Path Planning in Mobile Wireless Sensor Networks

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ABSTRACT Mobile wireless sensor network (MWSN) is a kind of wireless sensor network (WSN) with mobile sink, which is deployed in harsh environment to perform long-term tasks such as data collection and monitoring. Path planning is a fundamental problem in MWSN, which means movement of the mobile nodes in the sensing area should be designed effectively to complete the targets of data collection. However, path planning is a challenging multi-objective optimization issue. Existing schemes of path planning are classified, and their advantages and disadvantages would be compared in this paper. Finally, potential directions of future research are proposed in order to overcome shortcomings of the existing works.

1. INTRODUCTION

With the rapid development of communication technologies and embedded devices nowadays, wireless sensor network (WSN) has been widely used in agriculture, industry and military. The wireless sensor network is a new kind of ad-hoc network. It consists of a large number of nodes with low energy consumption, low computing capability and small storage, which performs special tasks such as environmental monitoring and target tracking. The sensor nodes sense, measure and collect data from the surrounding environment. Each node can not only collect, process, and transmit local data, but also store, calculate, and aggregate data forwarded by other nodes. Sink is a special type of node in WSN, equipped with powerful transmitter, battery, and large storage to collect data across the network and connect to users via the Internet or satellite.

Although applications in WSN are not the same, many of them have a common feature. That is, data of the sensor nodes needs to be collected to the sinks. Therefore, data collection is a very important issue in WSN. In traditional wireless sensor network, there are two main problems in data collection: (1) Because nodes are static, when collecting data, nodes near the sinks need to relay large number of packets forwarded by other nodes. That causes energy consumption of these nodes greatly increasing, which will result in a significant reduction in the lifetime of these nodes. Once these nodes are exhausted, they will not be able to continue relaying data and the lifetime of the WSN will be shortened. (2) Nodes must be densely deployed in the network to ensure network connectivity. However, in some applications, nodes are deployed in separate areas. Some nodes are not able to forward data to the sink directly through the links.

In order to address the problems above, mobile sink is proposed. By moving nearly to nodes that need to forward data, sink can directly collect data from the nodes in WSN or the data could be
forwarded with less relays. That would balance the energy consumption of the whole network and prolong its lifetime. At the same time, due to movement of sink, nodes that are not initially connected to the sinks can also transmit data to the sinks when the sinks are within their transmission range.

Path planning is a fundamental issue in data collection based on mobile sinks. Path planning is designing optimal mobile solution of sinks with the goal of minimizing the counts of relays and moving distance of sinks as much as possible. That could reduce not only delay of the whole network, but also the energy consumption of nodes near the sinks, which could prolong lifetime of the network.

Although mobile sinks could prolong lifetime of WSN, it still exists challenging issues. When path length of the mobile sinks becomes longer, energy consumption of nodes would be more balanced. That prolong lifetime of the network. But since the mobile sinks moving too long, the latency of collecting data would also be larger. It means that the path length of the mobile sinks should not be too long. Both energy consumption and delay should be taken into account. It is a challenging multi-objective optimization issue.

In WSN applications, a good path planning algorithm can serve the MAC protocol and routing protocol well. Meeting the demands of data collection and reducing network latency, and prolonging network lifetime are important issues in WSN. Many path planning algorithms have been proposed in recent years, but there are still some problems with these algorithms. This paper divides these existing works into two categories: single-hop data collection path planning and multi-hop data collection path planning.

The rest of this paper is organized as follow: the section 2 and 3 respectively review the single-hop data collection path planning and multi-hop data collection path planning. The section 4 discusses the advantages and disadvantages of single-hop data collection path planning and multi-hop data collection path planning, and point out the future work. Finally, section 5 concludes the whole paper.

2. SINGLE-HOP DATA COLLECTION PATH PLANNING

Clustering to collect data is a common method In WSNs. Divide a large WSN into different clusters, each with a cluster head. Clusters are the basic units of data collection. Cluster member would forward their data to the cluster head. And then the cluster head forwards data to the mobile sink. But in this way, the cluster head needs to relay data from a large number of cluster members, which will lose more energy than the other cluster members. This results in uneven energy consumption, and the short lifetime of the cluster head node makes the lifetime of the network shorter. Based on the considerations above, single-hop data collection path planning comes into being. This type of algorithm requires all nodes to forward data to the mobile sink in single hop.

In reference [1], DkM is proposed. It first uses k-means clustering algorithm to get a lot of rendezvous points (RPs). Then calculate the weight of each potential position of RPs according to the number of nodes in the RPs communication range, the distance of the node, and the average hop distance, so as to remove the redundant RPs according to the weight. It makes least RPs in network to achieve single-hop data collection for all nodes.

