible for sensing, computing and forwarding data to mobile sinks [1]–[8]. In the traditional static wireless sensor networks (WSNs), the relaying forward often causes hot spot problem [9]–[11], that is, sensor nodes close to the sinks deplete their energy quickly. On the contrary, in a WSN-MS, although sensor nodes are still stationary, mobile sinks can access sensor nodes by moving around them so that data from sensor nodes can be transmitted to the sinks directly or through less relaying, thus sensor nodes can save more energy and achieve long lifetime. Moreover, mobile sinks can also access the disconnected WSNs. However, WSNs-MS still have a crucial problem that the delivery latency may be too long for some applications due to the traveling of mobile sinks [5].

In a WSN-MS, the delivery latency is defined as the time that mobile sinks traverse the sensing range of sensor nodes [6], [9], [12]. The dominate reason which leads to long delivery latency is the movement of mobile sinks. There are many challenges to minimize the delivery latency in WSNs-MS. First, the number of candidate turning positions for mobile sinks is infinite and nondeterministic, and it is hard to decide which one is the best. In [6], the selection of polling points is proved to be a NP-hard problem, and the polling points are selected by achieving the maximum compatible pairs among sensor nodes. For simplicity, most of other works [13]–[17] make assumption that the candidate positions are given. Second, the travel route is hard to program for the circular travel route of the mobile sink which is regard as a traveling salesman problem (TSP). This problem is also an NPC problem. For simplicity, some works design the movement of entities as random walk, such as [18], some works use predefined trajectory, such as [19]–[21], and even some works neglect the moving time and moving path, such as [14], [22].

In this paper, we aim to minimize the data delivery latency in WSNs-MS composed of one mobile sink and some stationary sensor nodes which are randomly deployed on a plane. We assume that the positions of both the mobile sink and sensor nodes are known in advance. The mobile sink visits sensor nodes directly, in other words, the mobile sink must lie in the communication range of sensor nodes to collect data. Our main idea is that the mobile sink traverses sensor nodes in the network and simultaneously collects their data to minimize the delivery latency. In a data collection cycle, the mobile sink departs from the origin position, traverses every sensor node and goes back to the origin position.

The contribution of this work can be summarized as follows. First, we formulate the delivery latency minimization problem (DLMP) as an integer programming. Second, we further prove that the DLMP is an NP-

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complete problem, and show that the anchor points should be located at the border of communication range of sensor nodes such that the length of travel route would be short. Third, we propose a substitution heuristic algorithm to plan the travel route of the mobile sink by point substitution and line substitution and minimize the delivery latency by a relaxed linear programming. Finally, our extensive simulations validate the effectiveness of the proposed heuristic algorithm in terms of shortening route length and reducing delivery latency by comparing with a TSP heuristic algorithm and a random heuristic algorithm.

II. RELATED WORK

In recent years, several implementation techniques and network architectures of WSNs-MS have been proposed, which show that WSNs-MS are an effective approach for data gathering. In [21], Vlajic and Stevanovic simulated that the idealistic (zero-overhead) WSNs-MS can distribute routing load and prolong network lifetime. In [5], Ma and Yang utilized a mobile data collector, SenCar, to periodically traverse sensor nodes and collect data by clustering the sensor nodes via multi-hop routing. In [8], they further proposed a data gathering algorithm to minimize the length of each data gathering tour with multiple collectors.

In the meanwhile, minimizing data gathering time in WSNs-MS has also been studied. Zhao et al. [6] adopt the mobility and space-division multiple access technique to minimize the total data gathering time in the WSN with single or multiple mobile sinks, which is mostly related to our work. In [6], multiple antennas are equipped on each mobile sink so that distinct compatible sensor nodes may upload data concurrently, and the data gathering time problem is formulated as a problem of finding compatible pairs among sensor nodes. In contrast, we consider the scenario that the mobile sink traverses sensor nodes and at the same time gathers their data in a ubiquitous WSN-MS in which the mobile sink is only equipped with one antenna.

III. SYSTEM MODEL AND PROBLEM STATEMENT

A. System Model

In this paper, we consider a WSN-MS with a single mobile sink which is deployed on a plane randomly. Fig. 1 gives an example of the WSN-MS. The notations that are used in the rest of the paper are summarized in Table I. In the following, we give a theorem to describe the distribution of anchor points on the shortest travel route.

