A Mobile Sink-initiated Proactive Routing Protocol for Deadline-Aware Data Aggregation Method in Energy-Efficient Wireless Sensor Networks

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Abstract: In this paper, we focus on monitoring environments with wireless sensor networks in which mobile sink nodes traverse sensing fields in a specific spatial-temporal manner and aggregate various types of environmental data with different deadline constraints distributed over sensor nodes. For such environments, we propose an energy-efficient data aggregation method that reduces intermediate transmission in multi-hop communication while guaranteeing predetermined deadlines. The basic approach of the proposed method is to temporarily gather (or buffer) the observed data into several sensor nodes around the moving path of the mobile sink that would meet their deadlines at the next visit. Then, the buffered data is transferred to the mobile sink node when it visits the buffering nodes. We also propose a mobile sink-initiated proactive routing protocol with low cost (MIPR-LC) that efficiently constructs routes to the buffering nodes on each sensor node. Moreover, we simulate the proposed aggregation method and routing protocol to show their effectiveness. Our results confirm that the MIPR-LC method can reduce energy consumption by up to 23% when compared with a simple routing protocol. In addition, the mobile sink nodes can gather almost all of the observed data within the deadline.

1 INTRODUCTION

Based on recent advancements in micro-electro-mechanical systems (MEMS) and wireless communication technologies, wireless sensor networks (WSNs) have emerged as a promising tool for monitoring environments in a wide range of applications [1]. A WSN is generally composed of sensor nodes for observing environment data and sink nodes for aggregating the data distributed over the sensor nodes. In WSNs, aggregation mechanisms are often very dependent on multi-hop communication, i.e., because of limited radio ranges of sensor nodes, data transmission between sensor-sink pairs are routed through several intermediate sensor nodes. An increase of such intermediate transmission leads to obvious power consumption concerns, especially in large-scale WSNs, since it is widely recognized that data transmission is responsible for a large part of the total power consumption in sensor nodes [2]. Thus, as a means to reduce intermediate transmission, a mobile sink approach has attracted considerable attention over the last decade [3, 4, 5, 6, 7, 8].

In the mobile sink approach, a mobile sink node traverses a given sensing field and aggregates data observed in sensor nodes when it moves close to them. This approach can achieve an energy-efficient aggregation of data since it does not always use multi-hop communication, i.e., the mobile sink node can gather data directly from the sensor nodes without intermediate nodes. However, this approach increases the time delay that is required for the mobile sink node to visit the sensor nodes. To overcome the delayed aggregation, it is necessary for the sensor nodes to frequently use multi-hop communication in order to reach the mobile sink node, which also contributes to their large power consumption, as described above. Hence, the two objectives of realizing low power consumption and shortening the delay time appeared to be mutually exclusive during the aggregation of the observation data.

In this paper, we focus on monitoring environments with WSNs that require source-to-sink delay bounds according to the observation data. More specifically, in our system model, multiple mobile sink nodes exist to traverse a sensing field in a specific spatial-temporal manner and aggregate various kinds of environment data with different deadline constraints. For such environments, we propose an energy-efficient data aggregation method that reduces intermediate transmission in multi-hop communication while guaranteeing the delay bounds.

The basic approach of the proposed method is to temporarily gather (or buffer) the observed data into several sensor nodes that exist around the moving path of the mobile sink node. The buffered data is then transferred to the mobile sink node when it visits the buffering nodes. For these buffering nodes, the proposed method uses sensor nodes that would meet the deadline at the next visit of their mobile sink node. In addition, we also propose a mobile sink-initiated proactive routing protocol with low cost (MIPR-LC) that efficiently constructs routes to the buffering nodes on each sensor node, i.e., the routing table contains routes from the sensor node to the shortest buffering nodes for all the mobile sink nodes. Moreover, we evaluate the proposed aggregation method and routing protocol by performing simulation to show their effectiveness. As a result, we confirm that the MIPR-LC method can reduce energy consumption by up to 23% when compared with a simple routing protocol, and the mobile sink nodes can gather almost all of the observation data within the required deadline.

The paper is organized as follows. Section 2 describes the system model. Section 3 discusses related work. Section 4 presents the proposed aggregation method considering the data deadline and the energy-efficient routing protocols. Section 5 presents the simulation results. Section 6 concludes this paper.

