IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received November 28, 2019, accepted December 8, 2019, date of publication December 18, 2019, date of current version December 30, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2960596

Dynamic Rendezvous Node Estimation for Reliable Data Collection of a Drone as a Mobile IoT Gateway

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This work was supported in part by Institute for information and communications Technology Promotion(IITP) grant funded by the Korea government(MSIT) (No. 2019-0-00708, Integrated Development Environment for Autonomic IoT Applications based on Neuromorphic Architecture), and in part by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Science, ICT and Future Planning(No.NRF-2016R1C1B1015454).

ABSTRACT By using drones as mobile IoT gateways in wireless sensor networks, data collection can be possible even in areas where IoT wireless communication is not available. A drone can move near the rendezvous node of the wireless sensor networks and receive the collected data from the node. Then, the drone moves to an area where IoT wireless communication is possible and transfers the data to the IoT server. Because drones operate as a battery, it is important to optimize the energy consumption. Existing research reduces the drone's energy consumption by minimizing flight distance using predetermined information such as the orbit, sensor location and network topology. However, if data collection fails, the additional flying distance of the drone increases dramatically and energy consumption also increases. It is important to increase the success rate of data collection. In this paper, we propose a dynamic rendezvous node estimation scheme, taking into account the average of drone speed and data collection latency without predetermined information. Simulation results show that the proposed scheme is more reliable in terms of the data collection success rate.

INDEX TERMS Data collecting, drone, IoT gateway, rendezvous node, wireless sensor networks.

I. INTRODUCTION

As drone-related technologies are developed, many applications presently use drones [1]–[4]. Drone-assisted data collection of sensor networks in the Internet of Things (IoT) has especially been studied recently [5], [6]. Drones act as a mobile IoT gateway [7], [8], which is in the middle of sensor networks and the IoT server. Sensor nodes monitor their surroundings and relay sensing data to a network-wide sink node that gathers data and transmits the data to the mobile IoT gateway, which is a drone [9]. The sink node is a rendezvous point, where the drone can communicate with the sensor networks. We call the sink node as a rendezvous node.

The associate editor coordinating the review of this manuscript and approving it for publication was Chun-Wei Tsai.

A sensor node has a small form factor, which is a capable device with a restricted ability for processing and limited memory and a limited energy source like a battery [10]. A drone flies at low altitudes and can be used with a portable IoT gateway to reduce the required communication energy of sensor nodes [11]. A drone canenhance general connectivity for infrastructure monitoring of oil, water, and gas pipelines [12]–[14]. In these types of linear sensor networks, the failure of a single node is critical because in such cases the communication link is broken. To carry on communication and sensing tasks, a drone supports a fast recovery of the sensor network. Drone-assisted sensor networks are also used to monitor and manage many disasters [15], [16]. A vital point in saving lives is the response time during activities to manage disasters. A drone can decrease response time by flying to harsh target regions at a high speed.

A drone used to collect data on a sensor network, is very efficient if the drone visits all sensor nodes directly. Several studies have selected a rendezvous node to reduce the energy consumption and flight distance of a drone [12], [15], [17]–[20]. A rendezvous node is a kind of sink node that gathers data from all nodes of the networks and sends the data collected to a drone. Previous studies concentrated on decreasing the drone's energy consumption and optimizing the flight distance with predetermined information such as trajectory, route, entry point, and locations of the sensor node.

In this paper, we propose a new dynamic rendezvous node selection scheme based on an estimated proper rendezvous point considering the drone's speed and direction as well as the data collection latency of the sensor network without any pre-acquisition information. In the proposed scheme, the drone's position is estimated at the completion of data collection by considering the speed of the drone's initial entry and the latency required for data collection in the network. Then, the most suitable node for data transmission is selected as the rendezvous node. In short, considering the drone speed, data collection time in the network, and the data transmission time with the drone, the proposed method selects the node that can maximize the data transmission success rate as the rendezvous node.

The proposed scheme has the following advantages. Comparing with static rendezvous node selection (random selection) where rendezvous node selection with the highest residual energy, and rendezvous node selection farthest from the entering point, the proposed method can reduce energy consumption due to the less movement of collected data. The proposed scheme may not proceed with data collection if it is determined that data transmission to the drone is impossible. The rendezvous node selection is also optimized according to the drone's flight path, which increases the success rate of attempting to transfer the collected data to the drone.

The proposed scheme can be applied to systems that monitor natural disasters (forest fires and landslides), enemies, and specific targets. In a system that tracks the movement path of the enemy or the target to be tracked, when the photographs and images are collected through the drone, the meaning of the data at that time is very significant. It is particularly suitable for the collection of image data that requires post-processing operations and considerable computational power such as infrared and hyperspectral images, which are difficult to process directly from drones. Based on the simulation results, the proposed scheme shows better performance in terms of data collection success rate.