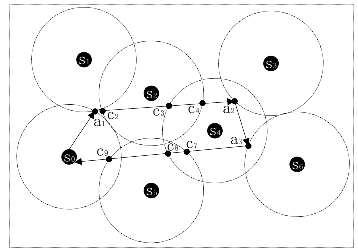

Fig. 1. An example of the system model. A mobile sink s_0 and six sensor nodes $S = \{s_1, s_2, s_3, s_4, s_5, s_6\}$ are deployed on a plane randomly. The set of anchor points $A = \{a_1, a_2, a_3\}$. The travel route $\rho = (s_0, a_1, a_2, a_3, s_0)$. The set of crossover points $C = \{a_1(c_1), c_2, c_3, c_4, a_2(c_5),\ a_3(c_6), c_7, c_8, c_9\}$. The set of travel segments $T = \{l(p(s_0), p(c_1)), l(p(c_1), p(c_2)), \ldots, l(p(c_8), p(c_9)), l(p(c_9), p(s_0))\}$.

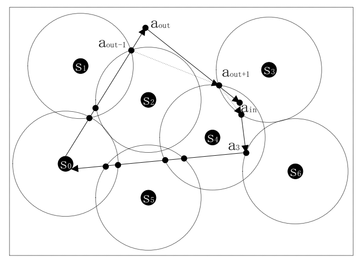

Fig. 2. An illustration of the anchor points on shortest route. For $l(p(a_{out-1}), p(a_{out+1})) < l(p(a_{out-1}), p(a_{out})) + l(p(a_{out}), p(a_{out+1}))$, anchor point a_{out} makes the travel route longer. Similarly, anchor point a_{in} also makes the travel longer.

Theorem 1 (Anchor Points on Shortest Travel Route): If a travel route is the shortest, its anchor points must be at the border of communication range of sensor nodes.

Proof: The proof can be derived from Fig. 2 and is omitted due to limited space. ■

B. Problem Formulation

Definition 1 (Delivery Latency): The deliver latency is defined as the sum of the time the mobile sink stays on crossover points, the time it travels on the uncovered travel segments and the time it travels on the covered travel segments in a data collection cycle, which can be expressed by

$$L(A, \rho) = L^{cp}(A, \rho) + L^{tsu}(A, \rho) + L^{tsc}(A, \rho) \quad (1)$$

Definition 2 (Delivery Latency Minimization Problem): In a WSN-MS, given mobile sink s_0 and a set of sensor nodes S which are deployed on a plane Ω, the DLMP problem we consider is to minimize the delivery latency $L(A, \rho)$ by selecting proper set of anchor points A and planing better travel route ρ, so as to easily derive crossover points C, travel segments T, matrix $R^{cp}_{n\times m}$, matrix $R^{ts}_{n\times p}$, and matrix $R^{tsc}_{n\times p}$. That is,

$$Minimize\ \ L(A, \rho) = [\sum_{i=1}^{n}(\tau(s_i) \cdot \overline{\delta}(\alpha(R^{ts}_{n\times p}, i))) + \sum_{j=1}^{p}(\frac{d(t_j)}{v_{max}} \cdot \overline{\delta}(\beta(R^{ts}_{n\times p}, j))) + \sum_{i=1}^{n}\sum_{j=1}^{p}(r^{tsc}_{ij})] \quad (2)$$

