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On-Demand Data Gathering with a Drone-Based Mobile Sink in Wireless Sensor Networks Exploiting Wake-Up Receivers*

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SUMMARY The introduction of a drone–based mobile sink into wireless sensor networks (WSNs), which has flexible mobility to move to each sensor node and gather data with a single–hop transmission, makes cumbersome multi–hop transmissions unnecessary, thereby facilitating data gathering from widely–spread sensor nodes. However, each sensor node spends significant amount of energy during their idle state where they wait for the mobile sink to come close to their vicinity for data gathering. In order to solve this problem, in this paper, we apply a wake–up receiver to each sensor node, which consumes much smaller power than the main radio used for data transmissions. The main radio interface is woken up only when the wake–up receiver attached to each node detects a wake–up signal transmitted by the mobile sink. For this *mobile and on–demand* data gathering, this paper proposes a route control framework that decides the mobility route for a drone–based mobile sink, considering the interactions between wake–up control and physical layer (PHY) and medium access control (MAC) layer operations. We investigate the optimality and effectiveness of the route obtained by the proposed framework with computer simulations. Furthermore, we present experimental results obtained with our test–bed of a WSN employing a drone–based mobile sink and wake–up receivers. All these results give us the insight on the role of wake–up receiver in mobile and on–demand sensing data gathering and its interactions with protocol/system designs.
key words: *wireless sensor networks, wake–up receiver, mobile sink, drone, experimental prototype and implementation*

1. Introduction

Mobile data gathering in wireless sensor networks (WSNs), where a *mobile sink* moves to the proximity of each sensor node and gathers their data with single–hop transmissions, has been proposed for avoiding multi–hop transmissions, thereby facilitating network management and improving the efficiency of data transfer in WSNs [1]. With the recent development of low–cost and safe unmanned aerial vehicles (UAVs) represented by drones, there have been many works on drone–based data gathering [2], [3], where a sink node is installed into a drone that has flexible mobility to fly over a sensing area.

While WSN incorporating a drone–based mobile sink is a promising approach, it inherits the fundamental problem on energy–efficiency of sensor nodes from original WSNs: the energy consumption of each sensor node should be minimized in order to prolong their battery lifetime. There have been mainly two approaches that have been investigated in literature to realize energy–efficiency of sensor nodes. The first approach is duty–cycling where each node operates with periodical wake–up/sleep of power–hungry radio interface (IF) in order to reduce the energy during idle state where there is no communications demand [4]. The periodical activation of radio IF is necessary in order to detect communication requests from the other nodes. The second approach is the employment of wake–up receiver that is installed into each sensor node as an extra hardware [5]. The wake–up receiver is dedicated to detecting the wake–up request from the other node and consumes much smaller power than the main radio IF. During idle state, only wake–up receiver is powered–on while the power–hungry main radio IF is switched off. When a node is required to communicate with the other node, it first transmits a wake–up signal to remotely activate the main radio IF of the target node in an on–demand manner. If the wake–up receiver at the target node successfully detects the wake–up signal, it switches the main radio IF on, followed by data communications between the corresponding transmitter and receiver. Considering the application to WSN with a drone–based mobile sink, the first approach of duty–cycling is inappropriate since each node needs to continuously repeat the activation of main radio IF even while the drone is not within their proximity. Thus, the second approach of on–demand activation with wake–up receiver is more attractive for WSN with a drone–based mobile sink, which is also confirmed with some numerical results in [6].

In this paper, we focus on mobile and on–demand data gathering with a drone–based mobile sink in WSNs employing wake–up receivers. In general, the battery resource of drone for mobility operation is limited. Therefore, the length of route for a mobile sink to gather data from each sensor node should be minimized while the duration of active period of each sensor node should be also minimized in order to reduce the energy consumption of each node. In this paper, we propose a route control framework which decides the short mobility route for a mobile sink while minimizing the active duration of each sensor node equipped with a wake–up receiver. The main contribution of this paper is threefold:

- We define two different wake–up mechanisms: *broadcast wake–up* where all nodes detecting a common wake–up ID are trigged to wake–up and *unicast wake–up* where only a single node specified by a unique

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wake–up ID conducts wake–up operation. From a viewpoint of energy efficiency of each node, the unicast wake–up is preferred since it enables a mobile sink to wake–up only a desired target node, thereby avoiding unnecessary wake–up and contention at medium access control (MAC) layer. However, the mobile sink needs to obtain the information on individual, unique wake–up ID and communication range of each node in order to apply the unicast wake–up. Therefore, we first suggest introducing a calibration process for obtaining these information, which is conducted at a given sensing field before actual data gathering from sensor nodes. Then, we propose a heuristic algorithm to decide a short route for a mobile sink to gather data from all sensor nodes deployed over a sensing field.

- With computer simulations, we analyze the optimality of the route obtained by the proposed algorithm by comparing its length with that of the optimal solution. We also analyze the trade–off observed between the achieved route length and reliability of data collections by varying different parameters in the proposed framework. Furthermore, we investigate the superiority of the proposed framework to data collections based solely on the broadcast wake–up. These analyses give us the insight on the interactions among wake–up process, physical layer (PHY)/MAC operations, and route optimization for mobile and on–demand data gathering in WSNs employing wake–up receivers.
- We implement a test–bed including a drone–based mobile sink and sensor nodes employing wake–up receivers, all of which are compatible with IEEE 802.15.4g standard [7]. By using our test–bed, we conduct experiments for the drone to gather data from sensor nodes with the route decided based on the proposed route control. With the obtained experimental results, we confirm the practicality of the proposed approach.