The rest of this paper is organized as follows. In Section II, we give an introduction to the background and related information. Section III presents the motivation, network model and our proposed scheme. Section IV is a performance evaluation of the proposed system. Finally, Section V summarizes the paper and gives concluding remarks.

II. RELATED WORKS

We will explain related research in this section. Various rendezvous node selection techniques have been studied to reduce drone flight distance and energy consumption, and extend the lifetime of wireless networks [12], [15], [17]–[19]. Table 1 shows the summary of the related works.

TABLE 1. Summary of the related works.

Schemes	Rendezvous node selection strategy
Wang et al. [12]	Random selection among the nodes
Alomary et al. [17]	Select Closest Rendezvous Points (CRPs) among the nodes in the network
Heimfarth et al. [18]	Select head nodes from each disconnected network to connect disconnected networks
Min et al. [19]	Select one which minimizing the flight distance while considering the energy consumption of each node
Martinez–de Dios et al. [15]	Select the node in the center of the network

Wang *et al.* proposed a drone-based data collection technique [12]. The proposed method randomly selects rendezvous nodes and optimizes the drone's movement path for collecting data. Since the rendezvous node is randomly selected, the selection process is simple, but the drone's flight distance can increase.

Alomary *et al.* [17] proposed a data-gathering scheme, using Closest Rendezvous Points (CRPs). One or more nodes of the network are connected to one CRP node. The mobile device for data collection visits the CRPs to collect data. Not all nodes in the network are visited directly for data collection. Therefore, the tour length of the mobile device, which is used for collecting the data can be reduced.

Heimfarth *et al.* proposed a disjointed segment connection scheme for wireless sensor networks based on an unmanned aerial vehicle [18]. Network disconnection problems cause very serious problems in wireless sensor networks. Supporting the connection scheme between disconnected nodes of the wireless network can extend its lifetime. In that scheme, each disjoint segment elects a cluster head which is a kind of rendezvous node that is responsible to interact with the Unmanned Aerial Vehicle (UAV). The UAV supports the transfer of data among cluster nodes to connect the disjoint segment of the wireless network.

Min *et al.* proposed a rendezvous node selection scheme [19]. The proposed scheme is focused on selecting rendezvous nodes, taking into account the energy consumption of each node while minimizing the flight distance of the drone which is responsible for collecting data.

Martinez-de Dios *et al.* proposed a method for selecting rendezvous nodes that are centrally located in a region for efficient data collection in large-scale monitoring areas [15]. Because the rendezvous node is centrally located in a region, it is efficient at collecting data but is likely to be disconnected if the rendezvous node goes down due to energy depletion.

In the previous schemes, they concentrated on decreasing the energy consumption of mobile node which is used for collecting data. In this paper, we propose a new dynamic rendezvous node selection scheme based on an estimated proper rendezvous point while considering the drone's speed and direction as well as the data collection latency of the network. Therefore, we can reduce unnecessary energy consumption by increasing the data collection success rate. and decreasing the number of retransmissions.

III. A RENDEZVOUS NODE ESTIMATION CONSIDERING THE DRONE'S PATH AND DATA COLLECTION LATENCY

In this section, we present a rendezvous node estimation scheme for efficiently collecting sensor data. First, we introduce the motivation, network model and concept of a rendezvous zone, and then we describe how our protocol works in varying sensor networks.

A. MOTIVATION

We designed our proposed scheme under the following assumptions.

- All nodes have same capacity and ability.
- All nodes know information about their location and amount of residual energy.
- All nodes share information about their neighbors by using heartbeat messages.
- It is possible that the network is partitioned.
- The failure of communication is ignored.
- The flight route of the drone is changed randomly in each round.

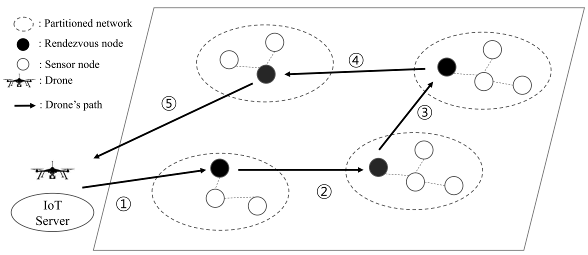


FIGURE 1. Cooperation a drone and tactical wireless sensor networks.

