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A Tree-Cluster-Based Data-Gathering Algorithm for Industrial WSNs With a Mobile Sink

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ABSTRACT Wireless sensor networks (WSNs) have been widely applied in various industrial applications, which involve collecting a massive amount of heterogeneous sensory data. However, most of the data-gathering strategies for WSNs cannot avoid the hotspot problem in local or whole deployment area. Hotspot problem affects the network connectivity and decreases the network lifetime. Hence, we propose a tree-cluster-based data-gathering algorithm (TCBDGA) for WSNs with a mobile sink. A novel weight-based tree-construction method is introduced. The root nodes of the constructed trees are defined as rendezvous points (RPs). Additionally, some special nodes called subrendezvous points (SRPs) are selected according to their traffic load and hops to root nodes. RPs and SRPs are viewed as stop points of the mobile sink for data collection, and can be reselected after a certain period. The simulation and comparison with other algorithms show that our TCBDGA can significantly balance the load of the whole network, reduce the energy consumption, alleviate the hotspot problem, and prolong the network lifetime.

INDEX TERMS Data-gathering scheme, cluster, mobile sink, wireless sensor networks.

I. INTRODUCTION

Wireless sensor networks (WSNs) have been widely applied in various industrial applications, e.g., patient monitoring and disease analysis, equipment monitoring and fault prediction, pollution monitoring and source detection, sea searching and tide monitoring. A WSN consists of a large number of tiny sensor nodes with low power, limited storage and transmission abilities [1]. Lots of energy of a sensor is consumed by communication phase in data gathering process, especially for a massive amount of heterogeneous sensory data. Also, in multi-hop communication, sensor nodes that near the sink tend to consume more energy as they are responsible for receiving and forwarding data from the whole network. It leads to a non-uniform energy consumption among nodes, i.e. the "hotspot problem". To alleviate the "hotspot problem" and balance the energy consumption, mobile elements (MEs) such as mobile sink and mobile data collector have been adopted for data gathering. However, for most of the data gathering algorithms, the data gathering latency is inevitable if the MEs perform data collecting via short range communications. On the contrary, if sensor nodes forward their data to the MEs via multi-hop transmissions, due to the overhead of control messages and communications, the energy consumption will be increased, which will largely reduce the network lifetime. Thus, it is necessary to balance the tradeoff between the relay hops of multi-hop communications and the tour length of the ME, which implies to achieve a long network lifetime with short data gathering latency.

To achieve this objective, many efficient mobile data gathering algorithms have been proposed. From the point of the view of consisting elements, these mobile data gathering algorithms can be divided into two categories:

- *Heterogeneous Sensor Network*: It consists of static sensor nodes, advanced nodes, mobile elements and a static base station (BS) [2]. The advanced nodes always have more resources than other nodes, so that they can act as rendezvous points (RPs) for data aggregation. Also the number and position of these advanced nodes must be constrained to limit the tour length of MEs, which in turn shorten the data gathering latency.
- *Homogeneous Sensor Network*: Some sensor nodes with shorter distance to the BS or mobile sink trajectory are recruited as polling points for the MEs to visit. This category of algorithms always limit the relay hops to a

small value to reduce the energy consumption of multi-hop transmissions.

However, to further investigate the characteristic and performance of these mobile data gathering algorithms, we divide the related literatures into two categories. The first category is a polling-based or rendezvous point-based approach, in which the mobile elements visit each of the selected polling points or rendezvous points, and collect the data of their associated sensors via short range communications [3]–[7]. In this category, when selecting the suitable pause locations for the mobile elements, the energy consumption and data gathering latency should be jointly considered. The second category adopts some existed clustering algorithms to select proper cluster heads (CHs) for data aggregation and uploading [8]–[13]. In this category, sensor nodes are organized into clusters and form the lower layer of the network. Cluster members upload their data to the CHs and the mobile elements collect data from the CHs at the higher layer. The cluster members and the CHs construct a backbone structure in the network.

In this paper, we propose a tree-cluster based data gathering algorithm with mobile sink, which is called TCBDGA for abbreviation. Contributions of this paper can be summarized as follows:

1) *Weight-Based Tree Construction:* It takes residual energy, the number of neighbors, and the distance to the BS into consideration.
2) *Tree Decomposition and Sub-Rendezvous Points Selection:* It constrains the local data collection scope.
3) *RPs and SRPs Re-selection*: It is performed by tree reconstructions after certain data collection rounds, and makes the energy consumption balanced.

The rest of this paper is organized as follows. First, recent research works are investigated in Section II. Then, in Section III, the network and sensor energy consumption model are described. And, in Section IV, we introduce and discuss the core algorithm TCBDGA, which includes three stage, tree construction, RPs and SRPs selection, and data collection. The simulation results and performance evaluation are given in Section V. And finally, Section VI concludes the paper.

II. RELATED WORK

A. OVERVIEW

The method of using mobile elements to gather data has drawn widely attention in recent years. In this section, we briefly outline some related typical literatures on mobile data gathering in WSNs, and group them into the following two categories:

1) *Direct Communicating Collection*, one or more MEs visit each sensor node and collect its data only via single-hop communication;
2) *Multi-hop Communicating Collection*, the MEs only visit a subset of sensor nodes or some designated positions, and other nodes need to send their data via a multi-hop path.

In the category of multi-hop communicating collection, MEs may visit only a set of locations, sensor nodes or some areas of the WSN and sensor nodes send their data to ME through multi-hop communication. Some related issues, such as schedule pattern, load balance, and data delivery latency, are also jointly considered along with routing to further improve energy efficiency. Therefore, Multi-hop communicating collection can further be divided into two sub-categories based on the amount of data needed to be collected:

- *Local Data Collection*, only interest data from source nodes need to be collected;
- *Full Data Collection*, data of the whole network needed to be collected.

To make our categories more clearly and well understood, we describe the related literatures in the following three classifications: direct communicating collection, local data collection, and full data collection. And finally, we give a summary at the end of this section.

B. DIRECT COMMUNICATING COLLECTION

Existing algorithms falling into this category always take advantage of the ME to gather data from a homogeneous network when it moves into the communication range of each sensor node. In general, only single-hop communication is required in these algorithms, which can achieve the longest network lifetime by minimizing the communication overhead on data gathering. However, the maximum energy use efficiency is achieved at the expense of extremely long delivery latency. Therefore, some of them just adopt some methods to compute a shortest path for the ME such that the data gathering latency can be reduced to a certain degree [15]. Additionally, others employ multiple MEs to further minimize the latency and the buffer overflow [16].

In [15], a data mule is exploited to collect data from all sensor nodes when it is in their communication range. The main objective of this protocol is to minimize data delivery latency by solving the Data Mule Scheduling (DMS) problem and achieve a shortest trajectory for the data mule under the location and time constraints. In [16], the target field is divided into several non-overlapped zones by a novel partition algorithm. To balance the data gathering latency, in each zone a mobile sink is adopted to visit every sensor node of that zone for data collection. The shuffled frog leaping algorithm is employed in the algorithm to calculate the optimal solution for the TSP and to reduce the traveling time of each mobile sink as well.

Existing protocols in this type only can be applied to some delay-tolerant applications. They are impractical when there are a large number of sensor nodes. So many researchers favor multi-hop communication for effective data gathering.

C. LOCAL DATA COLLECTION

To collect interest data from source nodes, some agent-based protocols employ one or more agents to track the latest location of the ME and then construct a optimal routing path from the source node to the ME for data forwarding via multi-hop communication [17]–[19]. Other approaches supporting query-driven, data-driven or both, would like to adopt some methods to establish the shortest data reporting routes and also reduce control overhead [20]–[22]. However, the hotspot problem still exists in these protocols. Also, the sink mobility can cause unexpected changes of network topology and it may bring excessive protocol overhead for route maintenance.

1) AGENT BASED APPROACHES

To enable efficient dissemination in large scale wireless sensor networks with sink mobility, an Intelligent Agent-based Routing (IAR) protocol is proposed in [17]. The closest node of the mobile sink is defined as an immediate relay node (IR). The IR is responsible for transmitting the relay path setup message (RPSP) to the agent along the shortest path. Then, data packets are routed along the reverse path of the RPSP. Moreover, the IR decides whether they must select a new path or existing path from the elected immediate relay to sources by distance comparison algorithm. The IAR can reduce the delay, energy consumption and the control overhead for data delivery.

To reduce the overhead of frequent location updates of the mobile sink, the authors in [18] adopt multiple agents that are located on the path between the source node and the mobile sink for data transmission. In the proposed Dynamic Multi-Agent-based Local Update Protocol (DMALUP), agents can be changed based on the location of the mobile sink so as to support the approximate shortest path. Only the last agent needs to update the latest location information of the mobile sink, which decreases the number of overheads. Further, the agent is dynamically changed and the proximately shortest route is created, and hence, the delay in data packet transmission is the minimum.