Many prior works also investigated the problem of route control for WSNs with a mobile sink, however, most of them do not include wake–up receivers in their system setting. While the concept of mobile and on–demand data gathering in WSNs with wake–up receivers has been advocated in several literatures [6], [8], there have been no specific designs of route control of a mobile sink, which takes account of wake–up mechanisms to be applied for realizing on–demand data collections. To the best of our knowledge, this is the first paper designing and implementing a specific route control framework for WSNs with a drone–based mobile sink, which includes wake–up receivers and on–demand wake–up operations as system components.

The rest of the paper is organized as follows. Section 2 describes the system model and problem definition. In Sect. 3, we present our proposed framework to decide an appropriate route for a mobile sink to gather sensing data. Section 4 analyzes the optimality and effectiveness of the route decided based on the proposed approach with computer simulations. Section 5 shows our test–bed implementation and experimental results of a WSN employing wake–up receivers and a drone–based mobile sink. Finally, Sect. 6 concludes the paper.

2. System Model and Problem Definition

2.1 System Model

The system model considered in this paper is shown in Fig. 1. Sensor nodes are deployed over a sensing field, and a sink node gathering sensing data from each sensor node is installed on a drone with flexible mobility, which constitutes a mobile sink. The mobile sink is capable of staying at a fixed position, e.g., by counting on a hovering functionality of drone, and of freely moving around within the sensing field. The sensor nodes do not have any functionality to relay data of the other nodes. That is, the mobile sink communicates with each sensor node with a single–hop transmission. Each sensor node is equipped with a wake–up receiver. During idle period where there is no communications demand, each sensor node is in a sleep state where power–hungry components of sensor nodes, such as main radio IF for data communications, are switched off while only wake–up receiver is active in order to detect a wake–up signal transmitted by the mobile sink. Since the power consumption of wake–up receiver is much smaller than that of radio IF for data transmission [5], a sensor node in a sleep state consumes only small amount of energy. This prevents each sensor node from consuming wasteful power while the mobile sink is not within their vicinity. Once the wake–up receiver at each sensor node detects the wake–up request transmitted by the mobile sink, it activates its main radio IF and transmits sensing data, after which it transits back to a sleep state. The mobile sink attempts to gather sensing data from all sensor nodes during a single data collection cycle that is periodically repeated, e.g., once per day. We assume that each sensor node possesses a single sensing data that is updated and to be gathered for every data collection cycle. As a propagation environment, we assume path loss, shadowing, and multipath fading. Considering that the sensing field is located in an isolated area (e.g., farm or forest located in local areas), we assume a relatively static environment, where shadowing is constant over long period of time

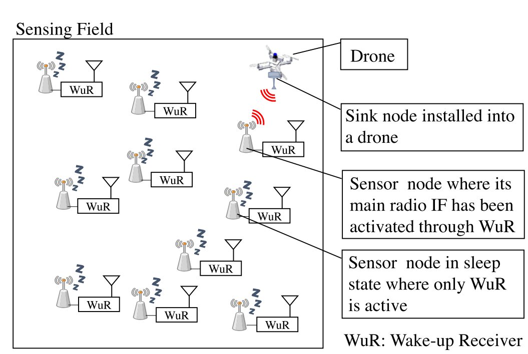

Fig. 1 System Model.

once the locations of sensor nodes are fixed while fading can vary over short period of time.

2.2 Wake–Up Mechanisms

In this paper, we define two different types of wake–up mechanisms: *broadcast wake–up (BCWu)* and *unicast wake–up (UCWu)*. The BCWu is introduced for realizing simultaneous wake–ups of multiple nodes with a single transmission of wake–up signal. The BCWu ID, which has similar functionality to broadcast IP or broadcast MAC address, is predefined and known to each wake–up receiver. When the mobile sink transmits a wake–up signal including BCWu ID, all nodes that correctly decode BCWu ID from the received wake–up signal are powered on†. On the other hand, with UCWu, only a node specified by a unique wake–up ID included in the wake–up signal is triggered to wake–up. We assume that a mapping between MAC address and UCWu ID is predefined and known to each node, which enables the mobile sink to obtain the information on UCWu ID of each node once its MAC address is known.

The BCWu has an advantage that the mobile sink can execute a wake–up trial without knowing the information on nodes and their wake–up IDs located within its wake–up range (i.e., an area where the transmitted wake–up signal reaches). However, since multiple nodes simultaneously wake–up and attempt to transmit sensing data to the mobile sink, there can be high level of congestion at MAC layer, which causes high probability of packet losses and large transmission delay. When carrier sensing multiple access with collision avoidance (CSMA/CA) is employed for resolving this congestion, these nodes spend large amount of time for carrier–sensing and back–off operations, which increases the amount of energy spent by each node. Furthermore, when the mobile sink transmits wake–up signals including BCWu ID from different positions within the sensing field during a data collection cycle, a sensor node can detect these signals multiple times, which triggers it to wake–up for each reception of wake–up signal. However, in our system model described in Sect. 2.1, it is sufficient for the mobile sink to gather a single data from each sensor node during a data collection cycle. Therefore, the multiple wake–ups caused by BCWu are redundant, which results in wasteful energy consumption. On the other hand, UCWu causes neither these redundant wake–ups nor MAC–level congestion at the mobile sink since it enables only a single node detecting a unique wake–up ID to wake–up, which realizes energy–efficient operation of each node. However, in order for the mobile sink to apply UCWu, it needs to transmit a wake–up signal at a position covered by the communication range of each node with an appropriate UCWu ID included in the wake–up signal. Thus, the mobile sink needs to have the information on possible communication range and UCWu ID of each node before data collections.

