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Cluster-Based Routing for the Mobile Sink in Wireless Sensor Networks With Obstacles

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ABSTRACT In wireless sensor networks (WSNs), the benefits of exploiting the sink mobility to prolong network lifetime have been well recognized. In physical environments, all kinds of obstacles could exit in the sensing field. Therefore, a research challenge is how to efficiently dispatch the mobile sink to find an obstacle-avoiding shortest route. This paper presents an energy-efficient routing mechanism based on the cluster-based method for the mobile sink in WSNs with obstacles. According to the cluster-based method, the nodes selected as cluster heads collect data from their cluster members and transfer the data collected to the mobile sink. In this paper, the mobile sink starts the data-gathering route periodically from the starting site, then directly collects data from these cluster heads in a single-hop range, and finally returns to the starting site. However, due to the complexity of the scheduling problem in WSNs with obstacles, the conventional algorithms are difficult to resolve. To remedy this issue, we propose an efficient scheduling mechanism based on spanning graphs in this paper. Based on the spanning graph, we present a heuristic tour-planning algorithm for the mobile sink to find the obstacle-avoiding shortest route. Simulation results verify the effectiveness of our method.

INDEX TERMS Wireless sensor networks, obstacles, energy-efficient routing, cluster-based, mobile sink, spanning graph.

I. INTRODUCTION

Wireless Sensor Networks(WSNs) have been applied in many respects including health monitoring, environmental monitoring, military surveillance, and many others as Internet of Thing (IoT) [1]–[5]. Energy efficiency has become the most key issue for WSNs. However, power supplies for sensor nodes are limited and hard to replace. In addition, compared with other nodes, nodes near the base station (also called the sink) consume more energy, since the nodes relay the data collected by sensor nodes far away from the sink. Hence, once these sensors near the sink fail, the data collected by other sensors cannot be transferred to the sink. Then, the entire network becomes disconnected, although most of the nodes can still have a lot of energy. Therefore, to extend the network lifetime, minimizing the energy consumption of sensor nodes is the key challenges for WSNs.

Different approaches are proposed to prolong the lifetime of WSNs. The paper [6] proposes a cross-layer optimized geographic node-disjoint multipath routing algorithm. Recent work shows that we can use mobile nodes to reduce the energy expenditure of WSNs to a large extent. Consequently, the lifetime of WSNs is prolonged. Compared with static nodes, mobile nodes have more energy and more powerful capabilities. Mobile nodes, which are usually mounted on a mobile vehicle equipped with enough energy, can collect data from all static nodes by moving across the sensing field. The data from static nodes can be collected by mobile nodes in one-hop or multi-hop way. The papers [7]–[10] have proposed several different approaches. In this paper, mobile nodes are used as the mobile sink which moves across the sensing field to collect data. On the one hand, the mobile sink reduces the communication overhead for sensor nodes close to the base station or the sink, which leads to the uniform energy consumption. One the other hand, with the movement of the sink, we can better handle the disconnected and sparse network. Therefore, the network lifetime can be significantly extended by the optimum control of the route of the mobile sink. In physical environments, the sensing field could contain various obstacles. Hence, to prolong the network lifetime, a research challenge is how to find an obstacle-avoiding shortest route for the mobile sink.

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In this paper, the mobile sink will move through the network with obstacles to find an obstacle-avoiding shortest route. At the same time, the mobile sink must consider the energy consumption balance among nodes while moving across the sensing field. To dispatch the mobile sink efficiently, we utilize the cluster-based method that is presented in [11] and [12]. According to the cluster-based method, all sensor nodes in the sensing field are divided into two categories: cluster heads and cluster members. Cluster heads collect data from corresponding cluster members which collect environment information, and then pass data to the mobile sink. We assume that WSNs can tolerate some extent of delay so that the mobile sink collects all sensing data from cluster heads. The mobile sink begins its periodical movement from starting site and finally returns. During its movement, the mobile sink collects the sensing data from cluster heads. Once its moving path is planned, the mobile sink can move near the cluster heads and consume less energy. Hence, the network lifetime can be prolonged significantly. In this paper, the network lifetime is defined as the time interval from sensor nodes start working until the death of all static sensors. However, in physical environments, the sensing field may contain various obstacles which make the scheduling for the mobile sink more complex. Here, the mobile sink can move to any site except the site of obstacles. Therefore, a research challenge is how to efficiently dispatch the mobile sink to find an obstacle-avoiding shortest route in the presence of obstacles.

To solve the scheduling for the mobile sink, we take some steps to make the dispatch problem simpler in WSNs with obstacles. Given the complexity of the problem, we present a grid-based method by which the sensing region is divided into the same size grid cells. Grid cells are considered to be the basic unit and their size is closely related to communication radius of static sensors. As the two-dimensional plane is divided into the same size grid cells, obstacles will contain some grid cells. Edges of obstacles intersect grid cells and obstacles may occupy part of some grid cells. Once obstacles occupy part of one grid cell, we assume that the grid cell is regarded as obstacles. Therefore, we obtain regularization shape of obstacles so that the scheduling for the mobile sink becomes easier. We can then construct a spanning graph in terms of the regularization shape of obstacles. With the search space of the mobile sink from all grid cells to the spanning graph obtaining grid cells, the scheduling for the mobile sink will become more efficient. Hence, we can finally find an obstacle-avoiding shortest route for the mobile sink.