To address sink mobility and save energy, a multiple mobile sinks data dissemination mechanism (MSDD) is introduced in [19], which supports both event-driven and query-driven application. It exploits a hierarchical monitoring mechanism based on a two-tier grid structure that constructed by a master sink. To make the detected events be reported to the appropriate sinks immediately, MSDD employs a global agent (GA) to maintain each sink's location. It is proved that MSDD can decrease the communication overhead.

2) QUERY AND DATA-DRIVEN APPROACHES

The authors of [20] take predictable mobility of the sinks into consideration and propose a Predictable Mobility-based Data Dissemination protocol (PMDD) for data collection. A virtual grid structure is constructed, and only grid heads need to forward the query of sink and data of source nodes. Sensor nodes in PMDD know future locations to which the sink will move, so that they can forward their data directly to the sink via multi-hop communications. The authors has validated that PMDD can decrease the energy consumption and increase the data delivery ratio efficiently.

In [21], an efficient data-driven routing protocol (DDRP) is presented. It exploits the broadcast feature of wireless medium for gratuitous route learning, and combines data-driven packet forwarding with random walk routing for data forwarding path construction. DDRP can reduce the protocol overhead for route discovery and maintenance caused by sink mobility while keeping high packet delivery performance. SinkTrail [22], an energy efficient proactive data reporting protocols, is proposed for mobile sink-based data collection. SinkTrail establishes a logical coordinate system for routing and forwarding data packets. Sensor nodes update their coordinates corresponding to the trail messages and the sojourn positions of the mobile sink, and then select next hop with the shortest logical distance to the mobile sink to establish data reporting routes. The proposed protocol feature low-complexity and reduced control overheads.

D. FULL DATA COLLECTION

In this category, recent protocols always introduce hierarchical structure to a homogeneous or heterogeneous WSN and select some positions, sensor nodes or areas to visit for data collection. To achieve a balance between energy consumption and data gathering latency, they should constraint the hop distance of the data relaying path and the tour length of the MEs to suitable values. These protocols can be divided into three categories just as described in [23]: PP/RP based approaches, cluster based approaches, and area based approaches.

1) PP/RP BASED APPROACHES

In this sub-category, they firstly select or predefine some polling points (PP) or rendezvous points (RP) for the MEs to visit, which bounds the tour length. Then other sensor nodes need to affiliate themselves to the proper PP/RP and send their data to the MEs via short range communications [3]–[7], [9], [11], [13]. When selecting suitable pause locations or sensor nodes for the MEs to visit, the energy consumption and data gathering latency should be jointly considered.

Two polling-based data gathering approaches are proposed in [3], which is called SPT-DGA and PB-PSA, respectively. The centralized algorithm SPT-DGA is to iteratively find some proper sensor nodes as PPs on a shortest path tree (SPT). The selected PPs need to link as many as possible sensor nodes with the limited relay hop bound, so as to obtain the minimum number of PPs for mobile collectors to visit and perform data gathering. The basic idea of the distributed algorithm PB-PSA is that sensor nodes need firstly know the number of its neighbors and the distance to the data sink, and then iteratively select the best set of PPs by comparing the two parameters. In this way, both of the two algorithms can have the advantage of the minimum number of PPs, which lead to a short tour length of the mobile element. But neither of them has considered the factor of residual energy of each node when selecting PPs, and the selected PPs always deplete their energy faster than other nodes after some data gathering rounds.

The authors of [5] take advantage of SDMA technique when designing data gathering protocol such that compatible sensors can upload their data to the SenCar concurrently. For the single SenCar case, their objective is to find the minimum set of polling points from the candidates for obtaining the tradeoff between the shortest moving tour and the full utilization of SDMA. While for the multiple SenCars case, a region-division and tourplanning (RDTP) algorithm is proposed in which the data gathering time is uniformly distributed among different regions by decompose the tree based on the weight of data uploading and moving time. All the proposed algorithms can successfully achieve a full coverage of network with the shortest data gathering latency, and make the network load balanced. However, this paper does not take the energy consumption and hotspot problem into consideration.

In [4], an M-collector is used to visit each of the selected PPs for data gathering. They mainly focus on the problem of minimizing the tour length of the M-collector and refer to it as a single-hop data gathering problem (SHDGP) when selecting PPs. What's more, when consider multiple M-collectors, they adopt the spanning tree covering algorithm to select the minimum number of PPs and find the shortest sub-tours of each M-collector for data gathering. This scheme can achieve short data gathering latency since it can obtain the minimum number of PPs. However, it does not consider the energy of each node, as well as the hotspot problem around the PPs.

A weighted rendezvous planning (WRP) method [6] is proposed to select suitable sensor nodes as RPs for the mobile sink to visit. In WRP, each of the nodes has a weight jointly considering the hop count and the number of forwarded packets. Therefore, sensor nodes farther away from the selected RPs or with more than one packet in their buffer have a higher priority of being recruited as RPs. Hence, visiting the final selected RPs for data gathering will reduce the number of multi-hop transmissions, and thereby reduce the energy consumption. But each time after selecting a new RP, the network needs to recalculate the weight of the rest of nodes, which will cause a large control overhead.

In [7], a concentric circular trajectories model with the same distance of each ring is used. In each sub-trajectory, a number of Waypoint nodes are distributed uniformly for the Mobile Data Harvester (MDH) to visit, in order to achieve the desired full coverage. Also, the one-hop neighbors of the Waypoint nodes are chosen as the Designated Gateways (DG) for data buffering, which means that other nodes only need to upload their data to these DGs rather than the Waypoint nodes. Then the MDH collects data from these DGs when arrives at these Waypoint nodes. This method alleviates the load of Waypoint nodes, but it does not consider the energy of each node and the nodes density, which may lead to a hotspot problem around the Waypoint nodes.

To alleviate the sink-hole problem, the authors of [11] make the mobile sinks move on a predetermined path, along the perimeter of a hexagonal tiling, and stop at multiple locations for data gathering. Meanwhile, they also propose a distributed algorithm used by the sinks to decide their next moving location such that the virtual backbone formed by the mobile sinks remains interconnected at all times. At the end of each data gathering round, a sink decides whether or not to move to a new location, depending on the energy levels of its one-hop sensor neighbors. But the mobile sink may stay at a location for a long time, which leads to a long data gathering latency.

The authors of [13] propose a moving strategy called energy-aware sink relocation (EASR) for mobile sink to alleviate the hotspot problem. In this strategy, the transmission range of sensor nodes and the moving strategy of the mobile sinks are adaptively adjusted according to the residual energy of them. The disadvantage of this algorithm is that the control overhead for changing the transmission range of nodes may be high, and the mobile sinks need frequently to check the residual energy of the sensor nodes and whether the moving condition is satisfied, which also incur large network energy consumption.

In [9], the authors consider a heterogeneous WSN which consists of a large number of sensor nodes, a few mobile data collectors (DCs), and a static BS. The DCs play the role of the cluster head and perform the cluster formation process at every pause location. Whenever the average energy of the nodes in the one-hop region of the DC is below the threshold value, the DC need to select its next position from its candidate list such that the average residual energy is the highest and the reliability R is satisfied. But multi-hop transmissions from sensor nodes far away from the DCs may lead to high energy consumption to the network. Also, the frequent changes of the positions of DCs may incur a large overhead for the network topology maintenance.

2) CLUSTER BASED APPROACHES

Protocols falling to this sub-category always take the advantage of some existed clustering algorithms to organize the sensor network into different clusters. The network may be homogeneous or heterogeneous. Proper cluster heads (CHs) need to be selected for data aggregation and uploading [8], [10], [12], [24]–[30]. Cluster members upload their data to the CHs and the MEs collect data from the CHs at the higher layer.

An efficient energy-aware distributed intelligent data gathering algorithm (DIDGA) is presented in [24], which includes cluster formation and path formation phases. DIDGA constructs a minimum connected dominating set (MCDS) based on maximal independent sets (MISs) to form a cluster, and selects the node with more power to be cluster head to prolong the network lifetime. Then, the mobile collector needs to communicate with each cluster head to gather sensed data. A path formation optimized algorithm (PFOA) combines ant colony algorithm and evolutionary algorithm is introduced for the mobile collector to solve the TSP problem and to satisfy the time-limited constraints.