† We keep the wake–up signaling, i.e., how to convey information on wake–up ID from the sender to wake–up receiver, out of the scope of this paper. For implementations presented in Sect. 5, we employ a signaling scheme which we have proposed in [9].

2.3 Problem Definition

Our goal is to reduce energy consumption of each sensor node as much as possible in order to prolong their battery lifetime. Therefore, it is desired to apply UCWu for each node to benefit from its advantages on energy–efficiency described in Sect. 2.2. However, as described above, UCWu requires us to introduce a process to grasp the information on the communication range and UCWu ID of sensor nodes deployed over a sensing field. One may argue that the route planning can be easily done if the location of each sensor node is recorded upon deployment. However, in a practical environment, the communication range of each sensor node has complex physical characteristics due to shadowing and fading, and does not solely depend on the distance between the mobile sink and sensor node. Therefore, a calibration process at a given sensing field, where the mobile sink makes preliminary examinations to find the possible communication range and UCWu ID of each node, is necessary. Furthermore, considering that the battery resource of drone for mobility operations is also limited, the length of a route for the mobile sink to collect data over a sensing field should be minimized. The most naive method is for the mobile sink to move to the best position within the communication range of each sensor node and to conduct UCWu–based data collection for each node. However, when the communication ranges of several sensor nodes are overlapped, the mobile sink can conduct UCWu–based data collection for multiple nodes at a single location within the overlapped area, which helps to reduce the length of route to be travelled per a unit node. Thus, the appropriate positions for the mobile sink to conduct data collection and route to move among these positions should be decided based on the information on the communication range of each sensor node so that the overall route length is minimized.

3. Proposed Route Control for Mobile Sink

In this section, we propose a route control framework that decides a route for the mobile sink to travel while applying UCWu–based data collection, considering the communication range of each sensor node. The proposed framework consists of two phases as shown in Fig. 2: calibration phase for route decision and data collection phase. In the calibration phase, a route for the mobile sink to employ during the data collection phase is decided. Note that the calibration phase is conducted only when the configuration of the sensing field is changed.

The calibration phase consists of the following three

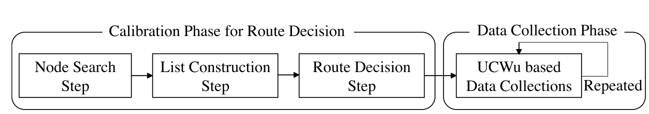

Fig. 2 The overview of the proposed route control framework.

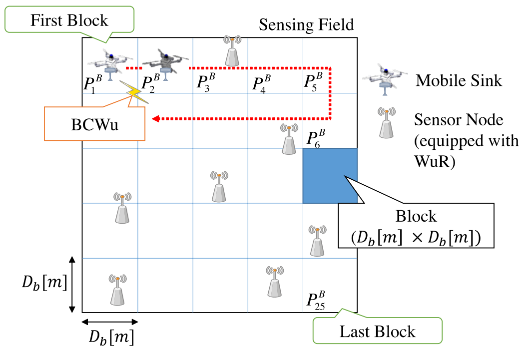

Fig. 3 An example of operation of node search step.

steps:

(1) Node Search Step

In this step, the mobile sink examines the target sensing field by exploiting the BCWu mechanism. Note that BCWu is employed only for the node search step, and it is not used for actual data collections in the proposed framework. Here, "node search" means the identification of the communication range of each sensor node and its UCWu ID (i.e., MAC address). The overview of node search step is shown in Fig. 3. In the proposed route control, we first divide the target sensing field into several *blocks*, where the size of each block is D_b [m] × D_b [m]. For simplicity to decide the best route of mobile sink and also for ignoring the impact of mobility on data collection performance, we only allow the data collection while hovering at a fixed position, not while travelling [2]. The mobile sink moves to the center of each block P_i^B ($1 \leq i \leq N_{Bmax}$) in turn, where N_{Bmax} is the maximum number of blocks ($N_{Bmax} = 25$ in the example of Fig. 3). We assume that the mobile sink is equipped with a localization device such as GPS receiver, and can ideally move to the center of each block. At the center of each block, the mobile sink conducts BCWu, i.e., transmits a wake–up signal including BCWu ID with its transmission power of P_T^{WU} [dBm] and waits for replies from sensor nodes. Once the mobile sink receives a reply from a sensor node, it records its MAC address, which is used for identifying UCWu ID, and received signal strength indicator (RSSI) of the received signal. Note that, if we employ higher transmission power of P_T^{WU}, sensor nodes that are located farther from the center of each block can wake–up. In this case, it is highly likely that nodes replying to the wake–up request are not restricted to those located inside the corresponding block. This parameter of P_T^{WU} plays an important role to control trade–off between the achieved route length and reliability of data collection as discussed with simulation results in Sect. 4. The successive executions of BCWu over all blocks constitute a single node search, which is repeated during the node search step. We define the number of repetitions as N_{BC}. When completing this step, we have a set of ID and RSSI of each reply received at each block.

Table 1 An example of list constructed in the list construction step.