TABLE I
LIST OF NOTATIONS

Notation	Definition
Ω	Plane deployed a WSN-MS.
s_0	Origin position of the mobile sink.
v_{max}	Maximization speed of the mobile sink.
S	Set of sensor nodes, $S = \{s_1, s_2, \dots, s_n\}$.
A	Set of anchor points, $A = \{a_1, a_2, \dots, a_k\}$.
$\rho(A)$	Travel route of mobile sink, $\rho(A) = (s_0, a'_1, a'_2, \dots, a'_k, s_0)$.
$C(\rho)$	Crossover points between travel route and communication ranges of sensor nodes, $C(\rho) = \{c_1, c_2, \dots, c_m\}$.
$\rho(C)$	Travel route redefined as the sequence of crossover points $\rho(C) = (s_0, c'_1, c'_2, \dots, c'_m, s_0)$.
$R^{cp}_{n\times m}(C)$	Relationship between the set of sensor nodes S and the set of crossover points C, $r^{cp}_{ij} = \begin{cases} 1, (c(p(s_i)) \cap c_j \neq \emptyset) \\ 0, (c(p(s_i)) \cap c_j = \emptyset) \end{cases}$
$T(\rho)$	Line segments of travel route divided by crossover points, $T(\rho) = \{t_1, t_2, \dots, t_p\}$ and $t_i = l(p(c_i), p(c_{i-1}))$.
$R^{ts}_{n\times p}(T)$	Relationship between the set of sensor nodes S and the set of travel segments T, $r^{ts}_{ij} = \begin{cases} 1, (d(p(s_i)) \cap t_j - \{c_j, c_{j-1}\} \neq \emptyset) \\ 0, (d(p(s_i)) \cap t_j - \{c_j, c_{j-1}\} = \emptyset) \end{cases}$
$L(A, \rho)$	Delivery latency.
$L^{cp}(A, \rho)$	Time that the mobile sink stays on the crossover points.
$L^{tsu}(A, \rho)$	Time that the mobile sink travels on the uncovered travel segments.
$L^{tsc}(A, \rho)$	Time that the mobile sink travels on the covered travel segments.
$R^{tsc}_{n\times p}$	Time assignment matrix that the time assigned for sensor nodes whose communication range is traversed by travel segments.
$p(w)$	Position of node w.
$d(p(w_i), p(w_j))$	Distance between w_i and w_j.
$c(w_0)$	Circle with center $p(w_0)$.
$b(w_0)$	Circular range with center $p(w_0)$.
$l(p(w_i), p(w_j))$	Line located on position $p(w_i)$ and $p(w_j)$.
$\alpha(R, i)$	Function to sum up the elements of the ith row of the matrix R.
$\beta(R, j)$	Function to sum up the elements of the jth column of the matrix R.
$\tau(s_i)$	Time that sensor node s_i transmits data to mobile sink in one data collection cycle.
$\delta(x)$	Function that $\delta(x) = \begin{cases} 1, (x > 0) \\ 0, (x = 0) \end{cases}$
$\overline{\delta}(x)$	Function that $\overline{\delta}(x) = \begin{cases} 1, (\delta(x) = 0) \\ 0, (\delta(x) = 1) \end{cases}$

$s \cdot t \cdot$

$$\prod_{i=1}^{n} \alpha(R^{cp}_{n\times m}, i) > 0 \tag{3}$$

$$\alpha(R^{tsc}_{n\times p}, i) \geq \delta(\alpha(R^{ts}_{n\times p}, i)) \cdot \tau(s_i) \tag{4}$$

$$\beta(R^{tsc}_{n\times p}, j) \geq \delta(\beta(R^{ts}_{n\times p}, j)) \cdot \frac{d(t_j)}{v_{max}} \tag{5}$$

$$A \subset \Omega \tag{6}$$

$$1 \leq i \leq n \tag{7}$$

$$1 \leq j \leq p \tag{8}$$

In the formulation, parameters A and ρ are optimization variables, and parameters $\tau(.)$, v_{max} and r are constants. Eq. (2) is the object function of the DLMP with variable A and ρ which are derived from Eq. (1). Eq. (3) is the direct access constraint that the mobile sink must access every sensor node by a single hop. Eq. (4) is the data transmission constraint that the total time assigned to a sensor node should be more than the time of transmitting its data. Eqs. (5) is the route traverse constraint that the total time assigned to the travel segment should be more than the time of traversing these segments at maximum speed. Constraint (6) shows the definition domain of the set of anchor points A.

Theorem 2 (Travel Route Programming Complexity): In the DLMP, the decision version of travel route programming problem is an NP-complete problem.

Proof: We can reduce any instance of the TSP problem to an instance of the DLMP. Since the TSP problem is an NP-complete problem, the DLMP is also an NP-complete problem. ■

Theorem 3 (Lower Bound of Delivery Latency): In the DLMP, the lower bound of delivery latency is the sum of data transmission time of all sensor nodes.

$$L \geq \sum_{i=1}^{n} \tau(i) \tag{9}$$

Proof: We can derive the result from Eqs. (2) and (4). ■

IV. HEURISTIC ALGORITHMS

A. Substitution

In the substitution heuristic algorithm, we perform two types of substitutions: point substitution (PS) and line substitution (LS). By Theorem 1, when anchor points are located at the border of communication range of sensor nodes, the length of travel route is shorter. Based on this property, the point substitution is to transfer anchor points from the center to the border of communication range of sensor nodes. The point substitution algorithm is described in Algorithm 1.