The author of reference [2] proposes TSP-DC. It uses straightforward simulated annealing algorithm to get a path. Then the gradient descent is used to optimize the location of the RPs so that the length of the new path is shorter than before. And all nodes are guaranteed to transmit data to the sink in single hop. The paper also proposes TSP-DA, which is an improved solution of TSP-DC. It can dynamically adjust the path based on actual data loads after computing a path by TSP-DC.

Literature [3] proposes a greedy algorithm for single-hop data collection, named Spanning Tree Coverage Algorithm. It calculates all the shortest distance between area covered by a RP and areas covered by the other RPs as cost. Calculates average cost according to the total cost and remaining uncovered nodes. Then searching for the candidate RPs that having the smallest average cost until all the nodes are cover. This paper also designs a solution for multiple mobile sinks for large networks.

In reference [4], considering that obstacles exist in sensing area, a heuristic tourism-planning algorithm is designed. Divide the sensing area into several grids with the same size and treat the
obstacles as rectangle. By designing a heuristic algorithm based on spanning graphs, a shortest obstacles-avoidance path could be found.

In reference [5], unmanned aerial vehicles (UAV) is used as mobile sink to collect data. Spiral path planning (SPP) algorithm was designed. The problem that uses UAV to collect data is seen as a traditional traveling salesman problem. The goal of the algorithm is to quickly compute a path with as short as possible. The algorithm divides the sensing area into multiple circles, and the UAV collects data one by one along the circles.

Literature [6] models the Resource Constrained Shortest Path Problem (RCSPP) with UAVs. The model takes into account the energy limitations of UAVs, the path length assignment between the UAVs, and collisions between UAVs. The goal of the RCSPP is to calculate the path and the number of UAVs for meeting demands. The paper proposes a scheme based on the column generation procedure, using path-decomposition formulation to compute a path, and ensure the target constraints.

Table 1 puts together the schemes for paths planning in single-hop data collection to compare their performance.

| Path planning strategy | Number of sinks | Path length | Node energy consumption | Delay | Non-uniform network | Obstacles | Scalability | Adaptive | Algorithm complexity |
|------------------------|-----------------|-------------|-------------------------|-------|---------------------|-----------|-------------|----------|---------------------|
| [1]                    | 1               | short       | low                     | high  | yes                 | no        | high        | low      | low                 |
| [2]                    | 1               | short       | low                     | high  | yes                 | no        | high        | high     | high                |
| [3]                    | ≥1              | short       | low                     | high  | no                  | no        | high        | low      | high                |
| [4]                    | 1               | long        | low                     | high  | no                  | yes       | low         | low      | high                |
| [5]                    | 1               | long        | low                     | high  | yes                 | no        | low         | low      | low                 |
| [6]                    | ≥1              | long        | low                     | high  | yes                 | no        | high        | high     | high                |

3. MULTI-HOP DATA COLLECTION PATH PLANNING

Single-hop data collection directly collects data generated by each node. It surely can reduce data relay counts of nodes near sinks and prolong lifetime of WSN. However, in this way, since the mobile sink must pass through the communication range of each node when collecting data, the path length becomes longer, resulting in a relatively large transmission delay. This is unacceptable for some delay-sensitive applications. Multi-hop data collection paths planning schemes could make the mobile sink not have to go through the communication range of all nodes, so as to reduce its path length to better solve the problem of transmission delay.

Literature [7] proposes a rendezvous-based solution for delay-constrained data collection with a mobile sink in WSN. This strategy is based on clustering protocol, which prolong lifetime of the entire network by selecting RPs in areas with sufficient energy. When planning a path, use Iterated Local Search (ILS), a heuristic algorithm, to get a shortest path.

Literature [8] proposes WRP, an algorithm based on RPs. The algorithm calculates a weight by size of data that needed to be forwarded and the distance between nodes and the nearest RPs. The nodes with largest weight will be selected as new RPs. These RPs will connect directly to the mobile sinks to forward data, thus avoiding excessive energy consumption.

Work done in [9] considers both obstacle-free network and obstacle network. This work divides the network into multiple regular triangles according to the communication range of sensors. In an obstacle-free network, each node is guaranteed to be covered by at least one RP. At the boundary of the network, the path length can be reduced by adjusting the position of the corresponding RPs. After adjusting the position of the RPs, MCPP, a heuristic algorithm, is used to compute a path. In network with obstacles, the same RPs selection strategy is adopted, and an algorithm for avoiding obstacles is used in the path planning.
Literature [10] proposes a mobile sink path selection (DBMSPS) algorithm with delay constraint. This algorithm first looks for node with the most nodes in its communication range as first RP. Then, by successive iterations, nodes with highest load are selected as RPs until all nodes can forward the data to the nearest RPs with no more than a given hops counts.

In [11], the sensing area is divided into several regular hexagonal regions, and the centers of each region are candidate RPs. The weight of each RP is calculated according to a cost function. Then iterations are repeated to select the RPs with the highest weight until the delay upper limit is met. Nodes will forward data to the adjacent RPs area if its area does not exist a RP. Then the data would be forwarded to the mobile sink.