2 SYSTEM MODEL

In this section, we show the system model used in this paper. In our model, multiple mobile sink nodes traverse a given sensing field in a certain pattern and gather various kinds of observation data with different deadline constraints. For example, typical applications include environment monitoring systems in a farm, for which various data such as temperature, humidity, and sunlight are collected for the primary purpose of monitoring crop growth. In this model, we assume farmers and farm machines to be mobile sink nodes. Next, we explain the details of sensor nodes, mobile sink nodes, environmental data, and performance metrics.

In this model, many homogeneous sensor nodes are deployed in a sensing field. A sensor node is static and battery powered. In addition, a sensor node periodically generates observation data that are then stored into its own local buffer that is sufficiently large (in terms of capacity) to store data until the next visit of a mobile sink node. Furthermore, two sensor nodes can directly communicate if they are within each other's radio range. The wireless communication between sensor nodes is generally stable, although at times, sensor nodes may fail to receive packets owing to packet collision and radio noise.

In this model, existing mobile elements in a sensing field, such as farmers, farm machines, and so on, are diverted to mobile sink nodes, i.e., mobile sink nodes are uncontrollable and act with a specific spatial-temporal pattern. Furthermore, we define their patterns as periodic with a given period for each mobile sink node. Mobile sink nodes move while broadcasting beacons at fixed intervals and gather data from the beacon-received sensor nodes.

A sensor node measures different kinds of environmental data. These data are gathered by the mobile sink nodes within specific deadlines according to their type. Then, the mobile sink nodes immediately transmit the collected data to a control center over a mobile phone network such as 3G or WiMAX. In this paper, the delay time is the time that elapses from the instant a sensor node measures data to the instant at which a mobile sink node receives the data. For example, in the environment monitoring system, we consider that there are no problems even if the delay time of the aggregation is approximately one day. However, in the case of mechanical controls (e.g., the opening or closing of the windows of a greenhouse based on results of the gathered data), the deadline of the data must be set to approximately one hour.

Finally, we describe two performance metrics for aggregation methods in our system model:

Energy consumption: Energy consumption is an important performance metric in data aggregation. The network lifetime of the WSNs can be drastically extended by realizing an energy-efficient aggregation method. The energy consumption of a sensor node is mainly dependent on the number of data transmission, including intermediate transmission, which are required for the multi-hop communication and message propagation for routing construction. Thus, increasing the energy efficiency of a data aggregation method leads to fewer data transmission for the collection of data.

Delay time: Another performance metric is the delay time for data aggregation. The delay time occurs owing to the nature of the mobile sink approach. The delay time is dependent on the cycle period of a mobile sink node. There is no problem if the delay time for gathering the data is within the deadline.

3 RELATED WORK

Over the last decade, a number of approaches have been proposed for exploiting mobile sink nodes for data aggregation in WSNs. From the perspective of data aggreagation architecture, these approaches can be broadly classified into three types: mobile base station (MBS)-based approach, mobile data collector (MDC)-based approach, and rendezvous-based approach. In this section, we introduce the three approaches.

3.1 MBS-based and MDC-based approaches

In the MBS-based approach, a mobile sink node gathers observation data directly from sensor nodes using multi-hop communication. In [3], the authors address the problem of determining the sojourn times on the moving path for the mobile sink node using the linear programming (LP) method in order to maximize the network lifetime, i.e., to balance the energy consumption of all of the sensor nodes required for the intermediate transmission. In [4], the authors propose a two-tier data dissemination mechanism for large-scale WSNs in which multiple mobile sink nodes are deployed in the sensing field. With this approach, sensor nodes transmit data to the nearest mobile sink node. For this MBS-based approach, the delay time is short because the data are directly delivered from the sensor nodes to the mobile sink node. However, many sensor nodes require more frequent intermediate transmission for the multi-hop communication. In addition, with this approach, the sensor nodes must update the route information to the mobile sink nodes by frequently propagating control messages.