Figure 1 shows the data collection process by using a drone. When the network is partitioned, it is useful to use a drone to collect data from the tactical wireless sensor network. The drone can fly among partitioned networks and connect them. However, it is impossible for the drone to visit and directly communicate with all sensor nodes while collecting sensing data. Therefore, sensor nodes create groups where a leader called a rendezvous node receives and summarizes all data from its member nodes. This grouping mechanism reduces the number of the drone's visiting spots and flight distance. When a sensor node runs out of energy, the node cannot send and receive communication messages. In the case of an intermediate node failure, the network is partitioned into two parts. As the number of partitioned networks increase, more rendezvous nodes must be visited by a drone and the flight distance increases. Therefore, the balance of the energy consumption of each node is an important issue as well as the flight distance during the rendezvous node selection process.

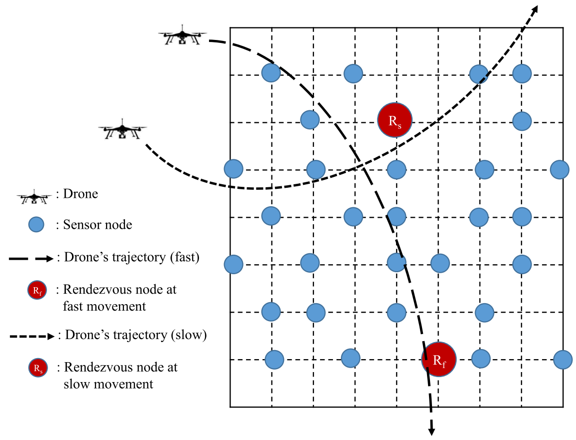


FIGURE 2. Location of Rendezvous node as drone speed.

Figure 2 shows the overview of the drone-assisted data collection scheme. A drone enters the target area at an arbitrary speed and direction. For reliable data collection, it is crucial to select a proper rendezvous node. If the drone is flying at a low speed, the ideal rendezvous point is close to the entry position of the drone, because the drone cannot change its direction depending on the situation. If the drone is flying at a high speed, the optimal rendezvous point is near the exit point of the drone because the rendezvous node requires enough time to collect data from all sensor nodes. Without considering the speed and direction of the drone when choosing a rendezvous node, such as choosing a node in the middle of the target region, or randomly selecting the rendezvous node, the drone will overrun the rendezvous node, particularly if the drone's route is unknown. We should also consider the data collection latency of the entire network because only considering the drone's status is insufficient. If the drone flies rapidly and the selected rendezvous node requires a long time to collect data from all the sensor nodes, the drone cannot obtain the data gathered from the rendezvous node even when the node is placed along its route.

B. NETWORK MODEL

We consider a sensor network with N randomly dispersed sensor nodes (see Figure 3.). We assume that all of the nodes have the same wireless transmission range R. We also assume that each SN_i knows its own position (coordinates) in advance and expects the link quality of the network through Expected Transmission Count (ETX) [21]. The nodes are neighbors if they are within the transmission range. The sensor nodes use a duty cycling mechanism where T and τ are wake-up and sleep time, respectively, for saving energy.

Using a drone as a mobile data collector for SN_i is an energy-efficient technique to prolong the network lifetime [22]. The drone intermittently passes through the sensor network, and the sensor network selects a rendezvous node for the data transfer to the drone. The drone periodically broadcasts a ***HELLO*** message including the current location

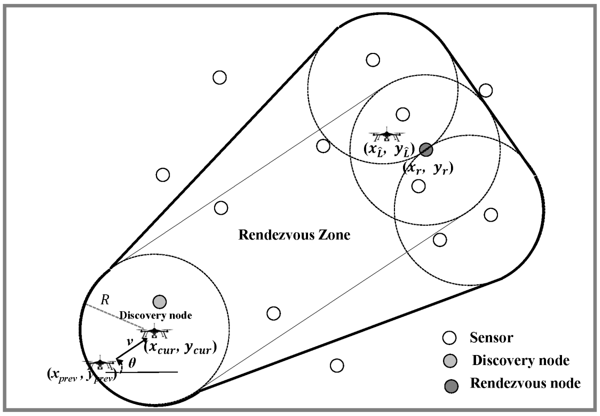


FIGURE 3. The network models.

TABLE 2. Notations used in this paper.

Notation	Description
N	The total number of nodes.
r	The effective communication radius.
SN_i	The ith sensor nodes
T	The wake-up time of duty cycle interval
τ	The sleep time of duty cycle interval
ρ	The duty cycle (i.e.,) ρ=T/(T+τ)
d	MAC layer back-off latency and the packet modulation/demodulation latency
r_i	The number of retransmissions for a packet at node i
${D_i}^{(n)}$	The latency for a n-hop packet transmission at node i
$\hat{L}$	The expected latency for data collection
ETX_i	The expected transmission count at node i

information periodically. The node that received the ***HELLO*** message twice consecutively, called discovery node, estimates a rendezvous node while considering the drone's speed and data collection latency. Other nodes around the path that the drone is heading towards the rendezvous node, called rendezvous zone, periodically check the drone's ***HELLO*** message to see if the drone is off the path. Table 2 shows the notations in this paper.