The remainder of this paper is organized as follows. Section II presents related work. Section III introduces problem definition, energy consumption models and cluster partition, respectively. We propose a heuristic obstacle-avoiding algorithm for the mobile sink to finding an obstacle-avoiding shortest tour in Section IV. Section V proposes the evaluation of our technique. Finally, we conclude the paper in Section VI.

II. RELATED WORKS

Recent work shows that the advantage utilizing the mobility of nodes has been well recognized. By using the mobility of nodes in WSNs, we can ease the traffic burden and enhance energy efficiency. Hence, the network lifetime is extended significantly. Many papers have proposed several different approaches. We then study the related works of the mobility of nodes in the literature.

In [13], the authors present a VGDRA scheme for the mobile sink to minimize the communication cost. The sensor field is divided into a virtual grid containing the same size cells and the nodes near the center are chosen as the cell-header nodes. In addition, a virtual backbone structure consisting of the cellheader nodes is constructed The mobile sink moves across the sensor field and collects the sensing data by communicating with the border cellheader nodes. To reduce the overall communication cost, the routes reconstruction process includes only a subset of cell-header nodes. In [14], the authors propose a mixed integer programming framework for base station to mitigate the suboptimal energy dissipation. To reverse the suboptimal energy dissipation trends, the base station mobility is introduced to WSNs. The network lifetime is finally extended by using mobility patterns for base station The paper [15] utilizes the support vector regression technique to construct a convex optimization model, by which the optimal trajectory of the mobile sink can be determined. The network lifetime is affected by the trajectory (called COT). To maximize the network lifetime, the mobile sink in the event-driven is used to collect the captured data of events In [16], the authors propose a mobile data-gathering tour for different sensor networks. An M-collector similar to a mobile base station is introduced to collect sensing data from static sensors. The MDC begins its periodical movement from the base station and finally returns for transferring the data to the base station. For some applications in large-scale networks, the authors take a divide-and-conquer strategy and use multiple M-collectors, each of which moves through a shorter data-gathering tour. In [17], the authors adopt a wireless energy transfer technology for charging sensor nodes. The Wireless Charging Vehicle (WCV) starts a periodical tour from the service station, moves across the network for charging some sensor nodes wirelessly, and finally returns. According to the novel Reformulation-Linearization Technique (RLT), the authors design a near-optimal solution for the optimization problem. In [18] and [19], the authors consider the dispatch of mobile sensors as a multi-round and multi-attribute sensor dispatch problem. In a hybrid WSN, static sensors monitor and collect environment information. Once events happen, each static sensor can only sense one attribute of events. Compared with static sensors, a mobile sensor can evaluate multiple attributes of events. According to the sensing data from static sensors, mobile sensors move to corresponding hot locations for more in-depth analysis. To minimize the energy consumption, the authors present

a two-phase heuristic algorithm to dispatch mobile sensor for hot locations. In the first phase, the authors dispatch MAM sensors to hot locations in a one-to-one approach. In the second phase, according to unassigned hot locations, the authors present a spanning-tree construction algorithm for the displacement of MAM sensors. Due to similar capabilities of sensors, a research challenge is how to dispatch mobile sensors to these hot locations. However, in [13]–[19], the authors don't consider that the sensing field may contain various obstacles. In fact, the route for mobile nodes in sensing field containing obstacles is more complex than that sensing field without obstacles.

In [20] and [21], the authors consider the dispatch of mobile sensors in the network area with obstacles, where static sensors detect environment information. Once mobile sensors receive the sensing data from the static sensors, they will move to these hot locations to conduct further analysis. A research challenge is how to find an obstacle-avoiding shortest path for the mobile sensor to the hot location. The authors propose modified Dijkstra's algorithm to solve scheduling for the mobile sensor in the presence of obstacles. In fact, in [20] and [21], the authors just consider that the shape of obstacles is convex. However, scheduling for mobile sensors in sensing field containing concave obstacles is more complex than that in sensing in sensing field containing convex obstacles.

In summary, current research has addressed some scheduling problem of mobile nodes in WSNs from different aspects. However, as discussed above, to prolong the network lifetime, a research challenge is how to find a shortest route for mobile nodes. In particular, once the sensing field contains obstacles of any shape and size, the deployment of mobile sensors will become more complex. This paper aims to presents a solution to this issue.

III. PRELIMINARIES

In this section, we present problem definition, energy consumption models and cluster partition, respectively.