With the MDC-based approach, a sensor node stores data into its own local buffer and waits for a mobile sink node to arrive within its transmission range. When the mobile sink node arrives, the sensor node transmits the stored data to the mobile sink node in a single-hop communication. In [5], the mobile sink nodes randomly traverse the sensing field to gather the data from the sensor nodes. Moreover, to minimize the energy consumed by the entire network, the authors in [6] solve a path selection problem in delay-guaranteed sensor networks by exploiting path-constrained mobile sink nodes. With the MDC-based approach, the sensor nodes can transmit data to the mobile sink nodes without the multi-hop communication. However, the delay time increases because the sensor nodes need to store the data in local buffers until visited by the mobile sink node. In addition, it cannot gather data that have been generated by sensor nodes that do not have contact with any mobile sink node. Although a controllable mobile sink node may solve this problem, the installation of such a controllable node would incur additional costs.

3.2 Rendezvous-based approach

The rendezvous-based approach is a hybrid approach that combines the MBS-based and MDC-based approaches. This approach introduces several rendezvous points (nodes) for a mobile sink node at which data are gathered from sensor nodes through multi-hop communication. These points then transmit the buffered data using the single-hop communication to the mobile sink node that visits them. In [7], the mobile sink nodes pass through predetermined anchor nodes (i.e., rendezvous points) while collecting data. To gather data at the anchor nodes, a tree structure-based aggregation method has been proposed. This method organizes a tree structure from a cluster node to its child sensor nodes using a routing protocol MintRoute [9]. The MintRoute protocol establishes the shortest route from the cluster node to each child. In addition, in [8], the authors assume that the mobile sink nodes can change their moving paths over time. Hence, they have proposed a data aggregation method that selects as the rendezvous nodes the sensor nodes that are to be frequently contacted by the mobile sink nodes. The rendezvous-based approach improves the energy efficiency relative to that of the MBS-based approach, in the sense that it reduces the number of intermediate transmission for multi-hop communication. Furthermore, it can also reduce the delay time relative to that of the MDC-based approach.

Our proposed approach can be considered to be a rendezvous-based approach. In this paper, we assume that observation data has a deadline time according to its type, and multiple mobile sink nodes with different cycle periods exist in the sensing field. For such a model, we need an energy-efficient aggregation method to satisfy the deadline for gathering the sensing data.

4 PROPOSED AGGREGATION METHOD

In this section, we propose an energy-efficient data aggregation method that reduces intermediate transmission in multi-hop communication while guaranteeing a maximum delay time for the observation data. Moreover, we propose the MIPR-LC protocol used in the proposed aggregation method to efficiently construct the routing paths for the aggregation on each sensor node.

4.1 Data aggregation

The basic approach of the proposed method is to buffer the observed data into several sensor nodes that exist around the moving path of the mobile sink node. The buffered data is then transferred to the mobile sink node when it visits the buffering nodes. The proposed method identifies sensor nodes that would meet the deadline at the next visit of their mobile sink node, and uses these sensor nodes as the buffering nodes. The identification is based on the predicted cycle periods recorded in its routing table. To reduce power consumption, it also uses the nearest buffering node out of all discovered ones. Then, the sensor node transfers the observation data to the shortest buffering node using the multi-hop communication. In this paper, the buffering nodes that exist around the moving path of a mobile sink are called mobile sink-path neighbor (MN) nodes. In addition, an MN node is said to be the shortest if it is the nearest one among all the MN nodes.

Fig. 1 shows an example of the proposed aggregation method. In this example, we assume that there are two mobile sink nodes: mobile sink node $M1$ with cycle period $T1$ and mobile sink node $M2$ with cycle period $T2$, where $T2 < T1$. Furthermore, a sensor node S transmits data with a $deadline$. In Fig. 1, if the $deadline$ is longer than $T1$, S transmits data to A. The destination node of the transmission is $D1$, which is reachable in a small number of hops ($H1$). If the $deadline$ is shorter than $T1$ and longer than $T2$, S transmits data to B bound for $D2$, which needs a large number of hops ($H2$).