The line substitution is to make the travel route shorter, whose main idea is to replace two adjacent travel segments with one shorter travel segment based on the principle that the sum of two sides of a triangle are greater than the third one in Euclidean space. The line substitution algorithm is described in Algorithm 2.

B. Visiting Schedule

The visiting schedule is to determine the time assignment matrix $R^{tsc}_{n\times p}$ and the travel time on the covered travel segments L^{tsc}. From Eqs. (2)-(8), we can see that only L^{tsc} is variable. To minimize the delivery

Algorithm 1 Point Substitution (PS)

Input:

ρ': travel route output by classical TSP algorithm

Output:

ρ: travel route generated by point substitution

$\rho_1 \leftarrow s_0$;
for $i = 2$ to $\|\rho'\| - 2$ **do**
  $\rho_i \leftarrow$ select a point on the border of communication range of sensor node $s_{\rho'_i}$;
end for
$\rho_{\|\rho'\|} \leftarrow s_0$;
return ρ;

Algorithm 2 Line Substitution (LS)

Input:

ρ': travel route output by point substitution

I: number of iterations; S: set of sensor nodes

Check(): check whether all sensor nodes can be traversed after line substitution

Output:

ρ: travel route generated by line substitution

$k \leftarrow 1$;
while $(k++) \leq I$ **do**
  $\rho_0 \leftarrow s_0$, $d \leftarrow null$;
  for $i = 2$ to $\|\rho'\| - 1$ **do**
    $d_i \leftarrow d(p(\rho'_{i-1}), p(\rho'_{i+1})) - d(p(\rho'_{i-1}), p(\rho'_i)) - d(p(\rho'_i), p(\rho'_{i+1}))$;
  end for
  order d by decreasing;
  for $i = 1$ to $\|\rho'\| - 1$ **do**
    if Check(ρ, S) and $d_{\rho''_i} > 0$ **then**
      $\rho'_i \leftarrow null$;
    else
      $\rho_i \leftarrow \rho'_i$;
    end if
  end for
  $\rho = s_0$;
  if $\|\rho\| == \|\rho'\|$ **then**
    return ρ;
  end if
  $\rho \leftarrow \rho'$;
end while
return ρ;

latency L, we can only optimize the traversing time on the covered travel segments L^{tsc}. We relax Eq. (2) by dropping constraint (3) and keeping constraints (4) and (5), which is formulated as

$$Minimize \quad L^{tsc} = \sum_{i=1}^{n} \sum_{j=1}^{p} (r_{ij}^{tsc}) \tag{10}$$

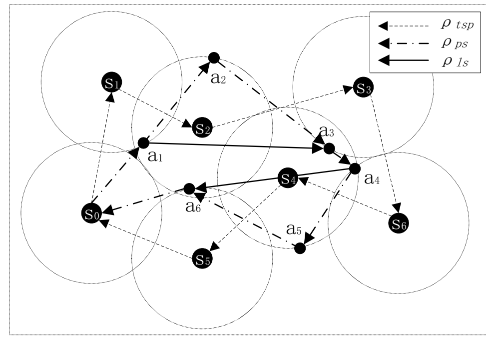

Fig. 3. Demonstration of substitution heuristic algorithm. The initialization travel route $\rho_{tsp} = (s_0, s_1, s_2, s_3, s_4, s_5, s_6, s_0)$, point substitution travel route $\rho_{ps} = (s_0, a_1, a_2, a_3, a_4, a_5, a_6, s_0)$ and the first iteration of line substitution travel route $\rho_{ls} = (s_0, a_1, a_3, a_4, a_6, s_0)$.

$$s \cdot t \cdot \quad \alpha(R_{n\times p}^{tsc}, i) \geq \delta(\alpha(R_{n\times p}^{ts}, i)) \cdot \tau(s_i) \tag{11}$$

$$\beta(R_{n\times p}^{tsc}, j) \geq \delta(\beta(R_{n\times p}^{ts}, j)) \cdot \frac{d(t_j)}{v_{max}} \tag{12}$$

C. Substitution Heuristic Algorithm

Substitution heuristic algorithm (SHA) mainly includes four steps. The first step is to select the positions of sensor nodes as the initial positions of anchor points. The second step is to use a classical TSP heuristic algorithm to generate the initial travel route. The third step is to utilize point substitution and line substitution to minimize the initial travel route. The fourth step is to determine the visiting schedule by solving a linear programming problem as shown in Eqs. (10)-(12). Fig. 3 demonstrates part of these steps. SHA is described in Algorithm 3.