The authors in [25] adopt a distance based range constrained clustering (RCC) algorithm to organize sensor nodes into groups. The cluster center is defined as stop points for the MDC. The tour of MDC is modeled as a TSP on the stop points. To reduce the data gathering latency, the RCC algorithm tries to obtain the minimum number of stop points but with full coverage. Moreover, a Edge-Fold (EF) heuristic is developed to get a balance between increasing the tour length and utilizing the wireless link, which further bring down the average packet delay.

In [8], a metric-based distributed clustering algorithm is presented for the lossy network. The authors have studied both one-hop and k-hop clustering algorithms. In this algorithm, both link qualities and residual energy are jointly considered in calculating the weight of each node for selecting proper CHs. However, the selected CHs are responsible for receiving all data of its members. It may lead to a fast depletion of their energy and storage space.

Some literatures may take the advantage of a heterogeneous architecture for WSNs composed of a few resource rich sensor nodes and a large number of simple static sensor nodes. The advanced nodes can help relieve sensors that are heavily burdened by high network traffic, thus extending the network lifetime. In [26], the network is assumed to be heterogeneous with some advanced sensor nodes and normal nodes. A mobile sink based improved stable election (MSE) algorithm is introduced. The mobile sink moves back and forth along a fixed center line of the sensing field. The selection of cluster heads is based primary on the fraction of advanced nodes with additional energy, and secondary on the ratio between residual energy and initial energy. Non-cluster head nodes need to affiliate themselves to the cluster heads with strongest received signal strength (RSS). The MSE protocol can achieve energy balancing and network lifetime prolonging, but the fixed trajectory may not suitable all the time.

In [12], a rendezvous-based data dissemination protocol based on multi-hop clustering (RDDM) is proposed. It exploits a Backbone-based Virtual Infrastructure (BVI) which uses only CHs for data routing. The RDDM provides enough backup nodes to substitute for a CH and enough backup paths between neighbor CHs, which provide high robustness against node and link failures. Moreover, when a source node wants to upload its packet to the destination, a shortest path will be found by the RDDM through signaling only between neighbor CHs. It can reduce the energy consumption. But the CHs may depletion their energy first due to their high burden.

The authors of [27] also construct a BVI which composes clusters of the sensor nodes and connects the cluster heads as a shared tree. The clustering algorithm used in this protocol is KOCA [28], which aims at generating connected overlapping multi-hop clusters in WSNs. The protocol can provide the shortest path from a source node to the mobile sink by exchanging routing tables between neighbor cluster heads. A mobile sink only registers the cluster ID of the current standing cluster into the root of the shared tree and finally, the source delivers data to the current standing cluster via the shortest path by the routing table.

A virtual grid based dynamic routes adjustment (VGDRA) scheme is presented in [29], which also constructs a BVI for data collection. It divides the sensing field into K equal sized cells, and selects nodes close to the center to be cell headers. The BVI is constructed by the cell headers. The mobile sink moves along the periphery of the field and communicates with the border cell headers for data collection. To reduce the communication cost, only a subset of cell headers needs to take part in re-adjusting their routes to the latest location of the mobile sink.

In [10], the authors build a cluster structure and propose a distributed protocol which only selects nodes with sufficient energy and in close proximity with the mobile sink (MS) for sufficient long time as Rendezvous Nodes (RNs). The clustering scheme used in this algorithm constructs a multi-size cluster structure, where the size of each cluster is inversely proportion to the distance of its cluster head from the MSs trajectory. By clustering and selecting the proper number of RNs, it can minimize the data loss and achieve great data throughput. Also, the replacement of RNs can lead to a balanced energy consumption of the network. But its application scenario is limited to non-real time applications.

Similar to [10], the authors of [30] preserve the benefits of the LEACH algorithm to form a cluster and improve CH selection by considering the residual energy of sensor nodes. They also combine them with the concepts of a mobile sink and rendezvous nodes (RNs). The selection of RN is also based on the distance from the MS trajectory. The proposed protocol can decrease the energy consumption in large-scale networks.

3) AREA BASED APPROACHES

In this category, the MEs visiting different areas for data collection have different effects on the network performance, such as load balance [31], [32] and decreased data gathering latency [33]. Sensor nodes in other areas need to transmit their data to these visited areas via multi-hop communication.

The authors of [31] propose an Energy-Balanced Data Collection (EBDC) mechanism. It considers a circular monitoring region, in which sensor nodes in different rings have different data-relaying workloads. To balance the energy consumption, the mobile sink needs to move along different tracks with different number of sweep repetitions to collect data. The number of sweep repetitions in each track is calculated by the energy consumption of each sensor node when the mobile sink move along that track.

Similar to [31], in order to balance the non-uniform energy consumption of sensor nodes in a circular area, the authors of [32] present a clustering-based routing algorithm in wireless sensor networks with mobile sink (CRA).

In the CRA, the mobile sink moves around a specified circle and the circular area near this trajectory is defined as buffer area. The buffer area has the largest load in the network, so in order to achieve maximum network lifetime, the main task in the CRA is to determine the radius of the buffer area and the radius of the moving circle of the mobile sink. Moreover, an improved algorithm CRA-1 is also introduced by using density controlling to further balance the network load.

A biased sink mobility with adaptive stop times is studied in [33], as a method for efficient data collection in wireless sensor networks. To achieve a balance of energy consumption and data gathering latency, when selecting the next area to visit, the mobile sink favors less visited areas to cover the network area faster, and adaptively stops more time in some regions that tend to produce more data.

E. SUMMARY

In summary, as listed in Table 1, direct communication approaches incur an extremely long data gathering latency, while some multi-hop communication for local data collection approaches such as agent-based approaches and other query/data-driven approaches still encounter the problems of non-uniform energy consumption and large control overhead due to long relaying hop distance. So it is necessary to jointly consider the relay hop distance and the tour length of the MEs when perform full data collection. In some cluster-based approaches, a CH buffers the data packets from its cluster members till the ME comes in contact, which may lead to fast depletion of the CHs due to the heavy burden. The proposed area based approaches are only feasible to some special network architectures with non-uniform load distribution.

TABLE 1. Related work summary.

	Categories	Advantages	Disadvantages	Rep.
	Direct commun	Minimum energy consumption	Long data gathering latency	[15], [16]
Local data collect.	Agent based	Real time	Hotspot, large control overhead	[17]–[19]
Local data collect.	Query/data driven	Real time	Non-uniform energy consumption, large control overhead	[20]–[22]
Full data collect.	PP/RP based	Dynamic to different requirements	Control overhead	[3]–[7], [9], [11], [13]
Full data collect.	Cluster based	Decreased energy consumption	Fast depletion and buffer overflow of CHs	[8], [10], [12], [24]–[30]
Full data collect.	Area based	Load balance, reduced coverage time	Only for special network	[31]–[33]

The PP/RP based approaches can jointly consider many decisive factors such as load balance, energy consumption and data gathering latency for improving the network performance when selecting the suitable moving locations of the ME. Moreover, it can dynamically adapt to different network environment and different application requirements. To this end, our work in this paper belongs to this type and learns from many relevant researches for constructing the network structure and selecting appropriate RPs. Furthermore, the SPT-DGA [3] is typical of these PP/RP based approaches, and it is similar to our TCBDGA in many aspects. It also constructs a tree topology from the beginning, and then divides these trees by selecting some appropriate PPs on them. The selected PPs are also regarded as sojourn locations for the ME to visit and perform data gathering. Moreover, to make a balance between energy consumption and data gathering latency, the selected PPs in both the SPT-DGA and our TCBDGA need to link as many sensor nodes as possible with a limited relay hop bound. Our work outperform SPT-DGA in some aspects, which will be validated by the simulation in the section of Simulation and Analysis.

III. NETWORK AND ENERGY CONSUMPTION MODEL

The WSN for our TCBDGA consists of N static and homogeneous sensor nodes deployed randomly over an $L \times L$ square area, as shown in Fig. 1. There is a static BS located at the center of the distributed area. A mobile sink moves in the field periodically from the BS to collect data. The mobile sink is assumed to be with unlimited energy, memory and computing resources. All sensor nodes are initially provisioned with the same amount of energy E_0 and location-aware abilities by using localization technology [34], [35], and the mobile sink knows all nodes' locations. Each node has a limited communication range R_s, and communication is always successful if other node is within its transmission range. Each of them generates data with the same rate and sends them only once in each data collection round. We assume that the whole deployment area is full covered and well connected.