A. PROBLEM DEFINITION

Recent years, Wireless Sensor Networks are developing rapidly, in which sensor nodes are used to gather environment information. In the past, we could only utilize static sensor nodes to collect the environment information. With technical progress, we introduce mobility to WSNs. For example, we can use mobile sensor nodes to collect information. Compared with static nodes, mobile nodes have more energy and are more convenient to use. In this paper, mobile nodes are used as mobile sinks which move through the sensing field. Note that there is only one mobile sink in our network. At the same time, we assume that there is no hole in the WSN and static sensors are the same in their capabilities. However, in physical environments, the sensing field may be uneven and contain various obstacles. Here, we assume that the mobile sink can't move through these obstacles. Hence, a research challenge is how to find an obstacle-avoiding shortest route for the mobile sink. In this paper, the mobile sink, which is usually mounted on a mobile vehicle equipped with enough energy, collects data from all static nodes by moving across the sensing field. Note that the network lifetime is defined as the time interval from sensor nodes start working until the death of all static sensors. To prolong the lifetime of the WSNs as long as possible, we propose an efficient scheduling scheme for the mobile sink in WSNs with obstacles. In physical environments, we assume that there are N sensor nodes distributed over a two-dimensional plane where M obstacles exist. Referring to Figure 1, 100 sensor nodes are deployed freely in the two-dimensional plane where there are four obstacles. In Figure 1, pentagrams and black irregular figures represent sensor nodes and obstacles, respectively. At the same time, we assume that a mobile sink exists, denoted by the red car locating in the top-left corner of the two-dimensional area. In this paper, we use a cluster-based method to find an obstacle-avoiding shortest route for the mobile sink. As to the cluster-based algorithm, we will introduce it in next section. The mobile sink begins its periodical obstacle-avoiding movement from starting site and finally returns. During its movement, the mobile sink collects the sensing data from cluster heads. Once its moving path is planned, the mobile sink can move near the cluster heads and consume less energy. Owe to balanced energy consumption of sensor nodes, the network lifetime can be prolonged significantly.

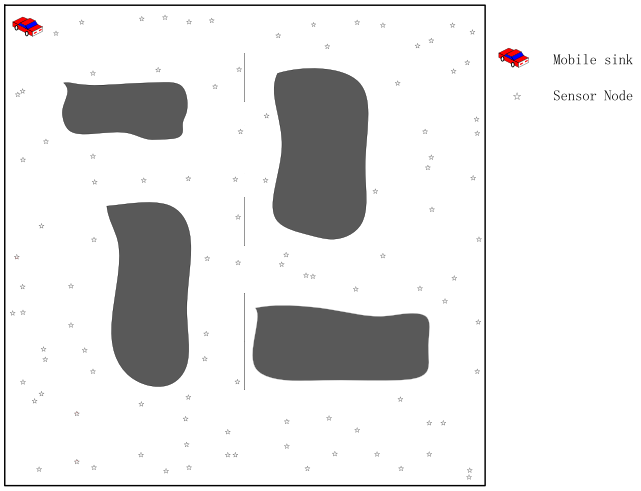


FIGURE 1. An example of scheduling for the mobile sink with obstacles.

B. ENERGY CONSUMPTION MODELS

In this paper, we assume that the mobile sink could be a vehicle or a mobile robot with enough energy. Hence, we just consider energy consumption of sensor nodes. In the course of their work, sensor nodes need consume energy. Compared with other operations, communication is the most critical energy consumption of sensor nodes, which includes transmission and reception. Figure 2 shows a radio energy dissipation model for the sensor node, which

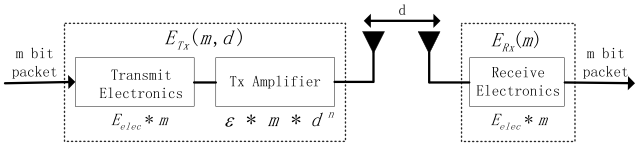


FIGURE 2. Radio energy dissipation model.

includes the transmitter energy dissipation model and the receiver energy dissipation model. In the transmitter energy dissipation model, the operations for radio electronics and power amplifier consume energy. In addition, in the receiver energy dissipation model, the operation for radio electronics consumes energy. Obviously, the transmitter consumes more energy than the receiver. Here, we assume that $E_{Tx}(m, d)$ is the energy dissipation for transmitting m bits over distance d and $E_{Rx}(m)$ is the energy dissipation by receiving m bits. Hence, the radio energy dissipation model can be formulated as follows.

$$E_{Tx}(m,d) = E_{elec} * m + \varepsilon * m * d^n = \begin{cases} E_{elec} * m + \varepsilon * m * d^2, & d \le d_0 \\ E_{elec} * m + \varepsilon * m * d^4, & d > d_0 \end{cases} \quad (1)$$

$$E_{Rx}(m) = E_{elec} * m \quad (2)$$

where E_{elec} and ε are constants decided by the environment, d is the distance between the receiver and transmitter, d_0 is a threshold value depending on the initiation setting, and the exponent n is determined by comparing the distance d with the threshold d_0, which equals 2 or 4.

C. CLUSTER PARTITION

To prolong the lifetime of the WSNs, the cluster-based method has been proven to be effective [11], [12]. According to the cluster-based algorithm, all sensor nodes in the network are divided into two categories: cluster heads and cluster members. Cluster heads collect data from their cluster members which collect environment information, and then forward the data to the sink either directly or via relaying across other cluster heads. Due to movement of the sink, the mobile sink can move nearest the cluster heads and consume less energy. We can balance energy consumption of sensor nodes by using the cluster-based algorithm. Therefore, the network lifetime will be prolonged significantly.