C. PROTOCOL

We focus on designing the communication protocol for the data collection/gathering process from sensor nodes via a UAV such as a drone. Our approach can reduce data collection latency by predicting a drone trajectory and selecting a rendezvous node in a wireless sensor network. A drone for data collection periodically sends ***HELLO*** messages. This message contains certain parameters that help sensor nodes in predicting drone's trajectory such as 'Packet Type', 'UAV ID', and 'Location Coordinates'. The Packet Type specifies whether the packet is a data or control packet. UAV ID is a unique ID to each drone. Location Coordinates are the current location of the drone.

The first node to receive the ***HELLO*** message twice is called the discovery node. This node can calculate velocity v and the approach angle θ from the previous location (x_{prev}, y_{prev}) and the current location (x_{cur}, y_{cur}) as shown in Equations (1) and (2).

$$v = \frac{\sqrt{((x_{cur} - x_{pre})^2 - (y_{cur} - y_{pre})^2)}}{\Delta T} \quad (1)$$

$$tan\theta = \frac{y_{cur} - y_{pre}}{x_{cur} - x_{pre}} \quad (2)$$

Then, the discovery node estimates the expected latency $\hat{L}$ for the data collection process based on ETX measurements [21]. When we assume that the modulation latency is a constant time, the expected latency $\hat{L}$ is calculated as Equation (3).

$$\begin{aligned} E\left[{D_i}^{(n)}\right] &= E\left[\sum_{i=1}^{n-1} {D_i}^{(1)}\right] \\ &= E\left[\sum_{i=1}^{n-1}\left\{r_i \cdot (\tau + T) + d + \frac{\tau}{2}(1-\rho)\right\}\right] \\ &= (\tau + T)E\left[\sum_{i=1}^{n-1} r_i\right] + (n-1)\left(d + \frac{\tau}{2}(1-\rho)\right) \\ &= (\tau+T)ETX_n - (n-1)\left(T + \frac{\tau}{2}(1+\rho) - d\right) \end{aligned} \quad (3)$$

Using Equation (3), we can simply predict the expected location of the drone $(x_{\hat{L}}, y_{\hat{L}})$ after that latency as follows:

$$(x_{\hat{L}}, y_{\hat{L}}) = \begin{cases} x_{\hat{L}} = v \cdot cos\theta \cdot (\hat{L}) + x_{cur} \\ y_{\hat{L}} = v \cdot sin\theta \cdot (\hat{L}) + y_{cur}. \end{cases} \quad (4)$$

The discovery node also designates a rendezvous node from 1-hop sensor nodes near the expected location$(x_{\hat{L}}, y_{\hat{L}})$ by considering the energy remaining amount. Our approach maintains a 'Rendezvous Count' (i.e. the number of times a sensor node served as a rendezvous node) to prolong the network lifetime and selects a node with the minimum rendezvous count. Our strategy is to have the nodes equally likely to be rendezvous nodes whenever possible. Note that the closer to the rendezvous node, the greater the energy consumption since the rendezvous node acts as a temporary data sink node. Finally, after the Rendezvous Count of the selected node is incremented, a ***RD*** message containing the rendezvous node' ID and Rendezvous Count is broadcasted to to update the information of the rendezvous node. Upon receiving the ***RD*** message, each node stores the information about the rendezvous node and then transmits the sensor data to the rendezvous node only if the message has not yet been forwarded. When the rendezvous node receives the ***RD*** message, it performs by to collecting data from the sensor nodes and interacting with the drone. The data collection process using a drone is shown in Figure 4.

D. RENDEZVOUS ZONE

Our protocol includes a mechanism to establish a trust between the drone for data collection and sensor nodes as the drone may not be able to communicate with selected rendezvous nodes due to the out of predicted drone trajectory.