We now analyze the complexity of SHA. We assume that c_1 denotes the complexity of the linear programming solver, and c_2 indicates the complexity of the classical TSP solver. The complexity of the visiting schedule is $O(n + n \cdot p + c_1)$. The complexity of SHA is, therefore, $O(n + I \cdot n + n \cdot p + n^2 + I \cdot n^3 + c_1 + c_2)$. By predigesting, the complexity of SHA is $O(I \cdot n^3 + c_1 + c_2)$.

V. Simulation Results

A. Metrics

In the simulation, we focus on two main metrics: delivery latency and route length. The delivery latency is defined in Definition 1 and is formulated as Eq. (1). The route length is defined as the total length of travel segments on a travel route. If travel route $\rho = (s_0, c'_1, c'_2, \ldots, c'_m, s_0)$, the route length can be formulated as $\|\rho\|$.

B. Comparisons

We compare the proposed SHA algorithm with other two algorithms: TSP heuristic algorithm (THA) and

Algorithm 3 Substitution Heuristic Algorithm (SHA)

Input:

s_0: original position of mobile sink
S: set of sensor nodes; $\tau(.)$: transmission time
v_{max}: maximum speed of mobile sink
I: number of iterations
$TSP()$: a classical TSP programming solver

Output:

ρ: travel route
L: delivery latency
$R^{tsc}_{n\times p}$: visiting schedule

1: $A \leftarrow S + \{s_0\}$;
2: $\rho'' \leftarrow TSP(A, s_0)$;
3: $\rho' \leftarrow$ PS with parameter ρ'';
4: $\rho \leftarrow$ LS with parameters ρ' and I;
5: $R^{ts}_{n\times m} \leftarrow$ the definition in Table I with parameter ρ;
6: $[L^{tsc}, R^{tsc}_{n\times p}] \leftarrow$ visiting schedule with parameters $R^{ts}_{n\times m}$, $\tau(.)$ and v_{max};
7: $L \leftarrow$ the formulas in Definition 1 with parameters L^{tsc} and $R^{tsc}_{n\times p}$;
8: **return** ρ, L and $R^{tsc}_{n\times p}$;

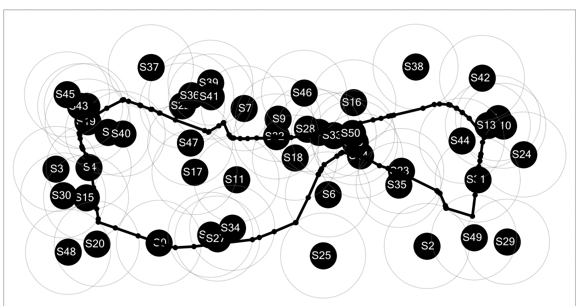

Fig. 4. Travel Route of SHA. Length of travel route is 1812.03, and delivery latency is 1823.03.

random heuristic algorithm (RHA). THA and RHA can be obtained in Algorithm 3 by rewriting Line 1, and dropping Line 3 and Line 4. The difference between THA and RHA is the method of anchor point selection. In THA, anchor points are located at the positions of sensor nodes, but in RHA, anchor points are randomly selected from the communication range of sensor nodes.