To solve the scheduling for the mobile sink, we use the LEACH (low-energy adaptive clustering hierarchy) protocol developed by Heinzelman *et al.* [11]. Once cluster heads are determined by the LEACH, the mobile sink can move closest to the cluster heads for gathering data. Hence, sensor nodes consume less communication energy which is the most critical energy consumption of sensor nodes. Here, the mobile sink mounted on a mobile vehicle is equipped with enough energy. Owe to balanced energy consumption of sensor nodes, it is obvious that the lifetime of the WSNs will be extended. In Figure 3, we assume that there are ten cluster heads in one round, which are represented by red pentagrams. If no obstacle exists, the mobile sink denoted by the red car can move along the dotted line and visit all cluster heads for collecting sensing data. Hence, the network lifetime can be extended significantly. In order to balance energy consumption of sensor nodes, clusters are re-partitioned in each round in terms of LEACH. Note that sensor nodes within clusters have the same initially energy. Cluster heads are elected based on the threshold formula as follows.

$$T(m) = \frac{p}{1 - p * [k \bmod (1/p)]}, \quad \forall m \in G \quad (3)$$

where p is the desired percentage of cluster heads, k is the current round index and G is the set of nodes which have not been a cluster head in the last $1/p$ rounds. Each node $m \in G$ chooses a random number r between 0 and 1 at the beginning of each round. The node will be elected as a cluster head in the current round k if a threshold $T(m)$ is more than the random number r.

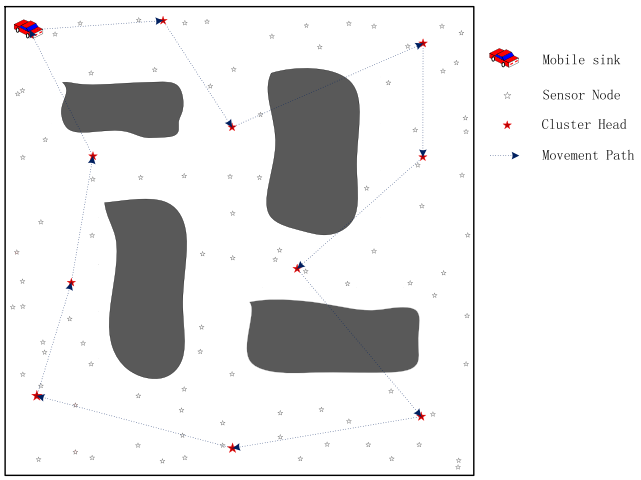


FIGURE 3. Cluster partition.

However, in physical environments, the sensing field may contain various obstacles which make the scheduling for the mobile sink more complex. Here, we assume that the mobile sink can't move across obstacles in Figure 3. Therefore, a research challenge is how to efficiently dispatch the mobile sink to find an obstacle-avoiding shortest route in the presence of obstacles. To solve the obstacle-avoiding shortest route problem, we present a heuristic obstacle-avoiding algorithm in the next section.

IV. HEURISTIC OBSTACLE-AVOIDING ALGORITHM

In this section, we present a heuristic algorithm to find an obstacle-avoiding shortest route for the mobile sink. In order to better solve the dispatch problem of the mobile sink, we use the algorithm to construct the spanning graph of the network model. According to the spanning graph, we obtain all obstacle-avoiding paths. Furthermore, the obstacle-avoiding shortest route for the mobile sink can be acquired from these obstacle-avoiding paths. We introduce specific steps of the heuristic obstacle-avoiding algorithm below.

A. SPANNING GRAPH ALGORITHM

In essence, the obstacle-avoiding shortest route problem is similar to the Traveling Salesman Problem (TSP) which is a classical problem. We can utilize the minimum spanning tree to solve the TSP. Hence, according to the minimum spanning tree, we can also find an obstacle-avoiding shortest route for the mobile sink. In this paper, a spanning graph is an undirected graph which contains all minimum spanning trees. In this section, we will discuss how to construct the spanning graph. Several studies have addressed the spanning graph construction [22], [23]. We can utilize the sweep line algorithm to construct the spanning graph [22]. The obstacle-avoiding spanning graph is the set of edges that can be formed by making connections between terminals and obstacle corners. Once a spanning graph is constructed, the infinite possible sites for the mobile sink movement will be reduced to a finite set of sites. Therefore, the algorithm based on the spanning graph makes it more efficient to schedule for the mobile sink.

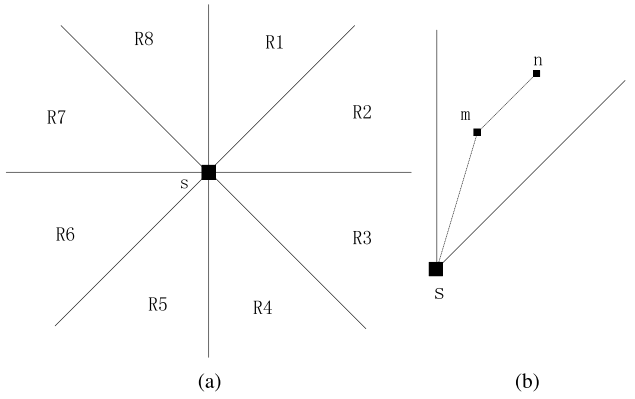


FIGURE 4. Eight regions of an endpoint and the uniqueness property. (a) Eight regions. (b) The uniqueness property.

We will describe how to construct the obstacle-avoiding spanning graph on the basis of eight regions of an endpoint in Figure 4(a). The plane with respect to the endpoint s is divided into 8 regions ($R1 \sim R8$) by the two rectilinear lines and the two 45 degree lines through s, as shown in Figure 4(a). The paper [22] has proven that for an endpoint s, a region R has the uniqueness property with respect to s if for every pair of points $m, n \in R$, $\|mn\| < \max(\|sm\|, \|sn\|)$. Note that the notation $\|mn\|$ represents the distance between points m and n. A minimal spanning tree is acyclic, so the $\max(\|sm\|, \|sn\|)$ in the region R is not included in the minimal spanning tree. For example, in Figure 4(b), the minimal spanning tree for the region R contains the edges (s, m) and (m, n), and the longest edge (s, n) is not contained in the minimal spanning tree. In order to simplify the calculations, we divide a plane into 4 regions in this paper. It is proved in [23] that the quadrant partition, compared with the octant partition, also exhibits good results.