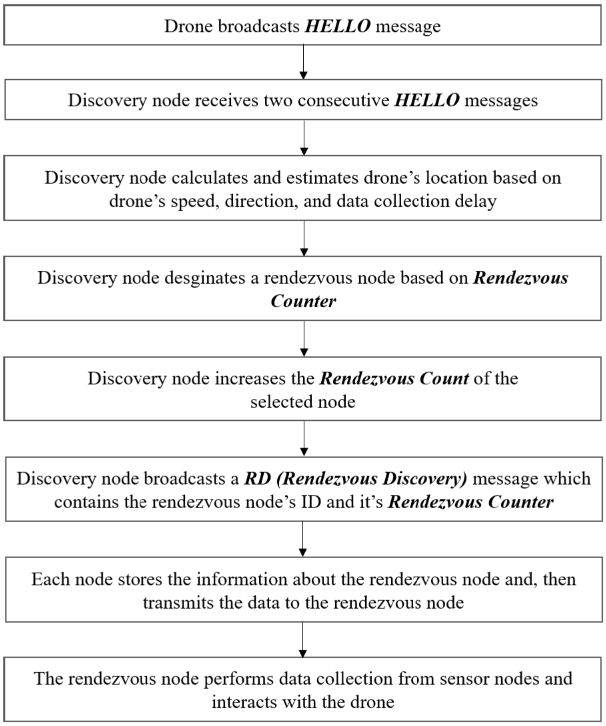


FIGURE 4. **Data collection process with a drone.**

As shown in Figure 5, we define a rendezvous zone, which is a set of locations that can communicate with a potentially selected rendezvous node around a drone's predicted path. Each node in the sensor network can determine whether it is a rendezvous zone by Equation (8), shown at the bottom of this page. When other nodes not in the rendezvous zone receive ***HELLO*** messages from the drone, they proceed with the initialization process by broadcasting the ***RENDEZVOUS DISCOVERY (RD)*** message to re-select the rendezvous node again.

Figure 5 shows a detailed rendezvous zone (Figure 5 (a)) and its approximation (Figure 5 (b)). The rendezvous zone is the area of coordinates at which nodes can receive ***HELLO*** messages while the drone moves at the estimated constant velocity v from the observed point to points A and B at the maximum reachable distance from the selected rendezvous node. Given the current location of the drone, $C(x_{cur}, y_{cur})$, and the rendezvous node location, $R(x_r, y_r)$, the rendezvous zone can be expressed as the d, α, and θ factors that can be computed from the coordinates of these two points by the following equation:

$$d = \sqrt{(x_r - x_{cur})^2 + (y_r - y_{cur})^2}, \tag{5}$$

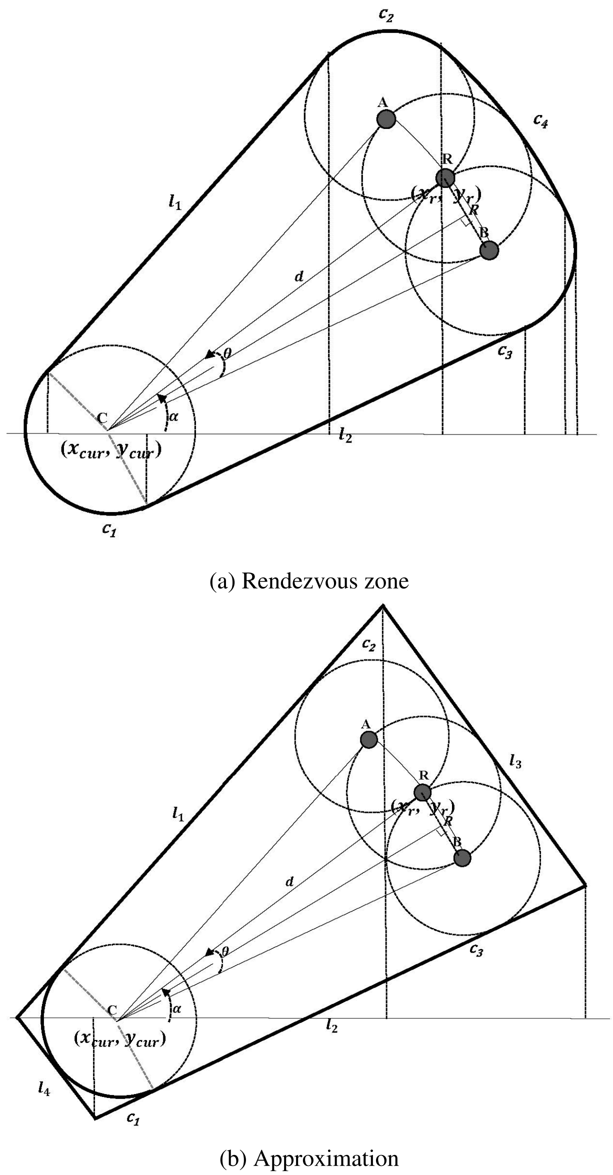


FIGURE 5. **Rendezvous zone.**

$$tan\alpha = \frac{y_r - y_{cur}}{x_r - x_{cur}}, \tag{6}$$

$$tan\theta = \frac{R\sqrt{4d^2 - R^2}}{2d^2 - R^2}. \tag{7}$$

Let d denote a distance from the current location of the drone to the rendezvous node and denote α as an angle of the rendezvous node from the x-axis about the current position of