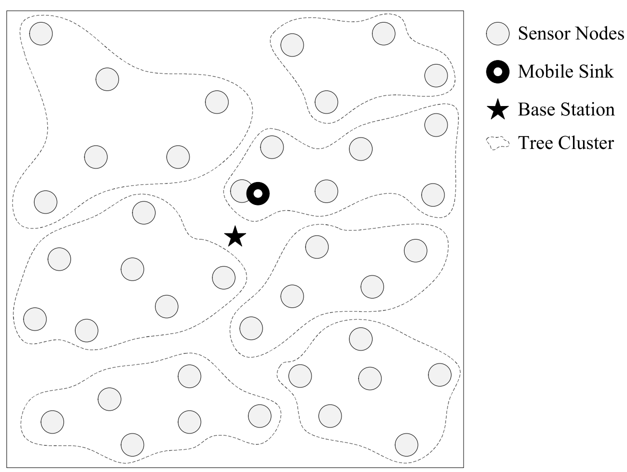

FIGURE 1. Network model.

The energy consumption of a sensor includes the power for sensing, receiving, and transmission. In this paper, we ignore the energy consumption for sensing since it is negligible compared with the other two types of energy consumption. The energy consumption of one node for sending or receiving a message with K bits is calculated by the following formula:

$$E_{Tx}(K, d) = E_{elec} \times K + \varepsilon_{amp} \times K \times d^2 \quad (1)$$

$$E_{Rx}(K) = E_{elec} \times K \quad (2)$$

Where d is the physical distance between two sensor nodes, and E_{elec} is the energy consumption factor indicating the power per bit incurred by the transmitting circuit or the receiving circuit, ε_{amp} represents the coefficient for the amplifier to send one bit.

IV. TCBDGA

A. OVERVIEW

In our proposed tree-cluster based data gathering algorithm, which is named TCBDGA for short, a mobile sink starts the data collection tour periodically from the BS, stops at each rendezvous point, collects data from the nodes in its one-hop range directly, and finally, return back to the BS for one round. The whole algorithm consists of three stages, tree construction, RPs and SRPs selection, and data collection. In tree construction stage, each node is weighted by its residual energy, its distance to the BS, the number of its two-hop neighbors and the average residual energy of its one-hop neighbors. By communicating with its one-hop neighbors and comparing their weight, every node treats the neighbor with the maximum weight as its parent node. Thus, the data-gathering tree can finally be constructed. In RPs and SRPs selection stage, every root node of the trees is considered as a Rendezvous Point. And each tree is decomposed into a set of sub-trees according to its depth and its traffic load. Then Sub-Rendezvous Points (SRPs) can be found in the sub-trees for further load balancing. In the data collection stage, the positions of RPs and SRPs are considered as the stop points of the mobile sink. Every sensor node will transmit its data to the corresponding one-hop neighbors of its associated RP or SRP, the latter will store and upload them to the mobile sink when it arrives.

In data collection stage, when the mobile sink visits each RP/SRP every round, the latter decides whether or not to send a tree-reconstructing request according to the residual energy ratio of its one-hop neighbors. If the condition is met, the corresponding RP/SRP sends the request to the mobile sink after it arrives. Finally, the sink decides whether to perform tree reconstruction according to the proportion of the number of requests to the number of RPs and SRPs.

B. TREE CONSTRUCTION

The main goal of selecting rendezvous points is to alleviate the "hotspot problem" so as to achieve load balancing, and also to balance the tradeoff between the energy consumption and data gathering latency. So the residual energy and average energy of its one-hop neighbors should be focused on when choosing the parameters of one node's weight to avoid the fast depletion of the heavily loaded nodes. Meanwhile, in order to get the minimum number of stop points of the mobile sink and minimize its tour length, sensor nodes with more neighbor nodes and closest to the BS should have a higher priority to be a rendezvous point. In addition, the authors of the literature "Bounded Relay Hop Mobile Data Gathering in Wireless Sensor Networks" [3] have proved that in order to pursue a tradeoff between the energy saving and data gathering latency, which achieves a balance between the relay hop count for local data aggregation and the moving tour length of the mobile sink, the relay hop count d should be constrained to a small level (2 or 3) to limit the energy consumption at sensors. Therefore, in this paper we only consider the number of two-hop neighbors of a node to calculate its weight.

1) PRELIMINARIES

In the beginning, every node needs to calculate the number of its two-hop neighbors and its corresponding weight. Therefore, each node should firstly broadcast a *BRO_MSG_T* message, which contains its *ID* number, residual energy E_r and a time to live *TTL* value. The initial value of *TTL* is set to 2, when a node receives a *BRO_MSG_T*, it forwards the message to its neighbors if *TTL* has not reached 0. Thus, every *BRO_MSG_T* will only be received by its two-hop neighbors.

After broadcasting, node i counts the number of its neighbors in its one-hop range N_i^{1-hop} and two-hop range N_i^{2-hop} respectively, according to the value of *TTL* and the number of the *BRO_MSG_T* it received. Meanwhile, for node i, the average residual energy of its one-hop neighbors can be calculated through the formula:

$$E_i^{1-hop} = \left(\sum_{1}^{N_i^{1-hop}} E_r\right) / N_i^{1-hop} \quad (3)$$

We also define the selection weight of node i as follows:

$$W_i = N_i^{2-hop} \times E_i \times E_i^{1-hop} / D_i \quad (4)$$

E_i denotes the residual energy of node i, and D_i denotes its distance to the BS which can be calculated by its coordinate.

2) PARENT NODE SELECTION

By exchanging weight information derived by the equation above with its one-hop neighbors, every node maintains a list of weights of its one-hop neighbors. By comparing its own weight with its one-hop neighbors', every node selects its appropriate parent node respectively in accordance with the following rules:

- If there are neighbor nodes whose weight are bigger than node i, then node i chooses the node with the maximum weight as its parent node, and node i itself is the child node. Here, if more than one neighbor nodes have the maximum weight, node i chooses the node with the biggest *ID* number as its final parent node.

To better understand this case, we illustrate an example in Fig. 2. There are six sensor nodes. Node 1, 3, 4, 5, and 6 are the one-hop neighbors of node 2. Here, we assume that

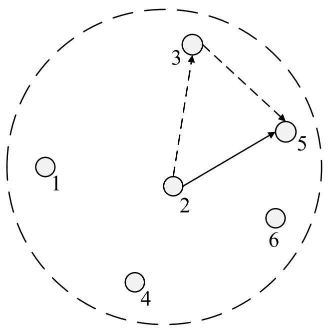

FIGURE 2. Example of selecting parent node with a bigger *ID* number.

the weight values of node 3 and node 5 are equal and the highest among them. In this case, node 5 will be chosen as the parent node of node 2 according to the rules above. If node 3 is selected as the parent node of node 2, then node 3 may regard node 5 as its parent node, which leads the transmission path of node 2 to increase one more hop. In order to avoid this situation, each sensor node needs to choose the neighbor with a bigger *ID* number as its final parent node when more than one neighbors have the maximum weight value.

- If none of the one-hop neighbor nodes of node i regards node i as its parent node, and the maximum weight value of them is less than the weight of node i, then node i is an isolated node. To avoid such situation, node i still chooses the neighbor node with the highest weight as its parent node.

To illustrate this situation, we give an example in Fig. 3, where node 2, 3, 4, and 5 are the one-hop neighbors of node 1. We assume that the weight of node 5 is the highest among these one-hop neighbors of node 1, but it is lower when compared with the weight of node 1. It's assumed that the parent node of node 2, 3, 4, and 5 are node 9, 8, 7, and 7 as illustrated in Fig. 3. None of the one-hop neighbors of node 1 will regard node 1 as its parent node, in this case, node 5 will be chosen as its parent node to avoid node 1 becoming an isolated node.

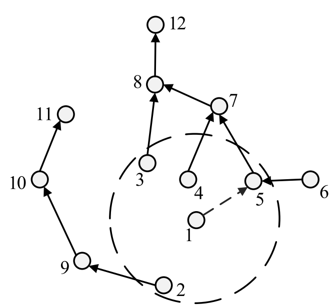

FIGURE 3. Example of selecting proper parent nodes.

- If node i finds that node j is the one-hop neighbor node with the maximum weight, and the weight value of node i and node j are the same, then node i compares the *ID* number of node j with its own. If $i < j$, then node i finally chooses j as its parent node to avoid the situation that both of them regard the other as its parent node, thus, a closed loop will not be formed. If $i > j$, node i does not need to find a parent node any more if it has a child node already, but if node i has no child nodes, the rule 2 above needs to be adopted to avoid node i to be an isolated node.

Based on these rules, each tree eventually has one and only one node whose child nodes set is not empty, but none of its neighbor nodes can be chosen as its parent node. Finally, the tree is set up.