Block No.	1	2	3	4	5	6	7	8	9
Nodes with high probability of data collection	A B	B	C E	D E	A B D E G	A	F	D F G H	H

(2) List Construction Step

In this step, based on the information obtained in the node search step, we construct a list of nodes at each block, from which the mobile sink can collect data with high probability by using UCWu at each block. First, at each block, we list node IDs with which the mobile sink has observed larger RSSI than P_r^{Th} [dBm] at least once over N_{BC} searches†. The initial value of P_r^{Th} [dBm] is set to P_r^{max} [dBm]. This list is created for each block, however, there can be nodes whose replies are received during the node search step, but their IDs are not listed in any block since their RSSIs are smaller than P_r^{Th} [dBm]. In this case, we decrease P_r^{Th} with the step of ΔP_r [dBm], and update the list by applying the above procedure to nodes whose IDs are not registered into the list. These procedures are repeated until all node IDs, whose replies have been detected during the node search step, are registered into the list or P_r^{Th} [dBm] reaches its minimum value of P_r^{min} [dBm]. Practically, P_r^{min} should be set to a value that is sufficiently larger than the minimum receiver sensitivity. Then, even with fluctuation of observed RSSI, the high probability of data collection can be ensured. An example of list constructed during this step is shown in Table 1. This table shows node IDs of A to H for different block numbers (1-9) when the number of blocks is 9. Here, we can find some nodes whose IDs are listed in several blocks (e.g., node ID A in blocks of 1, 5, and 6). This is because the communication range of sensor node A comprises several blocks, which means that the sensing data of node A can be obtained with high probability from any of these blocks.

(3) Route Decision Step

The constructed list tells us, if the mobile sink visits a block and executes UCWu for the nodes listed in the corresponding block, the data can be collected successfully with high probability. The goal of route decision step is to derive a route (i.e., the series of visiting blocks) with the minimum length while guaranteeing that each node ID appears at least once in the list of visiting blocks. Note that, by allowing the mobile sink to collect data of a single node at multiple blocks, the reliability can be improved. However, this can make the derived route longer and also make the complexity of route decision process higher. Therefore, for simplicity, we take an approach for the mobile sink to collect

†We have also tested an approach to use the averaged RSSI over N_{BC} searches. Due to the lack of space, we do not show results in this paper, but we found the similar insight to that presented in this paper.

Table 2 An example of updated list during the route decision step.

Block No.	1	2	3	4	5	6	7	8	9
Nodes with high probability of data collection			C				F	F H	H

data of each node at a single block considering that the reliability of data collection has been already ensured during the list construction step. One approach to this problem is to jointly solve set–covering problem and travelling salesman problem (TSP), however, these are both known to be NP–hard and hard to be applied when the number of blocks and sensor nodes becomes larger [10]. Therefore, in this paper, we introduce a heuristic algorithm with smaller complexity to decide a route that is as short as possible while collecting data from all nodes registered in the list. In the proposed algorithm, we set the first visiting block to that with the maximum number of node IDs in the constructed list. Then, we put the node IDs included in this first visiting block into S_1^{DC}, that is a collection set for this visiting block, and remove them from the list, which results in the new, updated list. With the example of Table 1, block 5 is set as the first visiting block, and node IDs for block 5, i.e., A, B, D, E, and G are put into S_1^{DC}, and removed from the list, which results in the new list shown in Table 2. Then, we set the next visiting block to that with the maximum number of nodes IDs in the updated list (block 8 in the example of Table 2), and update the list again. Now, S_2^{DC} includes nodes F and H. This process continues until no node ID is left in the updated list. Note that, when the several blocks have the same number of node IDs, a block with the shortest distance from the previous block is chosen as the next visiting block. The heuristic algorithm requires us to obtain a block with the maximum number of nodes (and comparison of the route length from the previous block when several blocks have the same number), in the worst case, $N_{Bmax} - 1$ times. Thus, the computational complexity of the heuristic algorithm is at most $O(N_{Bmax}^2)$, which can be easily calculated even for large number of blocks and sensor nodes.

Once the route is decided based on the above three steps, UCWu–based data collections with the decided route are conducted by the mobile sink periodically. The mobile sink applies UCWu to collect sensing data from nodes included in each collection set S_i^{DC} for the $i-th$ visiting block over the route. The transmission power of wake–up signal for UCWu is set to the maximum value since UCWu wakes only a single node up and there is no motivation to reduce its transmission power.

4. Numerical Results and Discussions

4.1 Simulation Model

The main simulation parameters are summarized in Table 3. We employ PHY configuration of IEEE 802.15.4g [7] and MAC protocol of IEEE 802.15.4 [11] that is based on CSMA/CA. We assume a wake–up signaling that shares the frequency band with data transmission (i.e., shared–channel wake–up signaling defined in [5]). In this section, for simplicity, we assume that the wake–up receiver has the capability to decode the wake–up signal transmitted by the mobile sink over the same channel as the data transmission (In Sect. 5, we introduce a concrete mechanism to realize this signaling in our implementation). The same PHY/MAC parameters are employed for transmissions of wake–up signals and data frames. The radio propagation between the mobile sink and each sensor node is assumed to follow path loss, log–normal shadowing, and flat Rayleigh fading. The simplified path loss model [12] is employed with the path loss exponent of 4. Considering a drone–based mobile sink, we set the height of mobile sink to 10 m. We assume the standard deviation of log–normal shadowing of 6.7 dB. Since we assume a relatively static environment as described in Sect. 2.1, the variation due to shadowing is fixed during each simulation trial while the effect of fading is independently varied for each node search and data collection phase. The starting position of mobile sink is assumed to be at the top–left corner of the sensing field. The sensor nodes are deployed over the sensing field with uniform distribution. The success of reception of wake–up signal and data frame is decided based on the instantaneous received signal–to–noise ratio (SNR). The bit error rate (BER) is calculated with $BER = Q(\sqrt{\gamma})$, where γ is the instantaneous received SNR and $Q(\cdot)$ is a Gaussian Q–function [12]. Based on the calculated BER and each size of wake–up signal and data frame, the probability of successful reception is derived, assuming bit errors occur uniformly over the channel, which is then used for the decision on success/failure of each reception.