$$Z(x_i, y_i) = \begin{cases} sin(\alpha + \theta)(x_i - x_{cur}) - cos(\alpha + \theta)(y_i + y_{cur}) + R \geq 0 \\ sin(\alpha - \theta)(x_i - x_{cur}) - cos(\alpha - \theta)(y_i + y_{cur}) - R \leq 0 \\ cos(\alpha)(x_i - x_{cur}) + sin(\alpha)(y_i - y_{cur}) + R \geq 0 \\ cos(\alpha)(x_i - x_{cur} - x_r) + sin(\alpha)(y_i - y_{cur} - y_r) - R \leq 0 \end{cases} \tag{8}$$

TABLE 3. Simulation environment.

List	Description
OMNeT++	Version 5.1
inet	Version 3.5.0
Mac layer	IEEE 802.15.4
Topology	Grid distribution
Routing protocol	LEACH + Multi-hop
Communication range	30m
Node number	50, 100, 500
Data size	50, 500, 5000B
Node' initial energy level	5J
Data collection interval	5 seconds
Drone visiting interval	3 min

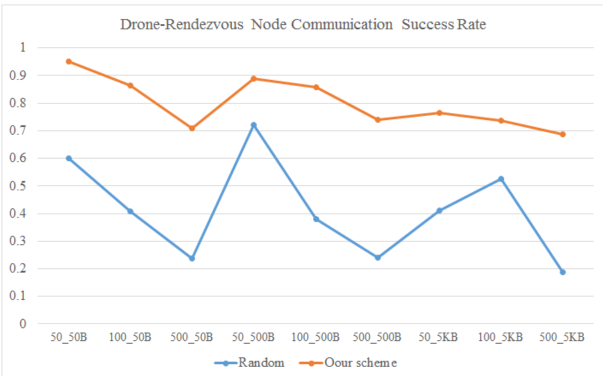
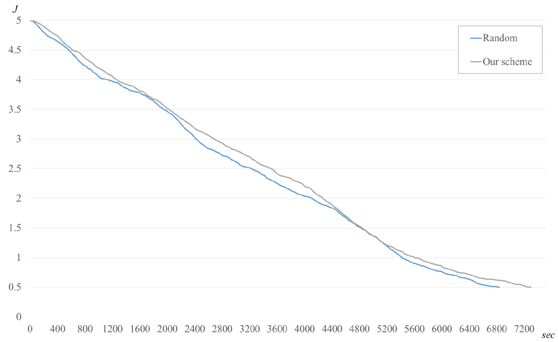


FIGURE 6. Data collection success rate between drone and rendezvous node.

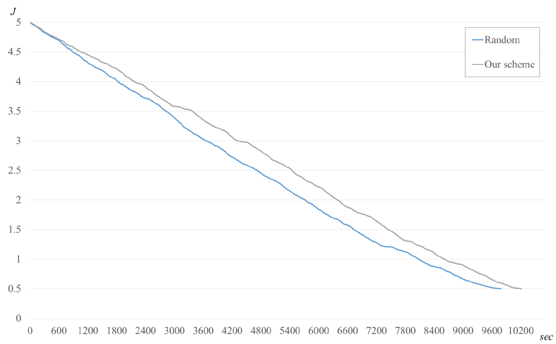
the drone. θ is the angle between point B and point R based on point C.

The naive rendezvous zone (see Figure 5 (a)) consists of four circles and two straight lines, which can be complicated. For more efficiency, we approximate the naive rendezvous zone with an inequality of only four straight lines, such as shown in Figure 5 (b). Here, the straight line l_1 is a common tangent line of c_1 and c_2. The straight line l_2 is a common tangent line of c_1 and c_3. l_3 is a straight line with a slope perpendicular to the circle of radius R around the position of the rendezvous node. l_4 is a tangent parallel to l_3 and is in contact with circle c_1.

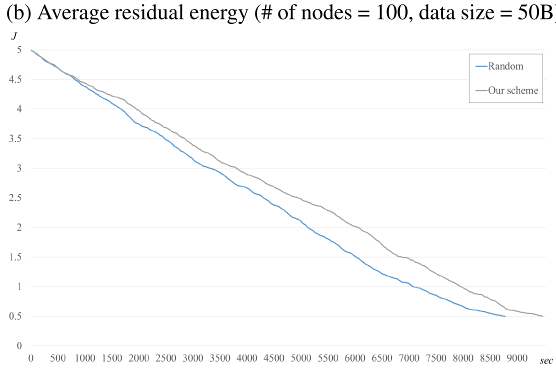
These inequalities can be summarized as Equation (8) where $0 < \alpha < 90$ and $d > R$. If d is less than R, the rendezvous zone is disabled because the rendezvous node already exists within the communication radius of the drone. This provides a way to determine which a node at position P(x_i, y_i) is in the rendezvous zone. Note that the node exists in the rendezvous zone when all four inequalities of Equation (8) are satisfied. This mechanism can prevent data loss by resetting the rendezvous node and the rendezvous zone as soon as nodes not in the rendezvous zone detect drone's trajectory. Furthermore, the rendezvous can be designed with flexible margins by considering the drone's mobility and the dynamic characteristic of communication quality.