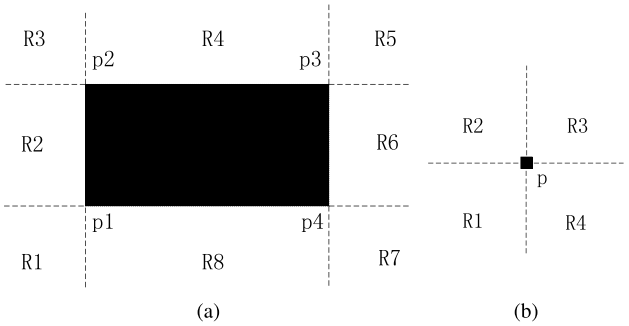


FIGURE 5. Search regions for blockage and pin. (a) Obstacle corner. (b) Pin vertex.

Algorithm 1 SpanningGraph

Input:
V: the set of nodes of pin vertices and obstacle corners;
Output:
G: the spanning graph for V;

1: $V_x \leftarrow$ sort V by non-decreasing x
2: **if** $V_i \subset V_x$ in region $R2$ and $R6$ of all obstacle corners **then**
3: EdgeGraph(V_i);
4: **end if**
5: $V_y \leftarrow$ sort V by non-decreasing y
6: **if** $V_i \subset V_y$ in region $R4$ and $R8$ of all obstacle corners **then**
7: EdgeGraph(V_i);
8: **end if**
9: $V_{x+y} \leftarrow$ sort V by non-decreasing $x + y$
10: **if** $V_i \subset V_{x+y}$ in region $R1$ and $R5$ of all obstacle corners and in region $R1$ and $R3$ of all pin vertices **then**
11: EdgeGraph(V_i);
12: **end if**
13: $V_{y-x} \leftarrow$ sort V by non-decreasing $y - x$
14: **if** $V_i \subset V_{y-x}$ in region $R3$ and $R7$ of all obstacle corners and in region $R2$ and $R4$ of all pin vertices **then**
15: EdgeGraph(V_i);
16: **end if**

Figure 5 describes the quadrant partition for an obstacle corner and a pin vertex, respectively. Algorithm 1 describes the spanning graph construction which is performed by using edge connection for different region of all pin vertices and all obstacle corners. Once the function EdgeGraph in Algorithm 2 is called in the region $R2$ and $R6$ of all obstacle corners, the corresponding edges will join the spanning graph (lines 1-4). Here, we sort elements of the list V by non-decreasing x coordinates. The line sweep sequence is reverse between the region $R2$ and $R6$, so the same sorted list V can be applied by changing the line sweep direction. Likewise, in the region $R4$ and $R8$ of all obstacle corners, we also call the function EdgeGraph in Algorithm 2. However, unlike sorted list V in the Region $R2$ and $R6$, we sort elements of the list V by non-decreasing y coordinates in

Algorithm 2 EdgeGraph

Input:
V_s: the sorted list V with non-decreasing corresponding coordinates;
Output:
G_s: the edge connection graph for quadrant partition;

```
1: 𝒩 ← ∅
2: for each s_i ∈ V_s do
3:   if s_i is not a corresponding location of blockage b_j then
4:     add s_i to 𝒩;
5:   else
6:     if 𝒩 ! = ∅ then
7:       𝒩 = ∅;
8:       if b_j is not a vertical blockage then
9:         delete points in quadrant partition of s_i which are from 𝒩;
10:      end if
11:      add these points located in quadrant partition of s_i to 𝒩_k;
12:      if 𝒩_k ! = ∅ then
13:        choose the points m and n from 𝒩_k which are closest to s_i and s_{i+1}, respectively;
14:        add the edges (s_i, m) and (s_{i+1}, n) to the edge connection graph G_s;
15:      end if
16:    end if
17:  end if
18: end for
```

the region $R4$ and $R8$ of all obstacle corners (lines 5-8). Besides the region $R1$ and $R5$ of all obstacle corners, the region $R1$ and $R3$ of all pin vertices is also added to our search region (lines 9-13). We sort elements of the list V by non-decreasing $x + y$ coordinates in the region $R1$ and $R5$ of all obstacle corners and the region $R1$ and $R3$ of all pin vertices. To construct the spanning graph, we call the function EdgeGraph in Algorithm 2. Likewise, in the region $R3$ and $R7$ of all obstacle corners and the region $R2$ and $R4$ of all pin vertices, we also call the function EdgeGraph in Algorithm 2. Here, the elements of the list V are sorted by non-decreasing $y - x$ coordinates (lines 14-18). According to the quadrant partition for an obstacle corner and a pin vertex, we finally construct the spanning graph. Consequently, with the search space of the mobile sink from the grid graph to the spanning graph, the possible locations for the mobile sink movement can be greatly reduced. Therefore, our algorithm makes it more efficient for the mobile sink to find an obstacle-avoiding shortest tour.