Work done in [12] proposes an algorithm called Energy density based trajectory (EDT). This algorithm is based on energy density of each sensor node. Nodes with the lowest energy density will be selected as the RPs until all nodes in the network are covered. The work was improved when considering delay factor, and an improved algorithm, called delay aware energy density based trajectory (DAEDT), is proposed. Based on EDT, the improved algorithm increases the number of nodes selected as RPs until the path length just does not exceed a given delay limit.

Literature [13] proposes an algorithm called NDCMC. The algorithm combines clustered routing and mobile sinks and is designed to easily adjust the balance between energy consumption and latency as needed. The algorithm uses a density-based cluster head selection algorithm. The network is divided into clusters based on the density of nodes and a given cluster radius. Finally, the path is computed by optimal nearest-neighbor algorithm.

The author of the literature [14] proposes ACO-MSPD. This work assumes that the data generated by nodes for each time period is different. And the sizes of data that needs to be forwarded are also different. It results in a certain difference in the load of relay nodes. The ACO-MSPD selects RPs based on the weights calculated based on a given path length of the mobile sink for maximizing network lifetime and minimizing delay. This work also designed a re-selection scheme for RPs, which improved performance of the algorithm.

Literature [15] proposes VRDG algorithm. The algorithm divides the sensing area into multiple data gathering areas (DGA), each containing 1 to 3 circular data gathering units (DGU). Each DGU has a cluster head node (CH). The algorithm calculates position of RPs based on the position of CH in each DGU. Finally, these paths are connected from beginning to end to get a moving path of mobile sink.

Work done in [16] considers the difference in data generation rate and limited storage of nodes. EARTH and eEARTH are proposed. The EARTH algorithm takes the data generation rate, hops counts, and the distance into consideration. Then a spanning tree is formed and RPs are selected by traversing the tree. An improved method eEARTH is subsequently proposed, which further reduces the number of RPs to reduce the path length.

Table 2 puts together the schemes for paths planning in multi-hop data collection to compare their performance.

| Path planning strategy | Number of sinks | Path length | Node energy consumption | Delay | Non-uniform network | Obstacles | Scalability | Adaptive | Algorithm complexity |
|------------------------|-----------------|-------------|-------------------------|-------|---------------------|-----------|-------------|---------|---------------------|
| [7]                    | 1               | short       | high                    | low   | yes                 | no        | high        | high    | low                 |
| [8]                    | 1               | short       | low                     | low   | yes                 | no        | high        | high    | low                 |
| [9]                    | 1               | long        | low                     | high  | no                  | yes       | low         | low     | low                 |
4. SUMMARY AND FUTURE RESEARCH
A number of path planning algorithms for data collection have been proposed, which address some problems in path planning. The single-hop data collection path planning algorithm collects data directly by collecting data in single hop, so that the energy consumption of the network is balanced and the lifetime is prolonged. But the path length is long, resulting in a high data collection delay. Multi-hop data collection path planning collect data only need to directly collect data from some nodes in the network, which greatly reduces the path length and reduces the data collection delay. However, this type of algorithm will also cause some nodes to consume more energy because they need to transfer large amounts of data, resulting in a short lifetime of the whole network.

Prolonging network lifetime and reducing data collection latency are two of the most important performance metrics for path planning problems. The main goal of the existing work is to improve the algorithms to obtain better path planning performance. But they still have certain problems, which should be solved in the future work.

a) Multiple mobile sinks. As the network scale continues to expand, a single mobile sink has gradually failed to achieve the required performance. Therefore, using multiple mobile sinks to simultaneously collect data from the sensing area will become a trend. How to divide the sensing area, plan the path, and enable multiple mobile sinks to effectively collect data and make them load balanced will become a focus of future work.

b) Path planning with obstacles. The environment in the sensing area is often harsh or obstructive. In the existing work, obstacles existing in the sensing area are rarely considered. How to solve this problem is a difficult problem in practical application.

c) Dynamic network. The existing work considers static networks, and the mobile elements are only mobile sinks. The movement of a general node causes the topology of the network to change. Implementing path planning in dynamic networks is also a difficult problem.

5. CONCLUSION
This paper summarizes a number of typical path planning algorithms for WSN that are published in recent years. These algorithms are divided into two categories: single-hop data collection path planning and multi-hop data collection path planning, which have their own advantages and disadvantages. The existing works have been analyzed respectively. And their performance has been compared. Finally, the paper points out the advantages and disadvantages of the two types of algorithms and potential directions of future research.
ACKNOWLEDGMENTS
This research is supported by the National Natural Science Foundation of China under Grant Nos: 61562005; the Natural Science Foundation of Guangxi Province (Grant No. 2015GXNSFAA139286), and Thousands of Young and Middle-aged Backbone Teachers Training Program for Guangxi Higher Education (Education Department of Guangxi (2017) No.49).

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