Table 3 Simulation parameters.

Frequency Band	920 MHz
Data Rate	100 kbps
Modulation	BFSK
MAC	CSMA/CA
macMaxCSMABackoffs	10
macMinBE	5
macMaxBE	10
P_r^{max}	−100 dBm
ΔP_r	5 dBm
P_r^{min}	−115 dBm
Size of Wake-up Signal	59 bytes
Size of Data Frame	123 bytes
Max. Tx Power	20 mW

4.2 Simulation Results and Discussions

4.2.1 Optimality of the Proposed Heuristic Algorithm

We first analyze the optimality of the heuristic algorithm introduced in the route decision step of the proposed route control framework by comparing its route length with that obtained by solving NP–hard problems. To this end, we newly define the following two approaches:

Optimal Solution: This is the route with the shortest distance with which the mobile sink can gather data of all sensor nodes existing in the sensing field out of all possible solutions. The number of solutions is $\sum_{i=1}^{N_{Bmax}} {}_{N_{Bmax}}P_i$ since it considers all possible number of visiting blocks and visiting sequences.

Hybrid Solution: With this approach, we first determine blocks for the mobile sink to visit in the same way as the heuristic algorithm. Then, by solving travelling salesman problem, we determine the shortest route to visit each block exactly once to gather sensing data.

Note that these solutions require us to solve NP–hard problems, to which we applied standard dynamic programming and branch–and–bound methods [10], therefore, it is hard to apply them to large–scale networks with more number of blocks and sensor nodes.

Figure 4 shows the average route length of the heuristic, optimal, and hybrid solutions against the number of sensor nodes. Here, the field size is set to 100 m × 100 m, and a block size of 25 m × 25 m (i.e., D_b = 25 m) is employed, which leads to the number of blocks of 16. For the node search step, we set N_{BC}=5 and P_T^{WU}=1 mW. The results in Fig. 4 are averaged values over 10 simulation runs. From this figure, we can first see that the average route length generally tends to become larger as the number of nodes is increased. With the increase of the number of nodes, the mobile sink needs to visit larger number of blocks in order to collect data from all sensor nodes, which makes route length longer. Next, we can see that the average route length of the hybrid solution is longer that of the optimal solution. The optimal solution is derived considering all possible sets and orders of visiting blocks while the hybrid solution decides visiting blocks by solely counting on the number of nodes included into each block. This makes the hybrid solution suboptimal, and its route length is longer than that of the optimal solution and more sensitive to the increase of the number of nodes. The heuristic solution is longer than the hybrid solution since it even decides the route to move around visiting blocks heuristically without optimizing it. We observe that the heuristic solution has longer route than the optimal one by around 50% for the number of nodes of 18, and its gap is expected to become larger for larger number of nodes and blocks. However, it is hard to derive the optimal and hybrid solutions for larger number of nodes and blocks since they require us to solve NP–hard problems. Therefore, for simulations with larger–scale setting presented below, we employ our heuristic algorithm, and keep the development of the other schemes to derive a route closer to an optimal value with lower computational complexity, e.g., by employing meta–heuristic such as genetic algorithm (GA), for our future work.

4.2.2 Basic Evaluations of the Proposed Route Control

Figure 5 shows the route length per node against number of node searches, i.e., N_{BC}, with different transmission power of BCWu employed in the node search step. The route length per node is calculated by dividing the length of the derived route by the number of sensor nodes whose data are successfully collected during the UCWu–based data collection phase. We also plot results on data collection rate, which is the percentage of the number of nodes whose data are successfully collected during the UCWu–based data collection phase, in Fig. 6. These results are obtained with the size of sensing field of 250m × 250m and a block size of 25m × 25m (i.e., D_b = 25m), which leads to the number of blocks of 100. The number of sensor nodes is assumed to be 50. All results presented below are averaged values over 50 simulation runs.

From Fig. 5, we can first see that the route length per node becomes shorter as N_{BC} increases. This is because the number of sensor nodes registered in each block on the constructed list is increased as N_{BC} becomes larger. During the node search step, the search is repeated N_{BC} times, and RSSI observed in each link between the mobile sink and each sensor node at each block varies among search trials due to random fading. In the list construction step, if a node observes

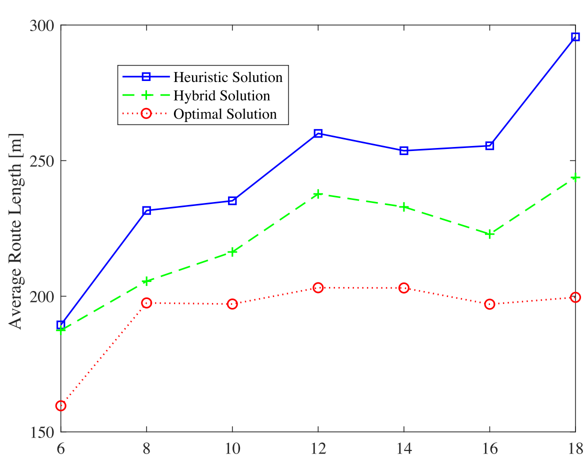

Fig. 4 Average route length of heuristic, hybrid, and optimal solution against number of nodes.