The algorithm of the construction of the edge connection graph in different search regions is summarized in Algorithm 2. We sort all points in V_s by non-decreasing order from the start. To use the sweep line algorithm, we need an active set for one point that knows all points in the set, which is a premise for using the sweep line algorithm. Consequently, we create an active set $\mathcal{N}$ where all points can be dynamically added and deleted. We initialize the active set $\mathcal{N}$ to an empty set and decide if each point s_i is in the sorted list V_s (lines 1-2). Then, we will add s_i into set $\mathcal{N}$ if s_i is not a corresponding location of a blockage (lines 3-4). Conversely, if s_i is a corresponding location of a blockage, the edge connection for s_i will be performed (lines 5-18). Here, we assume s_i is one of the four corners of the blockage b_j. Firstly, we choose the point s_{i+1} from list V_s, where the point s_i locates front-left of the point s_{i+1}. Secondly, we decide if each point s_i is in the an active set $\mathcal{N}$. Once the point s_i locates in the corresponding region of b_j, the point s_i is added to the set $\mathcal{N}_k$. If the blockage b_j is not a vertical blockage, we will delete points from $\mathcal{N}$ which are located in quadrant partition of s_i. Then, the point m closest to s_i and the point n closest to s_{i+1} are selected. Finally, we get two edges (s_i, m) and (s_{i+1}, n) which will be added to the spanning graph G. Note the point m could coincide with the point n in the set $\mathcal{N}_k$. We deal with the next point in list V_s after the set $\mathcal{N}_k$ is vacated.

B. OBSTACLE-AVOIDING SPANNING GRAPH CONSTRUCTION

In physical environments, the sensing field may contain obstacles with different shapes and sizes. Due to the irregular shape of obstacles, we can't directly construct the obstacle-avoiding spanning graph for the mobile sink scheduling on the basis of the spanning graph algorithm above. Therefore, a research challenge is how to utilize the spanning graph algorithm to find an obstacle-avoiding shortest route for the mobile sink. The papers [24]–[28] use grid-based techniques to analyze and solve problems in WSNs. Here, we also use grid-based techniques to solve the scheduling problem of the mobile sink. The sensing region is divided into the same size grid cells by using the grid-based techniques. Obviously, edges of obstacles intersect grid cells and obstacles may occupy part of some grid cells. Once obstacles occupy part of one grid cell, we assume that the grid cell is regarded as obstacles. Therefore, we obtain regularization shape of obstacles that makes it easier for the mobile sink to find an obstacle-avoiding shortest route. Let r_s and r_c be the communication range and sensing range of each sensor respectively. The paper [29] shows that if no hole exists in the sensing field, the grid size r will be $\min(\frac{r_s}{\sqrt{2}}, \frac{r_c}{\sqrt{5}})$. In this paper, we assume that the communication range r_c of each sensor is long enough. Hence, the grid size r is chosen to be $\frac{r_s}{\sqrt{2}}$ so that no hole exists in the sensing field.

Figure 6 shows the grid division of the sensing field in Figure 1. Referring to Figure 6, gray parts of the sensing field are also considered as obstacles where the mobile sink can't move through. To simplify the scheduling for the mobile sink, we assume that there is one position (called sink position) inside each grid cell, where the mobile sink can visit the position for collecting data from cluster head within the grid cell. In Figure 6, the sink position denoted by the red circle

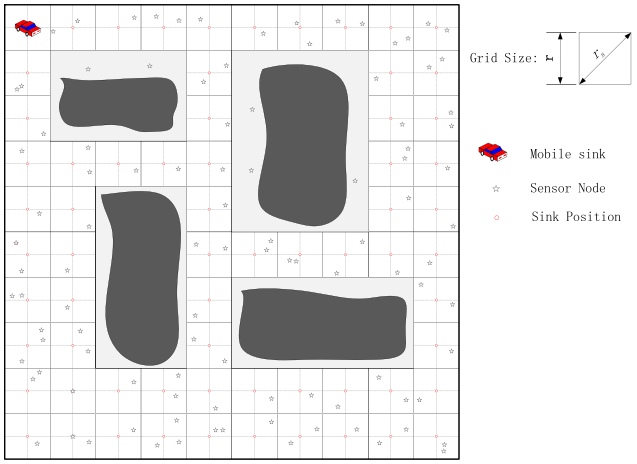


FIGURE 6. The grid graph of sensing field.

is usually located in the geometric center of the grid cell. Therefore, we obtain regularization shape of obstacles by using grid-based techniques.

In the previous section, we have described the cluster partition by which all sensor nodes in the sensing field are divided into cluster heads and cluster members. According to the positions of obstacle corners and sink positions with respect to cluster heads, we can construct the obstacle-avoiding spanning graph for the mobile sink scheduling by using the spanning graph algorithm above. Figure 7 presents the obstacle-avoiding spanning graph of the sensing field in Figure 3, in which the mobile sink visits each stop site(denoted by the black square) for collecting data from cluster heads along line segments and finally returns to the starting site.