Entry number	Mobile sink	Cycle period	Destination node	Next hop node	Hop count
1	M1	T1	D1	A	H1
2	M2	T2	D2	B	H2

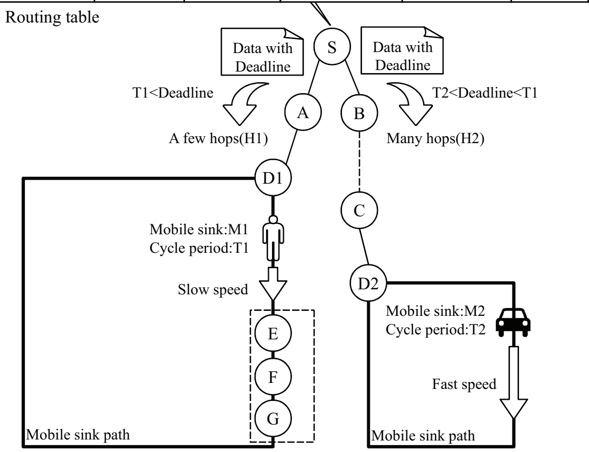

Figure 1: An overview of the proposed method

4.2 Route construction

To achieve the proposed aggregation method described in the previous section, each sensor node needs to construct routes to the shortest MN nodes for all mobile sink nodes. To construct routes, in this study, we propose two routing protocols: MIPR and MIPR-LC. The MIPR-LC method improves the MIPR method by reducing the routing cost required for constructing routing tables used in the MIPR method.

4.2.1 MIPR

The MIPR method is a proactive routing protocol that is initiated by a mobile sink node, i.e., the traversing mobile sink node periodically transmits trigger messages to one-hop neighbor sensor nodes (i.e., MN nodes). The received MN nodes broadcast control messages to the whole sensor network by employing flooding-based communication. More detailed steps in the route construction are shown below.

1. A mobile sink node sends trigger messages to neighbor sensor nodes while traversing the given sensing field, i.e., the message can be received by the sensor nodes that exist within its single-hop communication range.
2. The received sensor nodes recognize themselves as the MN nodes and broadcast a control message to all the sensor nodes.
3. Upon receiving the control message, each sensor node constructs the route to the source node of the message using the distance vector algorithm.
4. Each sensor node can construct routes to all MN nodes because all MN nodes broadcast the control messages. The sensor node therefore selects the nearest MN node from all of the MN ones.
5. Each sensor node can construct routes to the shortest MN nodes for all of the mobile sink nodes because each mobile sink node transmits trigger messages while moving.

The proposed method adopts a mobile sink-initiated protocol in order to realize the high maintainability of routing tables and to quickly construct routing tables even in large-scale WSNs.

4.2.2 MIPR-LC

In the MIPR method, a routing table is constructed for each sensor node by employing flooding-based broadcasts. The broadcasts increase the energy consumption of the sensor nodes owing to repeated retransmission of control messages in the sensor nodes. The goal of the MIPR-LC method is to reduce these retransmission. In the MIPR method, all MN nodes broadcast control messages and the received sensor nodes retransmit the messages (on the left side in Fig. 2). However, in the proposed aggregation method, it is sufficient that each sensor node constructs routes to the shortest MN node. Therefore, in the MIPR-LC method, a sensor node retransmits the message only when the coming path length for the received control message is the shortest (on the right side in Fig. 2).

We now consider the trigger timing when a mobile sink node sends a trigger message. Fig. 3 shows the transition of the propagation region in the MIPR-LC method in chronological order. In this figure, sensor nodes A, B, and C are MN nodes for the same mobile sink node. A, B, and C receive a trigger message at $t = t_1$, $t = t_2$ and $t = t_3$, respectively. In this figure, sensor nodes that have retransmitted a control message are marked as p, while sensor nodes that have not retransmitted any message are marked as f. It can be seen that the propagation region changes depending on the sending order, i.e., the propagation region is the narrowest when C sends the last control message. Thus, we consider the trigger timing of control messages to minimize the propagation region.