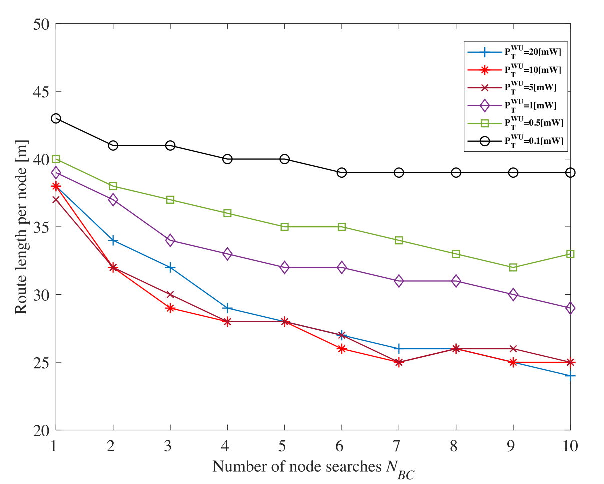

Fig. 5 Route length of mobile sink per node against number of node searches N_{BC} for different transmission power of BCWu in the proposed route control.

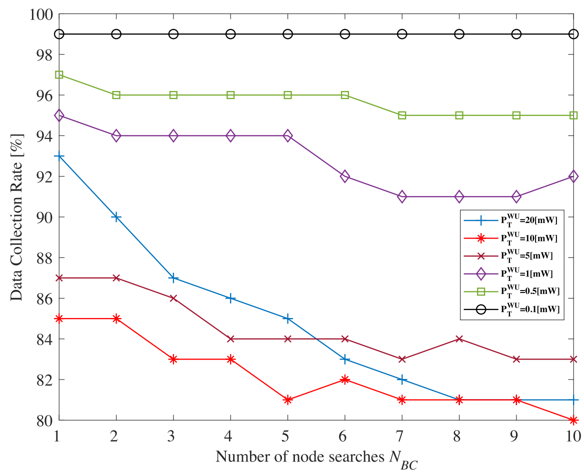

Fig. 6 Data collection rate against number of node searches N_{BC} for different transmission power of BCWu in the proposed route control.

a larger RSSI value than P_r^{Th} at least once, its ID is added to the corresponding block on the constructed list, which results in more number of nodes in each block with the increase of N_{BC}. A list with more number of nodes at each block indicates that the mobile sink can collect data from a larger number of nodes at each block, which results in smaller number of visiting blocks in the route derived in the route decision step. This is the reason why we have shorter route length with larger N_{BC}. However, with the increase of N_{BC}, we have higher probability for a worse link, which experiences a larger RSSI only occasionally, to be registered into each block on the list. The data collection using such a worse link can be failed with higher probability in the data collection phase, therefore, as can be seen in Fig. 6, the data collection rate is deteriorated as N_{BC} becomes larger. Thus, the route length and data collection rate are in a relationship of trade–off through the parameter of N_{BC}.

Next, focusing on the impact of transmission power of BCWu in the node search step, i.e., P_T^{WU}, on the route length and data collection rate, we find the similar trade–off to that through N_{BC}. That is, from Fig. 5, we can see that the route length tends to become shorter as P_T^{WU} is increased. With higher transmission power of BCWu, sensor nodes that are located at farther positions from the center of each block can be woken up by the wake–up signal, which results in more number of nodes added to each block on the constructed list. As stated above, this leads to shorter route derived in the route decision step. However, the link with a larger distance between the mobile sink and sensor node suffers from lower RSSI, which causes more failures of data collection in the data collection phase as confirmed in Fig. 6 where the data collection rate tends to become lower with larger P_T^{WU}. Note that the data collection rate cannot reach 100% even with P_T^{WU} that is smaller than 0.1mW since some nodes may not detect wake–up signals with smaller P_T^{WU}. This can be improved by increasing the number of blocks (by reducing each block size), i.e., by increasing the number of positions for data collection. The optimization of block size considering the trade–off between the route length and reliability is kept for our future work.

From the above results, we can conclude that the route length and data collection rate are in a relationship of trade–off through parameters of N_{BC} and P_T^{WU}, which should be appropriately controlled according to requirements given by the target application scenarios.

4.2.3 Comparison with BCWu–Based Data Collection

As mentioned in Sect. 2.3, our goal is to reduce energy consumption of each sensor node, which is the reason why we select UCWu instead of BCWu for data collections. Here, we numerically compare these two different approaches. To this end, we first define BCWu–based data collection. With BCWu–based data collection, like the proposed UCWu–based approach, the sensing field is divided into blocks with same sizes. Then, without any calibration process, the mobile sink visits each block in turn, and conducts BCWu at the center of each block. Each sensor node, after detecting the wake–up signal including BCWu ID, wakes up and transmits data back to the mobile sink. The mobile sink waits for replies from sensor nodes for sufficiently long period at each block.