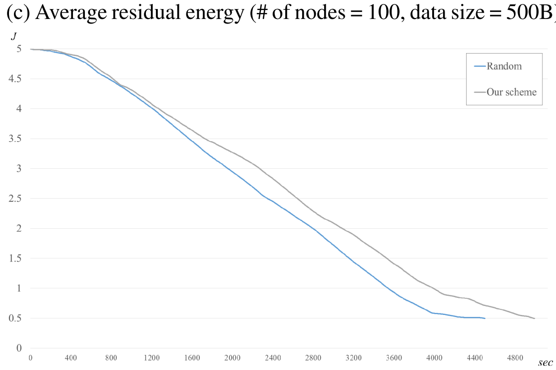
(a) Average residual energy (# of nodes = 50, data size = 50B)



(b) Average residual energy (# of nodes = 100, data size = 50B)



(c) Average residual energy (# of nodes = 100, data size = 500B)

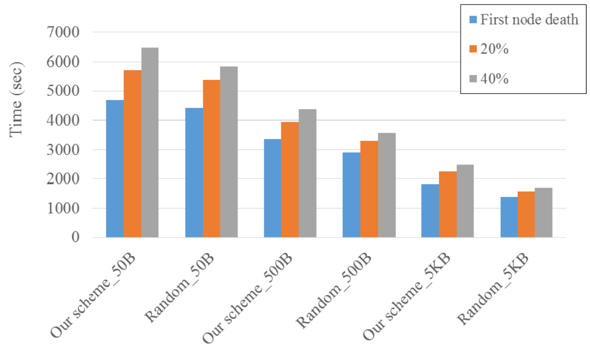


(d) Average residual energy (# of nodes = 500, data size = 5KB)

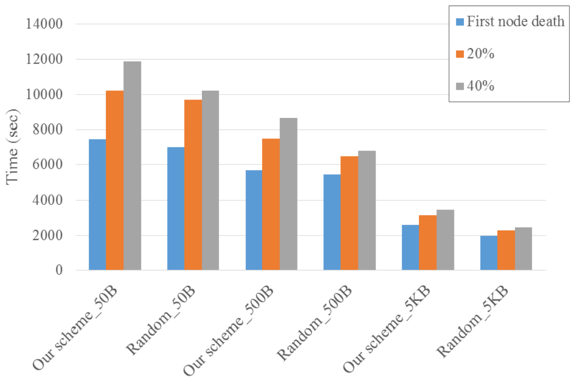
FIGURE 7. Average residual energy.

IV. SIMULATION RESULTS AND ANALYSIS

We simulated the proposed rendezvous node estimation algorithm based on OMNeT++ [23] and the simulation environment as shown in Table 3. We use LEACH [24] routing protocol, which is one of the clustering routing protocols. LEACH is used for reducing energy consumption in



(a) Network lifetime (# of nodes = 100)



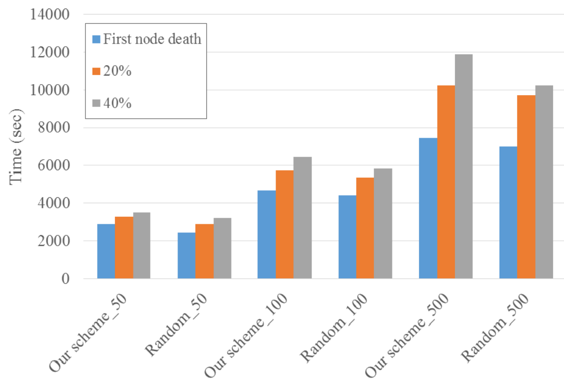
(b) Network lifetime (# of nodes = 500)

FIGURE 8. Network lifetime as the data size.