3) ROOT NODE AND LEAF NODE IDENTIFICATION

The sensor nodes in TCBDGA can be divided into three categories: root nodes, leaf nodes, and normal nodes. When node i finds that it only has child nodes and no parent node, it marks itself as a root node. When node i finds that it only has a parent node and no child nodes, it marks itself as a leaf node. Other nodes are normal nodes. Eventually, each tree only has one root node, and every node except root node on the tree has only one parent node respectively.

4) HOP COUNT CALCULATION

After root nodes are marked, each tree can be identified by the *ID* number of its root node. Each root node broadcasts a message *BRO_MSG_H* to all its child nodes, which contains two parts, the root *ID* and the hop level h. The initial value of h is set to 0, and it is increased by one when the *BRO_MSG_H* is received by a normal node or a leaf node. Every *BRO_MSG_H* will be forwarded until it reaches a leaf node. According to the information of *BRO_MSG_H* it received, every normal node, as well as leaf node, confirms its associated tree (the *ID* number of root node) and calculates its hop level to the corresponding root node. Also, the number of child nodes of each normal node and root node can be counted on the basis of the relationship between parent nodes and child nodes.

Now the tree construction phase is finished, and the whole network is divided into many tree clusters. Each tree is identified by the *ID* number of its root node at the top of the tree. Due to the forwarding relationship between child node and parent node of the tree, we can intuitively draw a conclusion that the root node may have the highest weight in the tree. Consequently, the residual energy, the average residual energy of their one-hop neighbors of the root nodes may be the highest, and the number of their neighbors may be the most. Moreover, each node on the tree knows its distance away from its corresponding root node and can calculate the number of its child nodes respectively. However, the depth of these trees are not under control. Some normal nodes may have a large number of child nodes and may be far away from the corresponding root nodes, which can cause heavy load and traffic flow, and greatly influence the performance of the whole network.

C. RENDEZVOUS POINT AND SUB-RENDEZVOUS POINT SELECTION

1) RENDEZVOUS POINT SELECTION

As mentioned in the tree construction phase, root nodes have the highest weight in the tree. Therefore, compared with other nodes, root nodes may have the highest residual energy and the maximum number of neighbor nodes. And the average residual energy of their one-hop neighbors may also be the highest. Hence, it is naturally to select root nodes as Rendezvous Points (RPs) for data collecting.

Since the neighbors of root nodes have relatively higher energy than the others on the same tree, when the root nodes are selected as RPs, these RPs can avoid early death due to the heavy load and traffic flow, which in turn leads to a balanced network load and uniform energy consumption distribution. In addition, when the mobile sink traverses the network and stops at these RPs to collect data, the denser region can firstly be visited, which shortens the data gathering latency in a way.

In this paper, we assume that each sensor forwards its sensory data to its corresponding parent node, all the data is transmitted in the direction of RPs. However, when the depth of a tree is too large, which implies that some normal nodes may have a heavy traffic load (i.e. too many child nodes) and a large hop count to the corresponding RPs, the hotspot problem of the nodes closer to the RPs and the unbalanced energy consumption still exist. Therefore, in order to alleviate the burden around the RPs and achieve uniform energy consumption, it's necessary to decompose the trees with large depth and heavy load into several sub-trees and select appropriate nodes to serve as Sub-Rendezvous Points (SRPs) in the sub-trees. The details are introduced in the next section.

2) SUB-RENDEZVOUS POINT SELECTION

The main objective of selecting Sub-Rendezvous Point (SRP) is to prevent sensor nodes with larger hop count to RPs and heavier traffic flow from forwarding their received data in the direction of RPs, but in the direction of SRPs. It further minimizes the energy consumption of each sensor due to multi-hop transmissions. So we jointly consider the hop count and the number of child nodes of each normal node to select suitable nodes as SRPs and decompose the trees.

Each node obtains some important information according to the *BRO_MSG_H* they received. It is listed below:

- Its hop count to the corresponding RP, i.e. the hop level $H(i, RP)$;
- The number of its child nodes $CN(i)$;
- The amount of data it forwards $DS(i) = (CN(i) + 1) \times k$ bit, where k indicates the amount of data every single node sensed for a specified period.

If $H(i, RP) > 2$ and $CN(i) \geq 2$, node i regards itself as a candidate SRP, then it calculates its cost weight $CW(i) = H(i, RP) \times DS(i)$. Hence, sensor nodes that are farther away from the selected RPs or have more than one packet in their buffers have a higher priority of being recruited as an SRP. All candidate SRPs exchange information with their two-hop child nodes for cost weight comparison. The rules are as follows.

In the same sub-tree, if one of the candidate SRPs finds that its parent node is not a candidate SRP but one or more of its child nodes are candidate SRPs, then these SRPs will compare their cost weight parameter and the node with highest cost weight is selected as the final SRP of the tree. If their cost weights are the same, then the ancestor node with less hop count (i.e. closer to its corresponding RP) will be recruited as the final SRP. If these candidate SRPs are within two hops away from each other, then all of them will regard themselves as the final SRPs.

As illustrated in Fig. 4, sensor node 6 and 7 is candidate SRPs. But only node 7 is recruited as final SRP for the reason that its cost weight is higher than that of node 6 in accordance with the above rules.

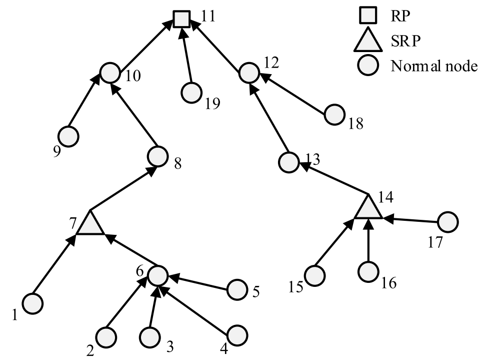

FIGURE 4. Example of constructed tree structure.

After all SRPs are identified, the tree decomposition operation is performed. And, sub-trees are set up. Thus, nodes with higher traffic load and larger hop count need not to forward data in the direction of their corresponding RPs. It reduces the number of multi-hop transmissions, and thereby minimize the energy consumption.

D. DATA UPLOADING, STORING AND DATA COLLECTION

1) DATA UPLOADING AND STORING

After all RPs and SRPs are selected, the mobile sink begins to perform its data gathering. When mobile sink moves to a RP or SRP, it polls each sensor within its transmission range. The sensors that receive the polling messages upload packets directly to the mobile sink via single-hop transmissions instead of sending large amount of data they received to the corresponding RPs or SRPs, which reduces the burden of RPs and SRPs significantly. Thus, child nodes in the one-hop range of RPs or SRPs need to be identified before data gathering process. After that, other nodes only need to upload the packets to its corresponding parent node. So all packets will be forwarded in the direction of the corresponding RPs or SRPs until being received and stored by the one-hop child nodes of RPs or SRPs.

Hence, RPs and SRPs only need to send a notification to their one-hop child nodes to inform them to be data storage nodes (DSNs) at first. When packets from child nodes have been forwarded to these DSNs, the data uploading process stops. Other nodes except these DSNs, may be two or more hops away from their corresponding RPs or SRPs, transmit their data to their corresponding parent nodes respectively. Obviously, all packets are stored by these DSNs and then can be uploaded to the mobile sink when it arrives.

To store all data of a tree in these DSNs, we can not only take advantage of the high residual energy of them, but also reduce the heavy load of the RPs or SRPs caused by receiving too large amount of data from the whole tree.

2) DATA COLLECTION

A data collection stage consists of many data collection round. After each data collection, the mobile sink decides whether to reconstruct the whole network trees based on some conditions. The details is discussed in the next subsection of ''RPs and SRPs Re-selection''. In each data collection round, the mobile sink needs to move in the network deployment area periodically to perform data gathering. The selected RPs and SRPs report their location information to the BS firstly. After getting these location information from BS, mobile sink invokes an approximation algorithm for the TSP (Traveling Salesman Problem) to plan an approximately optimal route for these RPs and SRPs. It then moves to these nodes one by one to gather data from sensors in the proximity via single-hop transmissions. When arriving at these RPs or SRPs, the mobile sink firstly sends a polling message to these DSNs and RPs or SRPs in its one-hop range, stops at these RPs and SRPs for data gathering, and then moves to another position until all data of the tree have been uploaded. In this manner, the mobile sink visits all the trees and finishes its one data collection round.