Table 4 shows the route length per node, data collection rate, and total active time of sensor nodes, which are achieved by UCWu–based data collection with the proposed route control and BCWu–based data collection. The total active time of sensor nodes reflects the energy–efficiency since longer active time means more energy consumed by sensor nodes. Here, the size of sensing field is set to be 1000m × 1000m and the number of sensor nodes is assumed to be 50. The block sizes for UCWu–based and BCWu–based data collections are respectively 25m and 100m, and N_{BC}=1 and P_T^{WU}=0.5 mW for UCWu–based data collection, which are decided based on our preliminary evaluations so that they can offer the best trade–off among the three performance metrics. From Table 4, we can first see that the total active time of sensor nodes can be drastically reduced by employing UCWu–based data collection. With UCWu–based data collection, the active time can be reduced almost by 90% in comparison to BCWu–based data collection. This is because each sensor node wakes up only once with UCWu–based data collection while, with BCWu–based data collection, nodes wake up and attempt to send data every time they detect the wake–up signal including BCWu ID transmitted by the mobile sink from different blocks. These multiple attempts of data transmissions contribute to a slight improvement of data collection rate for BCWu–based data collection as shown in Table 4, however, thanks to the appropriate calibration, UCWu–based data collection can also achieve the same level of reliability in terms of data collection rate. Furthermore, with the proposed route control, the required route length of UCWu–based data collection is significantly reduced in comparison to that of BCWu–based data collection.

Next, we show results with smaller sensing field (i.e.,

Table 4 Comparison between the proposed approach and BCWu–based scheme (Field Size 1000m × 1000m).

	UCWu–based (Proposed) (P_T^{WU}=0.5mW, N_{BC}=1)	BCWu–based (D_b=100m)
Route length per node [m]	129	401
Data collection rate [%]	96.0	99.5
Total active time of nodes [s]	0.6405	5.6895

Table 5 Comparison between the proposed approach and BCWu–based scheme (Field Size 250m × 250m).

	UCWu–based (Proposed) (P_T^{WU}=1 mW, N_{BC}=10)	BCWu–based (D_b=100 m)
Route length per node [m]	29	27
Data collection rate [%]	92.0	88.8
Total active time of nodes [s]	0.6342	9.6697

higher node density) of 250m × 250m in Table 5. The same block sizes and number of sensor nodes are assumed for Tables 4 and 5. With higher node density, the route in which the mobile sink visits most of the blocks tends to be derived for UCWu–based data collection, therefore, no significant difference on the route length per node is observed for two approaches. However, with higher node density, many nodes attempt to reply to the wake–up signal for BCWu, which degrades its data collection rate due to high level of MAC–level congestion in comparison to UCWu–based data collection. Furthermore, we can clearly see that the total active time of sensor nodes can be significantly reduced by employing UCWu–based data collection also for this scenario with higher node density.

5. Implementation and Experimental Results

In this section, we present our implementation of a WSN employing wake–up receivers and a drone–based mobile sink for collecting data from sensor nodes deployed over a sensing area.

5.1 System Configuration and Experimental Settings

5.1.1 Node Configuration

In our experiments, we employ our prototypes of sensor nodes that are equipped with wake–up receivers. The main radio IF for data communication is based on PHY/MAC protocols of IEEE 802.15.4g/802.15.4. The wake–up receiver has only the capability to detect the length of frame observed over 920MHz frequency band through simple envelope detection and on–off–keying (OOK) demodulation. For the detail of our prototype, readers are referred to [9]. One of the prototypes is used as a sink node that is always active and has a role to collect sensing data from deployed sensor nodes. When the sink node attempts to wake–up a target sensor node, it transmits IEEE 802.15.4g frame whose length corresponds to a wake–up ID assigned to the target node. The wake–up receiver, which only detects the length of received frames, outputs a wake–up command to its main radio IF once it detects a frame length assigned to itself as a wake–up ID. This enables wake–up signaling between IEEE 802.15.4g module and a simple, OOK–based wake–up receiver. For BCWu, a common broadcast wake–up ID (i.e., a common frame length) is assigned to all sensor nodes while, for UCWu, different wake–up IDs (i.e., different frame length) are assigned to different nodes.

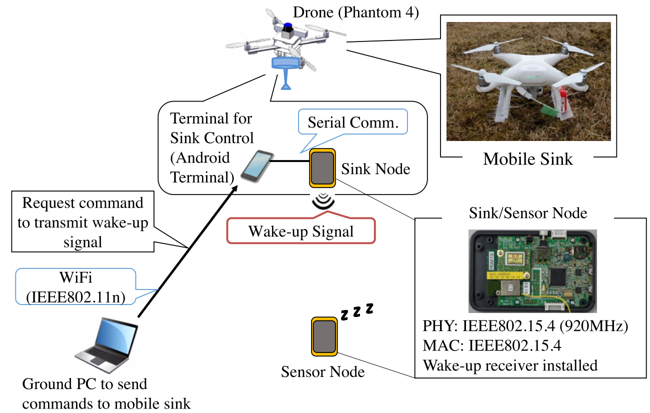

Fig. 7 The configuration and appearance of the drone–based mobile sink and sensor nodes.

5.1.2 Setting and Control of Drone–Based Mobile Sink

The configuration and appearance of the drone–based mobile sink is shown in Fig. 7. The sink node is installed on DJI phantom 4 that is a commodity drone [13]. As a terminal to control the sink mode, we use an Android terminal (NEC MediasX N-04E [14]). The Android terminal is connected to a laptop PC on ground with WiFi (IEEE 802.11n operating over 5 GHz). The sink node is controlled to transmit wake-up signals from the laptop PC through WiFi and serial communications. In this experiment, the movement of drone is manually controlled from a remote controller whose operating frequency is 2.4 GHz. Thus, there is no interference between radio signals for controlling the drone–based mobile sink (i.e., 5 GHz and 2.4 GHz) and those used for IEEE 802.15.4g–based on–demand data collection (i.e., 920 MHz).