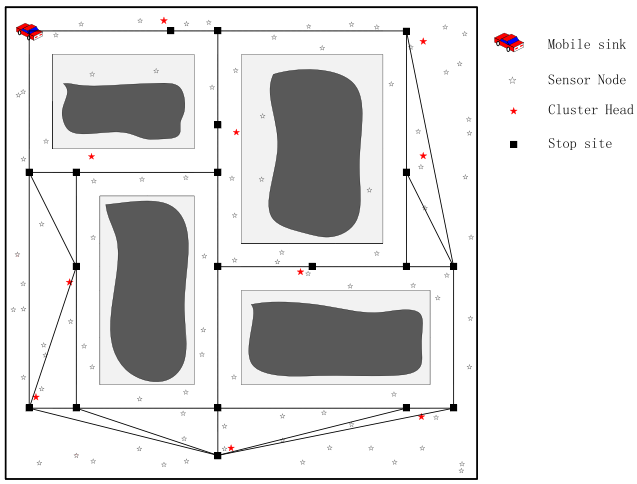


FIGURE 7. The spanning graph of sensing field.

According to the spanning graph of the sensing field in Figure 7, we can finally find the obstacle-avoiding shortest route for the mobile sink. In essence, the obstacle-avoiding shortest route problem is similar to the Traveling Salesman Problem (TSP) which is a classical problem. It has been proven that the TSP is a typical NP-hard problem and NP-complete problem. Due to the complexity of the TSP, we adopt an approximate algorithm to solve the scheduling problem of the mobile sink. One of the main assumptions regarding the TSP is that the input is a complete graph. However, the spanning graph that we have constructed is not a complete graph. Here, we can easily utilize the Warshall-Floyd algorithm to construct the complete graph in terms of the spanning graph. Based on the complete graph, we can easily find the obstacle-avoiding shortest route by the principle of one by one revision of two sides.

V. EVALUATION

In this section, we apply the heuristic obstacle-avoiding algorithm for the sensing field and evaluate the performance of the algorithm by using Matlab. The paper [30] presents a review of the most successful localization algorithms. However, in this paper, we assume that the location information of all nodes is known, to simplify the scheduling problem. Simulation settings and Evaluation Results are as follows.

A. SIMULATION SETTINGS

In this experiment, we assume that 100 sensor nodes are randomly distributed over a $100\times100\text{m}^2$ field where four obstacles exist. In this paper, we assume that no hole exists in the sensing field and static sensors are the same in their capabilities. At the same time, we assume that the mobile sink (denoted by the red car) is located in the top-left corner of the two-dimensional area and its coordinates are (5 m, 5 m). The mobile sink begins its periodical obstacle-avoiding movement from starting site and finally returns. Figure 1 shows an example of scheduling for the mobile sink in which the red car, pentagrams and black irregular figures represent the mobile sink, sensor nodes and obstacles, respectively. In the previous section, we have assumed that the communication range r_c of sensor nodes is long enough. Hence, the grid size r is determined by the sense range r_s of sensor nodes which is assumed to be equal to $10\sqrt{2}$m. According to the previous analysis between the grid size r and the sense range r_s of sensor nodes, the grid size r is obviously equal to 10m. Therefore, we can divide the two-dimensional plane into $10 \times 10 = 100$ grid cells (see Figure 6). Table 1 shows the system parameters used in our simulations. In this paper, in order to simplify scheduling for the mobile sink, we assume that the data collected by sensor nodes is the delay-tolerant data, i.e., they can wait for the mobile sink to come and pick them up.

B. EVALUATION RESULTS

In this section, we utilize the heuristic obstacle-avoiding algorithm to conduct numerous experiments in the sensing field with obstacles. According to the network lifetime and the movement path of mobile sink, we present experimental results of the algorithm which are introduced below.

TABLE 1. System parameters.

Parameters	Values
Grid size	$10m$
Dimension of sensing field	$10m \times 10m$
The number of nodes	100
Initial energy	$0.5J$
Transmitter/Receiver Electronics	$50nJ/bit$
Transmit amplifier	10 or 0.0013
Data aggregation	$5nJ/bit/report$

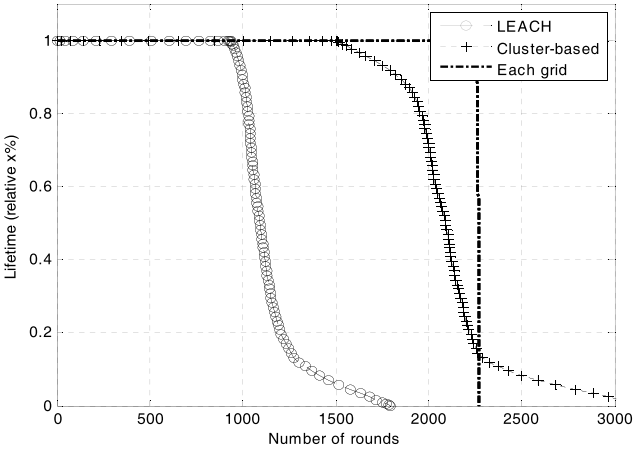


FIGURE 8. Relative *x*% network lifetime.