E. RPs AND SRPs RE-SELECTION

As discussed above, the energy consumption of DSNs significantly influences the network lifetime, since they have almost the heaviest load of their corresponding trees. Hence in each data collection round, after all data of the corresponding tree of the RPs or SRPs is uploaded to the mobile sink, the RPs or SRPs retrieve the residual energy of their one-hop child nodes (i.e. the DSNs), and then decide whether to send a request of performing tree reconstruction to the mobile sink. The mobile sink calculates whether to perform tree reconstruction according to the ratio of the accumulate value of requests to the number of RPs and SRPs. The details are as follows:

1) In each data collection round, after all data of the corresponding tree is received by the mobile sink, the corresponding RP or SRP retrieves the residual energy of its one-hop child nodes. If at least one of these nodes has residual energy below $m\%$ of its initial energy recorded in the first data collection round after the tree constructing or reconstructing, then the RP or SRP needs to send a request of tree reconstruction to the mobile sink before it moves to next position.
2) After these RPs and SRPs are visited by the mobile sink the mobile sink calculates the ratio of the accumulate value of requests to the number of RPs and SRPs before the next tree reconstruction stage. If it is higher than $n\%$, then the tree reconstruction is performed and new RPs and SRPs are selected as the stop points of the mobile sink for data gathering. Otherwise, in the next round the mobile sink still traverses the original RPs and SRPs of last round for data collection.
3) Every time after tree reconstruction, the new RPs and SRPs need to retrieve the residual energy of its one-hop child nodes and record it in the first data collection round. Then the value is a benchmark for these RPs and SRPs to make a decision about whether to send a tree reconstruction request to the mobile sink after each data collection round. And the mobile sink continues to calculate whether to perform a tree reconstruction based on the value of m and n.

From the procedures above, we believe that there is a tradeoff between the value of m and n and the cost of tree reconstructing. If m is too large, which means RPs or SRPs need to send a request when the residual energy of the DSNs is still very high, in order to reduce the cost of frequently tree reconstruction, n needs to be set with a large value, which implies that the mobile sink performs tree reconstruction when it receive a large proportion of requests. On the contrary, when m is set too small, which means the residual energy of the DSNs is very low, in order to avoid the fast depletion of them, n should be constrained to a small value to make the mobile sink perform tree reconstruction as soon as possible, which means to sacrifice the cost of tree reconstruction to prolong the whole network lifetime. We validate this by simulations in the next section.

V. SIMULATIONS AND ANALYSIS

In this section, in order to evaluate the performance of our TCBDGA and compare with other algorithms, we implement two different sets of simulations using the well-known tool MATLAB. First, we perform a set of experiments to validate the network performance with different values of m and n (introduced in the last section) under the same simulation conditions, and select a pair of m and n with approximately the best network performance for comparison with other schemes. Then we adopt the derived m and n for tree reconstruction in our TCBDGA and compare its performance with our TCBDGA with no reconstruction, and with the SPT-DGA under different scenarios.

A. SIMULATION MODEL

Table 2 summarizes the important simulation parameters and their values. In our simulations, sensor nodes are randomly deployed in a square area with the size of $L \times L$, and the value of L varies from $100m$ to $500m$. The number of the static sensor nodes N increases from 100 to 500. All the sensor nodes have the same communication range R_s and the same initial energy E_0. Also, there is a BS located at the center of the deployed area. Other parameters are listed in Table 2.

TABLE 2. Simulation parameters.

Parameters	Definition	Default Settings
E_0	Initial energy of each node	$0.5J$
E_{elec}	Power per bit incurred by the transmitting circuit or the receiving circuit	$50 \times 10^{-9} J/bit$
ε_{amp}	Coefficient for the amplifier to send one bit	$10 \times 10^{-12} J/bit/m^2$
N	Number of sensor nodes	100, 200, 300, 400, 500
L	Side length of distributed area	$100m$, $200m$, $300m$, $400m$, $500m$
R_s	Transmission range of each node	$10m$, $20m$, $30m$, $40m$, $50m$
k_0	Packet length of exchanged message	$128bit$
k_1	Packet length of sensory data	$2000bit$
m	Residual energy ratio of DSN	0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%
n	Threshold ratio of requests to the number of RPs and SRPs	20%, 40%, 60%, 80%, 100%

In all of our experiments, sensor nodes use the CSMA protocol for channel access and broadcasting the control packets. In each data collection round, each sensor node generates a fixed size packet and sends it to its parent. Note that there are two different sizes of packets in our TCBDGA, one is the messages of each node exchanged with their neighbors to select appropriate parent and to perform tree construction or reconstruction, which is used for calculating the expense of the tree reconstruction. The other type of the packets is the sensory data of each node, which is transmitted to their corresponding parent node, and then is uploaded to the mobile sink. In our experiments, we define these two types of packets as k_0 and k_1 respectively, and the value of them are listed in the Table 2. Moreover, we do not consider the packet loss due to collision and interference at the MAC layer for the reason that collisions among transmissions can be avoided by assigning different time slots to each of the child nodes. Also, sensing and computation cost for data aggregation are considered to be negligible in our simulations.

During the data gathering process of our experiments, we adopt the nearest neighbor (NN) algorithm for the problem of TSP [14] to determine an approximately optimal tour for the mobile elements in both our proposed TCBDGA and the SPT-DGA, which allows the mobile elements to start from the BS and choose the nearest unvisited RPs or PPs for the next visit, and eventually move back to the BS.

To verify the network performance, we choose the following performance metrics:

- *Network Lifetime:* The number of the data collection round until the first sensor node of the network dies as a result of depleting its energy resources.
- *Average Tour Length:* The average tour length of the mobile element that starts from the BS, traverses each of the selected RPs or PPs using the NN algorithm and finally returns back to the BS in each of the data collection rounds. It represents the data gathering latency of the corresponding algorithm.
- *Average Times of Reconstructions:* The average times of reconstructions in each data collection stage of our proposed TCBDGA with different values of m and n.

B. PERFORMANCE OF TCBDGA WITH DIFFERENT VALUES OF m AND n

We conduct a set of experiments of our proposed TCBDGA with different pairs of m and n to evaluate the influence of them on the network performance. We assume that 200 sensor nodes with the same initial energy E_0 and the same transmission range $30m$ are distributed randomly and uniformly in a $200m \times 200m$ square area. And a BS is located at the center of the square area. Each sensor node generates a fixed size (i.e. $k_1 = 2000$) of packet and uploaded it to its corresponding parent node in each data collection round. Other parameters are listed in the Table 2.

As described in Section IV, the variation of the ratio m and n significantly influences the frequency of tree reconstruction, which leads to different energy consumption of the network. To verify the difference, we set m from 0 to 100, and n to 20, 40, 60, 80, and 100, respectively. The average times of reconstructions and network lifetime are illustrated in Fig. 5 and Fig. 6, respectively.

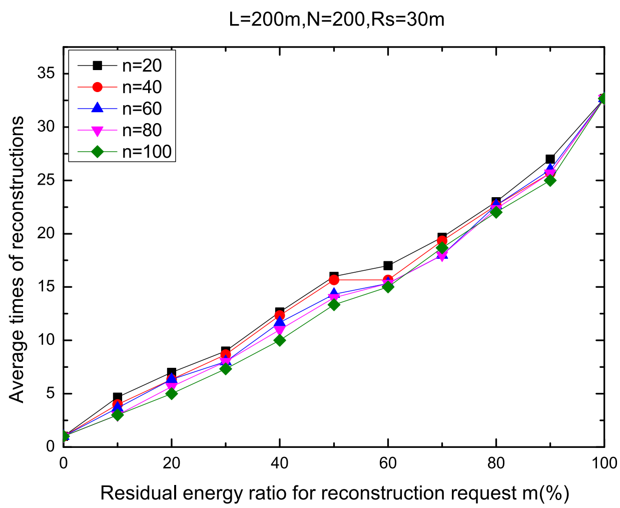

FIGURE 5. Average times of reconstructions of TCBDGA with different pairs of *m*% and *n*%.

From Fig. 5, we can clearly see that the average times of reconstructions increases monotonously as m increases, no matter what the value of n is. It is easily to understand for the reason that m represents the residual energy ratio of DSNs. When the residual energy ratio of a DSN is below m%, it sends a request of reconstruction to the mobile sink. Therefore, when m is set to a small value, these DSNs sends the reconstruction requests until they consume a large amount of energy, thus leading to a low frequency of reconstructions. However, when m becomes larger, the mobile sink receives a lot of reconstruction requests and perform tree reconstruction frequently when the DSNs still have enough energy.