5.1.3 Node Deployment

The experiment was conducted at JUIDA ATR Keihanna Test Air Field [15]. Within an outdoor 120 m×45 m field, 8 sensor nodes are deployed as shown in Fig. 8. The area is relatively small for the possible communication range of IEEE 802.15.4g, therefore, we shield some nodes (node 1, 2, 5, and 8 marked with (S) in Fig. 8) with radio wave absorbers. We assume that the block size is 30 m×22.5 m. The height of drone–based mobile sink is controlled to be 10 m.

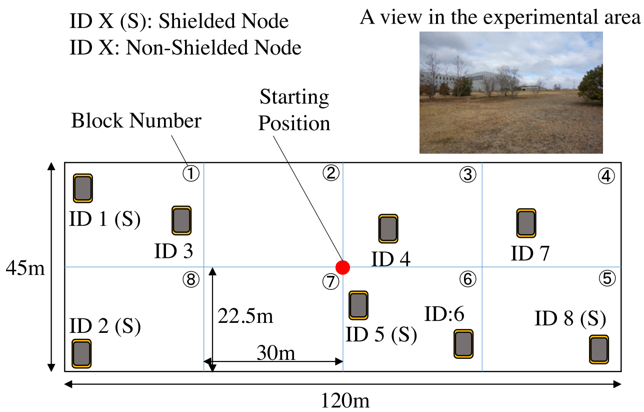

Fig. 8 The node deployment in the experiment.

5.2 Experimental Results and Discussions

In the experiment, we first applied the proposed route control framework to the deployed sensor nodes. For the node search step, N_{BC} and P_T^{WU} are respectively set to be 10 and 20 dBm. We show in Table 6 the list that was constructed during the list construction step with $P_r^{Th} = -60$ dBm, $\Delta P_r = 5$ dBm, and $P_r^{min} = -90$ dBm. From this table, we can see that the communication range of each sensor node exhibits complex characteristic that does not simply depend on the distance between the sink node and each sensor node. For instance, it was found that the data of node 7 could be collected with high probability from the blocks ①, ④, and ⑤ while it is not listed in the blocks of ② and ③. Furthermore, node 3 is listed in several blocks, however, it is not listed in its closest block of ①. One of the reasons for this complex characteristics could be the propagation effects such as shadowing and fading. The experimental area has several trees and its ground level is not completely flat, which can cause each sensor node to experience different shadowing and multipath effects toward the drone–based sink node. The other reason could be the antenna directivity of each sensor node and sink node.

Based on the list shown in Table 6, the route was created through the route decision step. The obtained route was ⑥ ⇒ ⑤ ⇒ ⑧ ⇒ ① with $S_1^{DC} = \{5, 4, 6\}$, $S_2^{DC} = \{7, 8\}$, $S_3^{DC} = \{3, 2\}$, and $S_4^{DC} = \{1\}$. Then, by using the decided route, we ran data collection phase, i.e., UCWu–based data collections, 10 times. As a result, we observed the data collection rate of 98.8 %. We had only a single failure for node 6 during the data collection phase. This failure is probably due to the temporal variation of propagation characteristic for node 6, which was not experienced during the node search step. However, from the obtained results, we can conclude that the data collection can be made with high reliability by employing the decided route in a real–world setting, which confirms the practicality of the on–demand data gathering with a drone–based mobile sink employing the proposed route control framework.

Table 6 The list constructed in the list construction step in the experiment.

Block No.	①	②	③	④	⑤	⑥	⑦	⑧
Nodes with high probability of data collection	1 7	3 4		7	7 8	5 4 6	3 4	3 2

6. Conclusions

In this paper, we have proposed a framework to control route of a mobile sink for mobile and on–demand data gathering in WSNs employing wake–up receivers. In order to reduce the energy consumption of each sensor node, UCWu–based data collection has been employed in the proposed framework. This requires us to introduce a process to identify the communication range and wake–up ID of each sensor node, which is conducted in the proposed framework as a calibration phase before UCWu–based data collection. Based on the identified information, the route of a mobile sink is decided with a heuristic algorithm so that the route of mobile sink is minimized. With computer simulations, we have investigated the optimality of the route obtained by the proposed route control and analyzed the trade–off between the achieved route length and reliability of data collection, which was observed by varying parameters employed in the proposed framework. Our numerical results have shown the superiority of UCWu–based data collection to BCWu–based data collection in terms of route length and energy–efficiency of sensor nodes. Furthermore, we have presented experimental results obtained with our test-bed consisting of a drone–based mobile sink and sensor nodes that are equipped with wake–up receivers. With our experimental results, we have confirmed the practicality of the on–demand and mobile data gathering with a drone–based mobile sink employing the proposed route control framework.

In this paper, we have assumed a relatively static environment where shadowing effect is constant over long period of time and shown the effectiveness of the proposed approach. However, when considering more dynamic propagation environment, the calibration phase is needed for every data collection phase, which causes significant overhead. In this case, BCWu–based data collection may be more appropriate since it does not require any prior information for applying data collection. Thus, an appropriate strategy should be applied considering the variation of propagation environment over time. Our future work also includes the development of algorithms to derive a route close to an optimal one with lower computational complexity. Furthermore, the consideration of reliability of data collection for the route decision step, e.g., by allowing the collection of data of a single node at multiple blocks, is an important future work.

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