Figure 8 shows the network lifetime comparison between our cluster-based scheme, the LEACH scheme, and the each grid scheme for the obstacle-avoiding shortest route. Here, the each grid scheme is that the mobile sink moves to each grid cell for collecting sensing data. Note that the network lifetime is relative and we use $x\%$ network lifetime to represent the network lifetime, i.e., that $(100 - x)\%$ sensors have exhausted their energy. In this paper, the network lifetime of the three schemes is based on the number of rounds. In addition, the mobile sink begins its movement from the starting site at the beginning of each round and returns to the starting site at the end of each round. Referring to Figure 8, compared with the LEACH scheme, our cluster-based scheme and the each grid scheme can significantly extend network lifetime. For example, the number of rounds is equal to 1503 and 2231 respectively when the first sensor node dies in our cluster-based scheme and the each grid scheme. However, the number of rounds is equal to 949 when the first sensor node in the LEACH scheme dies. Although relative network lifetime of the each grid scheme is longer than that of our cluster-based scheme, the run time of our cluster-based scheme is greatly reduced.

Figure 9 shows the route length of our cluster-based scheme and the each grid scheme. Referring to Figure 9, with the increase of the number of Hamilton circuits, route lengths with the smallest total weight of the two schemes become shorter. Once the number of Hamilton circuits gets to one value, the route length with smallest total weight will

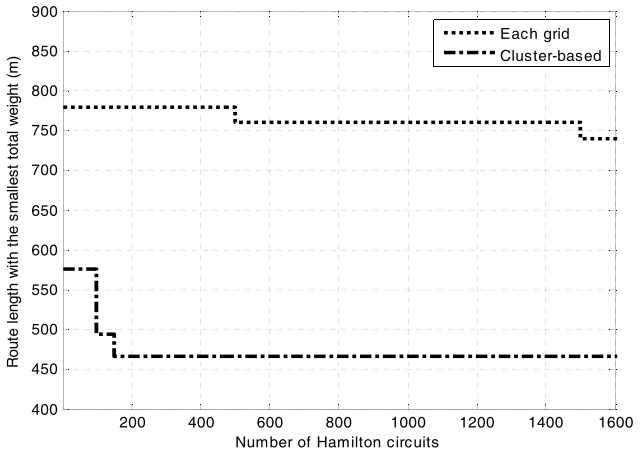


FIGURE 9. Tour length comparison for a different number of Hamilton circuits.

not change, i.e., we obtain the obstacle-avoiding shortest route. For example, route lengths with the smallest total weight of our cluster-based scheme and the each grid scheme are equal to 466m and 740m, respectively. Here, we use the principle of one by one revision of two sides to measure route lengths. In Figure 9, if the number of Hamilton circuits equals 100, 500, and 1500, the tour length with the smallest total weight of the each grid scheme will equal 780m, 760m and 740m, respectively. At the same time, the tour length with the smallest total weight of our cluster-based scheme equals 576m, 495m and 466m, when the number of Hamilton circuits equals 10, 100, and 175, respectively. The mobile sink in our cluster-based scheme need not visit each grid cell, so the tour length with the smallest total weight of our cluster-based scheme is shorter than that of the each grid scheme. Figure 10 shows the movement path of the mobile sink in our cluster-based scheme, when the number of Hamilton circuits equals 200. In Figure 10, the mobile sink(denoted by the red car), which visits each stop

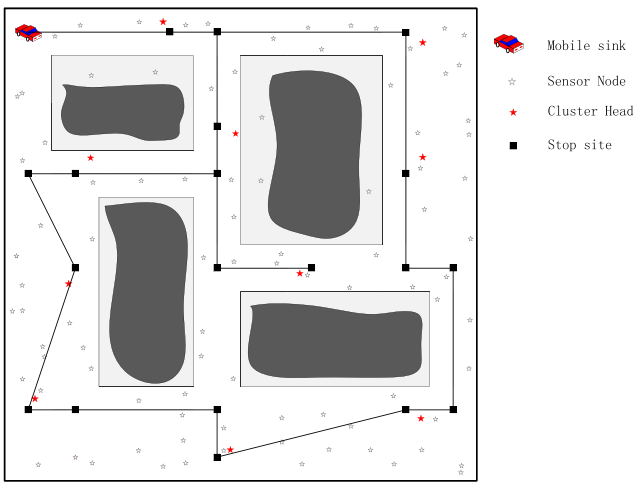


FIGURE 10. The movement path of the mobile sink.

site(denoted by the black square) for collecting data along line segments, begins its movement from the starting site and finally returns to the starting site. Here, we assume that the mobile sink collects data only once each round at the stop site.

We have analyzed the three schemes by experiments from the aspects of tour length and lifetime. Taken together, our cluster-based scheme is more efficient than the other schemes. These experiments demonstrate that we can use the heuristic obstacle-avoiding algorithm to find an obstacle-avoiding shortest route for the mobile sink. In particular, our cluster-based scheme shows better performance.

VI. CONCLUSIONS

In this paper, we utilized the mobile sink to prolong the network lifetime. In physical environments, the sensing field could contain various obstacles. To simplify the scheduling for the mobile sink, we introduced the grid-based technique to the WSN with obstacles. At the same time, we constructed the spanning graph for the mobile sink to find an obstacle-avoiding shortest route. Based on the cluster-based method, we applied the heuristic obstacle-avoiding algorithm to dispatch the mobile sink. We also conducted simulation by using Matlab and experimental results show that our cluster-based approach is feasible for the dispatch of the mobile sink. We finally found an obstacle-avoiding shortest route for the mobile sink and the network lifetime was prolonged.

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this article.

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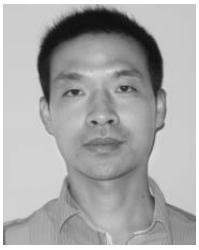
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