C. Results

We set parameters $\Omega = [0, 800] \times [0, 600]$, $S = \{s_1, s_2, \ldots, s_{50}\}$, $r = 80$, $v_{max} = 1$, and $\tau(.) = 1$. Fig. 4 show the travel routes obtained by SHA. The impact of the moving speed on the three algorithms is shown in Fig. 5. Fig. 5(a) presents the following observations. First, the route length will not be affected

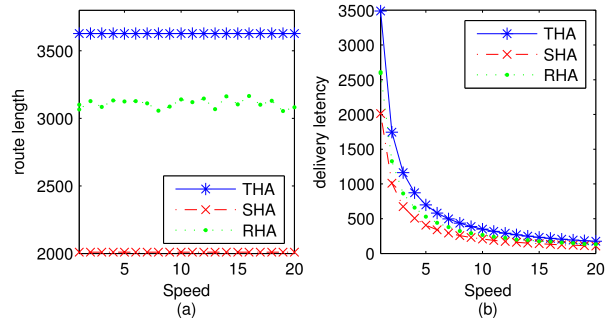

Fig. 5. Impact of moving speed on three algorithms.

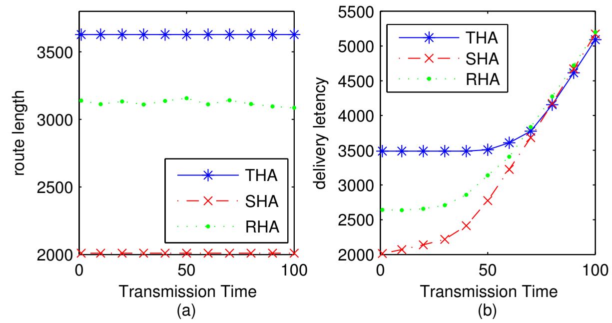

Fig. 6. Impact of transmission time on different algorithms.

by the moving speed of the mobile sink. Second, the route length of SHA is always the shortest. Third, the average route length of RHA is not stable. From Fig. 5(b), we can see that the delivery latency of the three algorithms drops very quickly with the increase of the moving speed. We can also find that the delivery latency of the three algorithms converges to a constant when the speed is greater than 10. It is not difficult to observe from Theorem 3 that the delivery latency of the three algorithms will get close to the smallest delivery latency when the moving speed becomes higher. The impact of transmission time on the three algorithms is shown in Fig. 6. Fig. 6(a) reflects that the route length will not be affected by transmission time. From Fig. 6(b), we have the following observations. First, SHA can achieve shorter deliver latency than other two algorithms when $\tau(\cdot) < 70$. Second, the delivery latency will increase as transmission time becomes larger. Third, the delivery latency of the three algorithms will intercross together and then increase linearly when $\tau(\cdot) \geq 70$. By Theorem 3, we can find that the value on the cross line approaches the smallest delivery latency.

The impact of communication radius on different algorithms is shown in Fig. 7. We have the following results from Fig. 7(a). First, as the communication radius becomes larger, the route length of THA remains unchanged, whereas the route length of SHA decreases. Second, the average route length of RHA decreases with the increase of the communication radius. How-

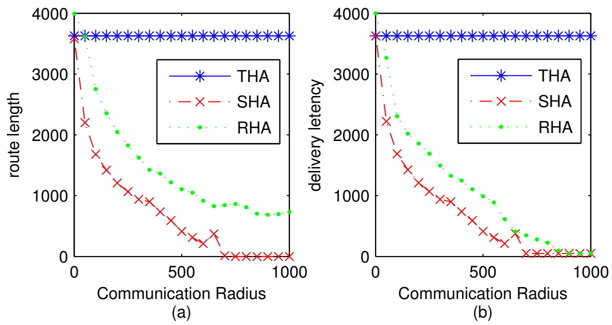

Fig. 7. Impact of communication radius on different algorithms.

ever, the decrease of SHA is faster than that of RHA. Similarly, the delivery latency renders the same variation when the communication radius becomes larger. Fig. 7(b) shows that the delivery latency of SHA equals the smallest value when $r \geq 700$, and the delivery latency of RHA equals the smallest value when $r \geq 850$.

VI. Conclusions

In this paper, we have studied the delivery latency minimization problem in a wireless sensor network with a mobile sink deployed on a plane randomly. The minimization problem is formulated as an NP-Complete integer programming problem. To solve the problem, We propose a substitution heuristic algorithm which utilizes TSP algorithm to produce the visiting sequence of anchor points, and uses substitutions to reduce the route length. By comparing with two other algorithms, TSP heuristic algorithm (THA) and random heuristic algorithm (RHA), we find that the proposed SHA algorithm outperforms THA and RHA in terms of shortening delivery latency and reducing route length.

VII. Acknowledgments

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