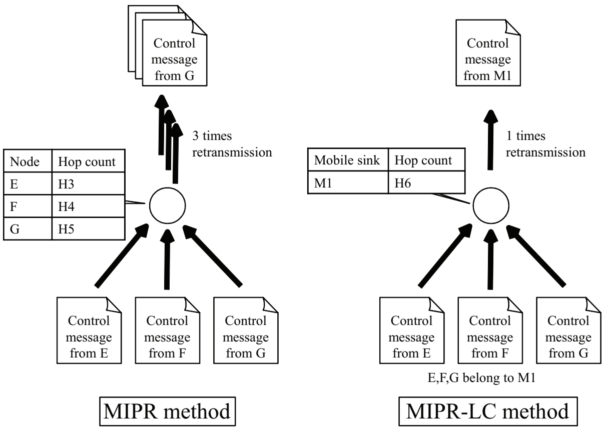

Figure 2: Propagation for control messages

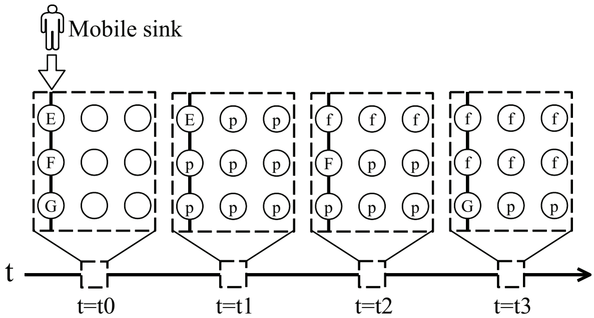

Figure 3: Propagation region

5 PERFORMANCE EVALUATION

In this section, we evaluate the proposed aggregation method by performing simulation. The routing protocol and aggregation method proposed in this paper are implemented on the network simulator platform QualNet version 5.0.1[10].

5.1 Routing protocol

First, we evaluate the average energy consumption for sensor nodes, i.e., the number of control message retransmission that is required to construct routes to the MN nodes that are the shortest of all mobile sink nodes. We describe our results and compare them to

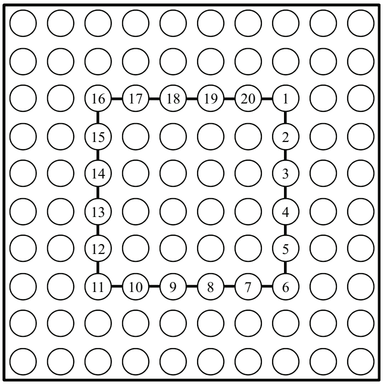

Figure 4: Simulation environment for evaluating routing protocols

Table 1: Evaluation results for the proposed routing protocols

	(1)			(2)
	(1-1)	(1-2)	(1-3)	
Transmission energy consumption[nJ]	0.58	0.43	0.36	2.52
Received energy consumption[nJ]	3.08	2.30	1.97	13.44
Total energy consumption[nJ]	3.66	2.73	2.33	15.96

those obtained using the MIPR-LC method (called (1) hereafter) and the MIPR method (called (2) hereafter). As shown in Fig. 4, in this simulation, 10×10 sensor nodes and 20 MN nodes numbered from 1 to 20 are regularly placed at intervals of 150 m. Each sensor node can communicate with its neighbor nodes. In addition, the transmission rate, transmission power, and received power for transmitting one control message are 1 Mbps, 100 mW, and 130 mW, respectively. The MN nodes transmit control messages once every second. Furthermore, in (1), we evaluate the impact of the change of the trigger timing on the results. More specifically, we implement the three trigger timings, (1-1), (1-2), and (1-3) and represent the control messages sent by each node $(1, 2, 3, \cdots, 19, 20)$, as well as by all three nodes $(1, 4, 7, \cdots, 15, 18)$ in a diagonal manner $(1, 11, 6, 16, 2, 12, 7, 17, \cdots, 10, 20)$.

Table 1 shows the result. From the table, the energy consumption of (1) is 23% lower than that of (2). This is because the sensor nodes do not retransmit unnecessary control messages in (1), i.e., they retransmit control messages only when the next path length is shorter than previous path lengths, as described in Section 4.2.2. Furthermore, we confirm the effect of the trigger timing on the energy consumption. From the table, the timing (1-3) has the lowest energy consumption of all the timings. This is because in (1-3), the sensor nodes can transmit control messages in the most spatially distributed manner.