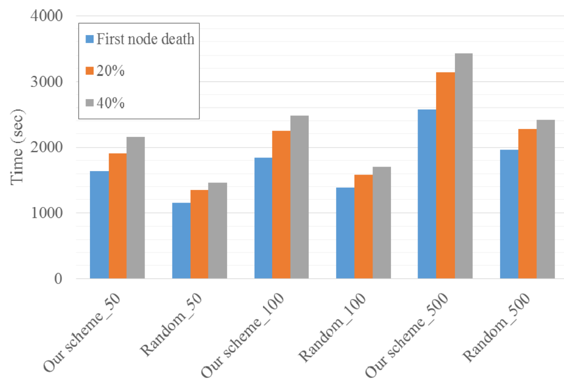
creating and maintaining clusters. We adjusted the number of sensor nodes and the data size of a packet. If we select a predetermined static rendezvous node, the rendezvous node and its neighbor nodes spend more energy than the remaining nodes. The network is easily partitioned and its lifetime is reduced. The 'Random' scheme uses a LEACH algorithm to collect data from whole sensor nodes and sends collected data to the randomly selected rendezvous node without considering drone's path and data collection latency. Our scheme uses a modified LEACH algorithm that considers not only the residual energy of sensor nodes but also drone's path and data collection latency during a rendezvous node estimation.

Figure 6 shows the data collection success rate between the drone and the rendezvous node. The rate of the proposed scheme is higher than the rate of the Random scheme as increasing the number of sensor nodes and data size of a packet. If a rendezvous node fails to send collected data of all sensor nodes to the drone, a rendezvous node sends the collected data to a new rendezvous in the next round. This retransmission of the collected data between the previous rendezvous node and the new rendezvous node consumes a lot of energy. The proposed scheme also skips data collection process to save energy when there is no rendezvous node candidate in the rendezvous zone.

A comparison of average residual energy between the proposed and random scheme is shown in Figure 7. Average residual energy of the proposed scheme is higher than one of the Random scheme in all cases. If the number of sensor nodes and data size are small, the difference of the average residual energy between the proposed and random scheme is also small as shown in Figure 7a. However, the difference is significant if the number of sensor nodes and the data size are large as shown in Figure 7d. This means that the Random scheme spends more energy than the proposed scheme and the difference increases as the number of sensor nodes and data size of a packet increase. Whenever a randomly selected rendezvous node fails to send collected data to the drone, the rendezvous node retransmits the collected data to the next rendezvous node. In this retransmission process, the previous rendezvous node and intermediate nodes between the previous and a new rendezvous node spends energy relative to the size of the collected data. The size of collected data increases as the number of sensor nodes and data size of a packet increase.



(a) Network lifetime (data size = 50B)



(b) Network lifetime (data size = 5KB)

FIGURE 9. Network lifetime as the number of nodes.

We also compare the network lifetime between the proposed and random scheme as shown Figures 8 and 9. In the case of Figure 8a and 8b, the lifetime decreases as the data size increases. In the case of Figure 9a and 9b, the lifetime increases as the number of sensor node increases due to the high density. If each sensor node evenly spends its energy, the network lifetime prolongs. To achieve this goal, each node fairly performs roles including the member node, cluster head, intermediate node, and rendezvous node in the proposed scheme. We reduce unnecessary energy consumption by increasing the data collection success rate and decreasing the number of retransmissions. the data collection success rate between the drone and the rendezvous node depends on the accuracy of the estimated rendezvous node location. The proposed rendezvous zone increases the estimation accuracy and decreases the number of retransmissions.

V. CONCLUSION

In the case of IoT's including wireless sensor networks, it is important to reduce energy consumption to prolong the lifetime of the networks. A drone can be useful in the case using a drone as a mobile IoT gateway, which receives the collected data from the sink(rendezvous) node of wireless sensor networks. By using drones as mobile IoT gateways in wireless sensor networks, data collection can be possible even in areas where IoT wireless communication is not available. The drone can move near the rendezvous node of the wireless sensor networks and receive the collected data from the node. Then, the drone moves to an area where IoT wireless communication is possible and transfers the data to the IoT server. The rendezvous node is changed whenever the drone approaches the wireless sensor networks.

Because drones operate as a battery, it is important to optimize the energy consumption. Existing research reduces the drone's energy consumption by minimizing flight distance using predetermined information such as the orbit, sensor location and network topology. However, if data collection fails, the additional flying distance of the drone increases dramatically and energy consumption also increases. Therefore, it is important to increase the success rate of data collection.

In this paper, a dynamic rendezvous node estimation scheme is proposed, taking into account the average of drone speed and data collection latency without predetermined information. When a drone approaches the wireless sensor networks, the node discovering the drone at first estimates the drone's path and the position of the rendezvous node. Then, the estimated rendezvous node acts as a sink node and collects data from other sensor nodes. Finally, the rendezvous node transmits the collected data to the drone. Simulation results showed that the proposed scheme is more reliable in terms of the data collection success rate.

ACKNOWLEDGMENT

(Hong Min and Jinman Jung contributed equally to this work.)

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