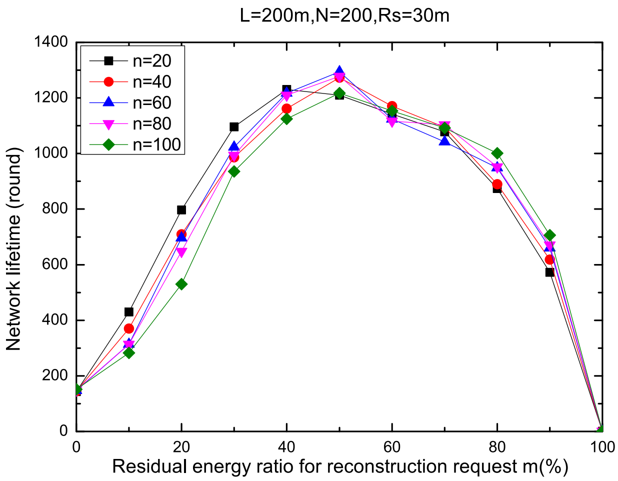

FIGURE 6. Network lifetime of TCBDGA with different pairs of *m*% and *n*%.

Fig. 6 shows the network lifetime performance of our TCBDGA with different pairs of m and n, and we can see that it increases from the beginning with the increasing value of m and then drops sharply when m is above 50. That's because the average times of reconstructions influences the network lifetime greatly. As illustrated in Fig. 5, when m is set to a small value, only few reconstructions need to be performed, which alleviates the load of these nodes with heavy burden to some degree. However, a large value of m (i.e. above 50) incurs frequent tree reconstructions. It obviously causes a huge expense of energy consumption. When the cost of tree reconstruction plays the major role of energy consumption compared with other communication costs, it influences the network lifetime most and makes it drop sharply.

Moreover, we can also figure out the relationship between m and n from Fig. 6. When m is below 50, it is obvious that the network lifetime is longer when n is smaller (such as $n = 20$). While, when m is above 50, it is the opposite. It is reasonable, because if m is set too small, which means the DSNs deplete the majority of their residual energy. In order to avoid the fast depletion of their energy, n should be constrained to a small value to make the mobile sink perform tree reconstruction as soon as possible. It means to sacrifice the cost of tree reconstruction to prolong the whole network lifetime. When m becomes larger, RPs or SRPs need to send a request when the residual energy of the DSNs is still very high. In order to reduce the cost of frequently tree reconstruction, n needs to be set to a larger value to make the mobile sink perform tree reconstruction only when it receives a large proportion of requests.

At the same time, there are three particular situations. They are $m = 0, 50, 100$ in Fig. 6. For the case $m = 0$, it means that our TCBDGA only performs tree reconstruction when every DSN depletes its energy, which implies to construct the tree only once before the first round and then with no reconstructions any more, the network consume energy only by transmitting or receiving data in each of the data collection round until the network dies. For the case $m = 100$, it means that the tree reconstruction is performed after every data collection round until the network dies. For the case $m = 50$, we can see the network lifetime is the longest, so we just select the approximately optimal pair of $m = 50$ and $n = 60$ for our TCBDGA in comparison with other algorithms in the next sub-section.

C. PERFORMANCE COMPARISON UNDER DIFFERENT PARAMETERS

The SPT-DGA [3] is similar to our TCBDGA in some way, such as the tree topology it builds and the method it uses to select a set of optimal PPs. Also, the selection of PPs from the constructed tree in SPT-DGA is just like tree decomposition and the selection of RPs and SRPs in our TCBDGA. And, to select these stop points for the mobile elements, both SPT-DGA and TCBDGA have limited the relay hop bound to a small value to minimize the energy consumption of data transmissions. In addition, both of these two algorithms choose a typical set of sensors for the mobile elements to visit using the same NN algorithm for the TSP problem.

However, the SPT-DGA has some limitations, such as:

- It does not consider the energy factor of each node when selecting PPs;
- There is no strategy for the replacement of the selected PPs, while these PPs are responsible for receiving large number of packets from their child nodes. It may lead to a fast energy depletion of the PPs if they are not replaced after a few rounds.

In this sub-section of simulations, both of these two algorithms consider sensor nodes with the same initial energy deployed over an $L \times L$ square area, and there is a BS located at the center of the deployed area. To verify the performance of our TCBDGA compared with the SPT-DGA, three scenarios are conducted by adjusting three parameters, the number of sensor nodes, transmission range and the size of the network. The number of nodes varies from 100 to 500, the transmission range R_s varies from $10m$ to $50m$, and the side length of the network L is set from $100m$ to $500m$. Other parameters are the same as that in Table 2.

Also, the relay hop bound d in the SPT-DGA is set to 2 when compared with our proposed algorithm. We select the pair of $m = 50$ and $n = 60$ in our TCBDGA for comparison since the network lifetime is approximately the longest. We analyse the network lifetime performance and the average tour length of TCBDGA from two aspects. One is the comparison with SPT-DGA, which can be treated as a data gathering algorithm without reconstructions, and the selected PPs are not changed in every data collection round until the first node dies. The other one is the comparison with itself, but without reconstructions, which can be obtained by setting $m = 0$ as discussed in the sub-section above.

Hence, there are three algorithms to compare:

- TCBDGA ($m = 50$, $n = 60$)
- SPT-DGA ($d = 2$)
- TCBDGA (no reconstructions)

1) THE IMPACT OF THE NUMBER OF NODES N

Fig. 7 and Fig. 8 plot the performance of the three algorithms as a function of N. N varies from 100 to 500, L is set to 200m, and the transmission range R_s is equal to 30m.

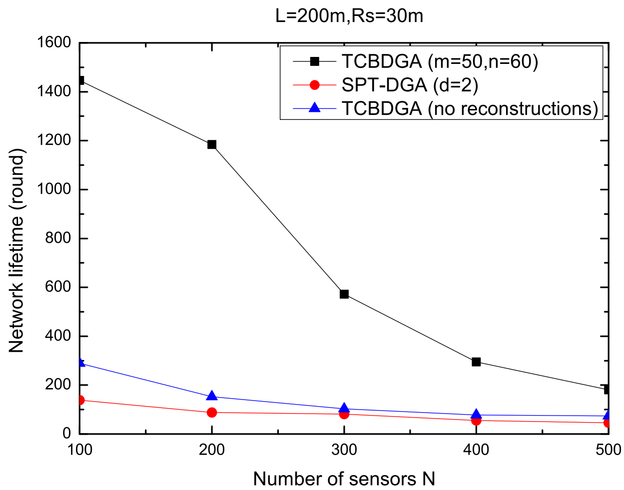

FIGURE 7. Comparison of network lifetime.

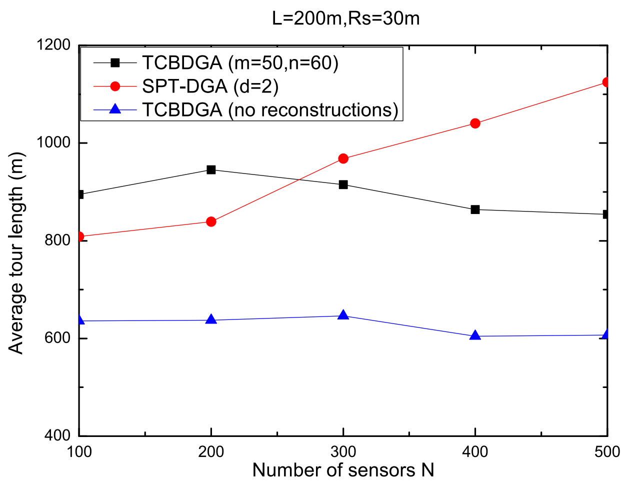

FIGURE 8. Comparison of mobile sink average tour length.

From Fig. 7, we can see that the network lifetime of our TCBDGA is almost 9.4 times than that of SPT-DGA when N is set to a small number 200, and even the TCBDGA with no reconstructions has a longer lifetime than that of SPT-DGA. As the number of nodes increases, the network lifetime in our TCBDGA decreases, but always longer than that of SPT-DGA. There are three reasons accounting for this phenomenon. First, we take the energy factor into consideration when selecting parent node and RPs, only nodes or their neighbors with higher energy can be recruited as RPs. Secondly, the selected RPs need not to receive large amounts of data compared with the SPT-DGA, which further reduce the burden of the RPs, SRPs and the DSNs around them. Finally, we adopt the adjusting strategy of RPs and SRPs, and the tree reconstruction operation balances the load of the whole network to a degree. All these three aspects contribute to prolonging the network lifetime.

Fig. 8 shows the average tour length of the three algorithms. When N is small, the SPT-DGA performs a little better than TCBDGA, but when N becomes larger, the average tour length of our TCBDGA decreases. That's because that we consider the node density when selecting parent node of each node, so that the selected number of RPs is less than that of SPT-DGA. This significantly influences the tour length when the number of nodes becomes larger. Also, we can see our TCBDGA without reconstructions always has the shortest tour length about 640m compared with the other two algorithms, but we do not regard it as the best one for the reason that it does not consider the load balancing of the whole network. The result implies that it reduces the data gathering latency by sacrificing the energy saving.