Table 2: Simulation parameters

Parameter	Meanings	Value
$N_{sensors}$	number of sensor nodes	200
$N_{mobilesinks}$	number of mobile sink nodes	2
$T_{mobilesinkA}$	cycle period of mobile sink node A	200[s]
$T_{mobilesinkB}$	cycle period of mobile sink node B	600[s]
λ	data arrival rate	12[packets/hour]
P	packet size	100[byte]
D_{dataA}	deadline of data A	300[s]
D_{dataB}	deadline of data B	700[s]

5.2 Aggregation method

Next, we evaluate the proposed aggregation methods. In this simulation, we measure the number of data that has been stored within the deadline and the energy consumption of the sensor nodes. We compare the results of three methods: our proposed data aggregation method (called (3) herafter), an MDC-based aggregation method that always uses the shortest mobile sink nodes regardless of the delay bound constraints (called (4) herafter), and an MDC-based aggregation method that always uses the fastest mobile sink nodes regardless of the energy consumption (called (5) herafter). In this simulation, the route for each sensor node is constructed by the MIPR-LC method.

The simulation parameters used in our experiments are summarized in Table 2. Furthermore, 10×20 sensor nodes are placed at fixed intervals of 150 m. Each sensor node can communicate with its neighbor nodes. In addition, the sensor nodes generate two sets of data (A, B) with different deadlines. The deadlines of the data are longer than the cycle periods for mobile sink nodes. In this simulation, two mobile sink nodes are positioned: mobile sink node A with a short cycle period is placed on the left side of the field, and mobile sink node B with a long cycle period is placed on the right side. The mobile sink node traverses the field at a constant speed. In addition, the transmission rate, transmission power, and received power for transmitting one control message are 1 Mbps, 100 mW, and 130 mW, respectively. The simulation time is one hour.

Table 3 shows the summarized results of the measurements. In this table, the data aggregation ratio is the number of data generated divided by the number of data aggregated, and the data aggregation ratio within the deadline is the number of data generated divided by the number of data aggregated within the deadline. All of the aggregation methods achieve aggregation ratios of over 94%. However, for (4), the data aggregation ratio within the deadline is about 80%. This is the worst performance of all the aggregation methods, since (4) does not consider the delay bounds. On the other hand, (3) and (5) achieve good performance. Moreover, the energy consumption of (3) is lower than that of (5). Thus, we conclude that the proposed method (3) improves the energy consumption of (5) while guaranteeing the deadline, as in (5).

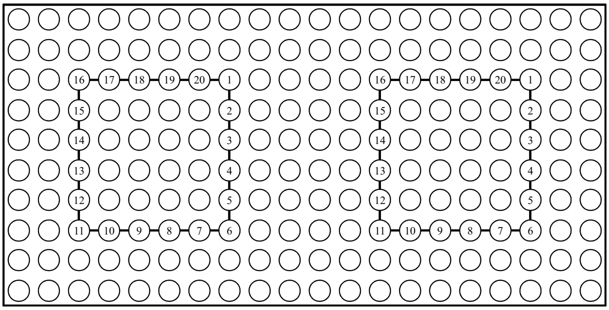

Figure 5: Simulation environment for evaluating aggregation methods

Table 3: Evaluation results for the proposed aggregation methods

	(3)	(4)	(5)
Number of data generated	2400	2400	2400
Number of data aggregated	2326	2257	2380
Data aggregation rate [%]	96.9	94.0	99.1
Number of data aggregated within the deadline	2326	1926	2380
Data aggregation rate within the deadline [%]	96.9	80.2	99.1
Total energy consumption in transmission [nJ]	191.8	113.5	280.0

6 CONCLUSIONS

In this paper, we proposed a data aggregation method that reduces intermediate transmission in multi-hop communication while guaranteeing a bounded delay. In our proposed approach, the observed data with deadlines are gathered for a set of MN nodes having a mobile sink node that can satisfy the deadline at the next visit. More specifically, each sensor node selects a mobile sink node that meets the deadline of the observed data, which is based on a prediction of arrival interval. The observed data is then transmitted to the shortest MN nodes that correspond to the selected mobile sink node. In addition, we propose a MIPR-LC protocol that is required for the proposed aggregation method that efficiently constructs a routing table on each sensor node. As a result, we confirm that the MIPR-LC method can reduce energy consumption by up to 23% when compared with a simple routing protocol, and the mobile sink nodes can also collect almost all observed data within the data deadline.

In future, we will study a data aggregation method that can reduce intermediate transmission even if the deadline is longer than the shortest cycle period of mobile sink nodes. In addition, we will examine in more detail the trigger timing for control messages. Furthermore, we will evaluate the proposed aggregation method and routing protocol in more generated situations.

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