2) THE IMPACT OF THE TRANSMISSION RANGE R_S

To verify the effect of transmission range of nodes R_s on the network lifetime and average tour length of each data collection round, N is set to 200 and L is equal to 200m when R_s varies from 10m to 50m.

Fig. 9 shows the network lifetime performance of the three algorithms as a function of R_s. Obviously, we know more sensor nodes can become neighbors to each other as R_s increases. As a result, the energy consumption of data transmitting or receiving have a rise due to the increasing of child nodes of each RPs and SRPs. It leads to a decreasing network lifetime. However, the network lifetime of our TCBDGA is always as twice as that of SPT-DGA, for the reason that our TCBDGA adopts the adjusting strategy for RPs and SRPs. Even TCBDGA without reconstructions perform a little better than SPT-DGA for that it considers the energy factor for selecting RPs.

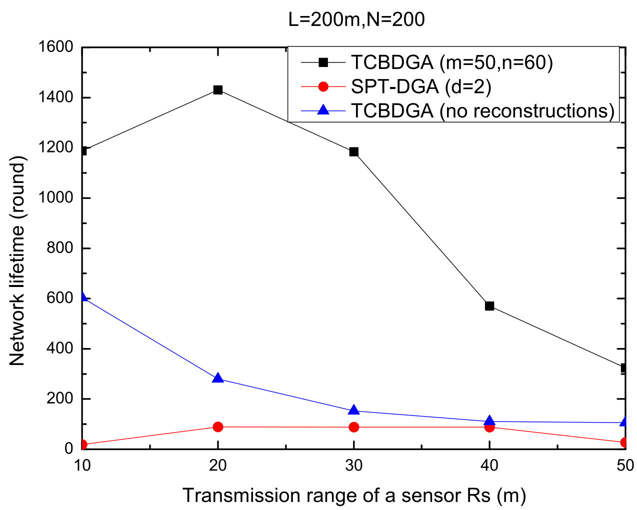

FIGURE 9. Comparison of network lifetime with varying transmission range R_S.

Fig. 10 illustrates the average tour length of the three algorithms as a function of R_s. As with the increasing of R_s, each of the RPs or SRPs in our TCBDGA or PPs in the SPT-DGA are able to link more sensor nodes.

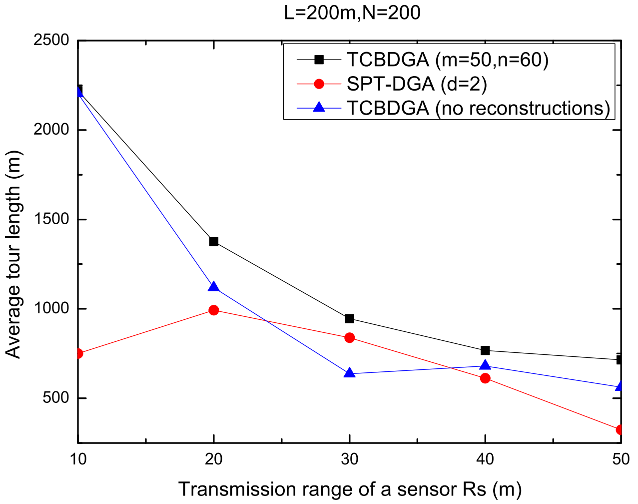

FIGURE 10. Comparison of average tour length with varying transmission range R_S.

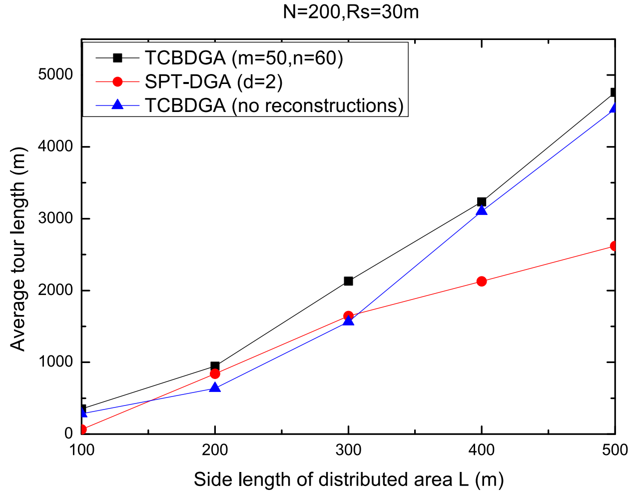

FIGURE 12. Comparison of average tour length with varying side length of distributed area L.

Therefore, the average tour length of the mobile elements is greatly shortened with the reduction of stop points. But the tour length of TCBDGA is always larger than that of SPT-DGA no matter what the R_s is, for example, when R_s is $10m$, the tour length of TCBDGA and the SPT-DGA is $2250m$ and $750m$, respectively. When R_s increases to $45m$, they are $800m$ and $400m$, respectively. That's because when selecting RPs and SRPs in our TCBDGA, in addition to the distance of nodes to the BS, we also consider the residual energy of each node, which balance the tradeoff between the energy consumption and data gathering latency.

3) THE IMPACT OF THE SIDE LENGTH OF DISTRIBUTED AREA L

Fig. 11 and Fig. 12 further plot the performance of different algorithms when the side length L of distributed area varies from $100m$ to $500m$. The number of nodes N is set to 200, R_s is $30m$. All other settings are kept unchanged as in the previous set of simulations.

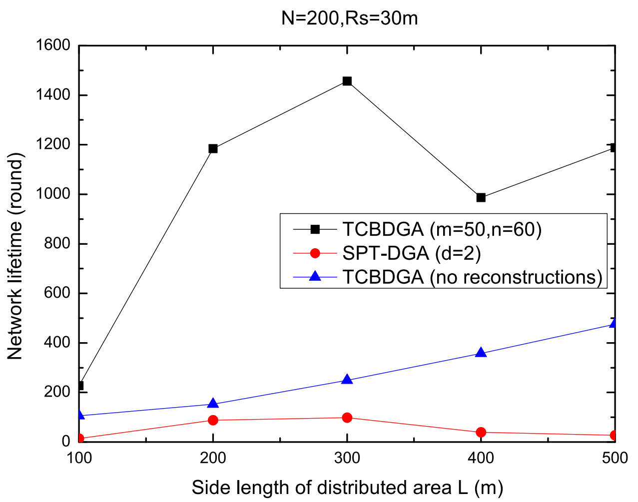

FIGURE 11. Comparison of network lifetime with varying side length of distributed area L.

In Fig. 11, due to the different tree construction strategy of the TCBDGA, the network lifetime has a fluctuation as L increases. But our TCBDGA always performs better in the network lifetime than that of SPT-DGA for the reason that the RPs and SRPs are reselected after reconstructions. Also, we consider the residual energy of each node when selecting RPs and SRPs for load balancing in the algorithms of TCBDGA with or without reconstructions. It further prolongs the network lifetime.

From Fig. 12, we can see that as L increases, the average tour length of all algorithms becomes longer. That's reasonable because sensor nodes are more sparsely distributed as L becomes larger. The number of the stop points in our TCBDGA and SPT-DGA, and the distance of them is increased, which leads to a long tour length for the mobile elements. But it is noticed that the tour length of our TCBDGA and the TCBDGA with no reconstructions are almost 67 percent and 55 percent longer than that of SPT-DGA when L becomes a larger value such as $400m$. That is because we consider the energy of each node when selecting suitable RPs and SRPs, but sacrifice the data gathering instantaneity for obtaining a longer lifetime.

VI. CONCLUSION

In this paper, we investigate recent typical literatures on data gathering algorithms, and classify them according to the sensed data uploading path or affected area. Based on the comparison and analysis, we propose a tree-cluster based data gathering algorithm with a mobile sink for WSNs. First, we introduce a weight-based tree construction method, where the weight of each sensor node jointly considers the average residual energy, the distance to the BS, and local node densities. After the trees are constructed, RPs are selected.

Then a tree decomposition method is proposed. Both the hop count and the amount of data of each node are taken into consideration when selecting SRPs on sub-trees, which further balances the energy consumption. We also introduce an adjusting method for the RPs and SRPs reselection, in order to alleviate the heavy burden around them. The simulation results demonstrate that our TCBDGA can prolong the network lifetime significantly compared with the other data gathering algorithm SPT-DGA. It is more suitable for wide area, especially in industrial environment involving massive amount of heterogeneous sensory data.

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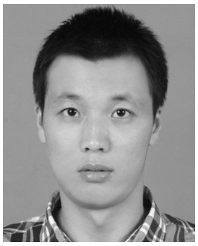

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