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UAV-assisted data gathering in wireless sensor networks

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Abstract An unmanned aerial vehicle (UAV) is a promising carriage for data gathering in wireless sensor networks since it has sufficient as well as efficient resources both in terms of time and energy due to its direct communication between the UAV and sensor nodes. On the other hand, to realize the data gathering system with UAV in wireless sensor networks, there are still some challenging issues remain such that the highly affected problem by the speed of UAVs and network density, also the heavy conflicts if a lot of sensor nodes concurrently send its own data to the UAV. To solve

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those problems, we propose a new data gathering algorithm, leveraging both the UAV and mobile agents (MAs) to autonomously collect and process data in wireless sensor networks. Specifically, the UAV dispatches MAs to the network and every MA is responsible for collecting and processing the data from sensor nodes in an area of the network by traveling around that area. The UAV gets desired information via MAs with aggregated sensory data. In this paper, we design a itinerary of MA migration with considering the network density. Simulation results demonstrate that our proposed method is time- and energy-efficient for any density of the network.

Keywords Unmanned aerial vehicle (UAV) · Wireless sensor networks · Data gathering · Mobile agents

1 Introduction

Wireless sensor networks (WSNs) are very important infrastructures in modern society for human life. WSNs for environment observes noise level, ultraviolet level, or level of pollution, and issues warnings if some parameters are over the thresholds, so that damage to human and the environment can be avoided [10,14,16]. WSNs for agriculture gathers the data of temperature, humidity, and sunlight, to well-control the production conditions for increasing the quality and quantity of the crops [13]. WSNs for disasters monitors the change of water level in a river, the possibility of mudslides in a mountain, the speed and direction of winds, or the amount of rain or snow, to reduce the damages due to the disasters [1]. It may also be used to find the alive after disasters such as earthquakes, to rescue them [11]. WSNs in a battle fields detect the obstacles, poison gas, possible weapons of enemy such as bombs and landmines to reduce the damages, and the positions of enemy to take advantages over the enemy [2].

The types of a sensor network could be with an infrastructure or without an infrastructure [8,9]. Communication of sensor nodes of an infrastructure type is well-organized directing to a server, which is connected with the internet or other backbone networks to monitoring center. Sensor networks without infrastructure use ad hoc communication. The density of sensor networks, e.g. the distance and degree of neighbor nodes, is another parameter of a sensor network. A dense network has many sensor nodes close to each other. A sparse network has few sensor nodes in a short distance. The deployment of sensors could be well-planed and performed, say a team goes around the field to deploy them, e.g. sensors for observation of river water level can be deployed regularly along the river. Or they can be roughly deployed using an airplane to battle fields or a mountain. For reducing the cost of deployment and due to some physical limitation, to deploy the sensors by spraying from a moving object such as an airplane is generally employed. Considering the methods of deployment of sensors, the hard working/maintenance conditions of sensors, and running down of energy, an ad hoc type sensor network without infrastructure, or a combination of infrastructure and ad hot type is more practical than only infrastructure type.

Furthermore, the density of a network may be variable, due to the deployment method and application requests, e.g. some highly dangerous locations should have more sensors, and other locations may not need so many sensors. Data sensed by a sensor network is collected and processed to get useful information about the situations of the fields. For example, the pollution situation of the environment, the maximum water level in a river or all dangerous positions along the river, the average temperature in a field or the best conditions for a kind of crop. There are simple computation and advanced/complex computation for data gathering and aggregation. For example, to get a maximum temperature is a simple computation in an infrastructure type network, by collecting the data of neighbors (say the children nodes) and computing and sending the maximum to their parent, and so on. However, to know the situation of damage by a disaster or the degree of pollution may need many types of parameters and complex computation to those parameters/data. In some cases, the computation algorithms are on-demand and developed based on new findings and ideas when the disaster happens. That is, the programs for computation may need to be sent to each sensor node dynamically, not in advance.

In the literature, several approaches have been proposed, such as mobile agents (MAs) based and an unmanned aerial vehicle (UAV) based data gathering. The MA is a software program which can migrate from node to node for collecting and computing sensory data so that each sensor node does not need to install the programs in advance and can deal with dynamically environmental changes. On the other hand, the UAV approach has a merit of energy distribution because the server communicates with each sensor node one by one which can solve a hotspot problem of sensor networks.

By taking both advantages of MAs and the UAV, in this paper, we propose the UAV-assisted data gathering method with help of the MAs. The UAV dispatches MAs to sensor networks. Every MA is responsible for collecting the data from sensor nodes around an area, by traveling around the sensor nodes, and returns back from a node. If necessary, the UAV will dispatch more agents when it finds there are still some areas which have not been visited. We assume that the sensor network is ad hoc type and try to make groups by communication between neighbors closed to each other. A node with the most energy remaining will be the leader of a group. The number of groups is dependent on the density of the networks. The UAV will only communicate with the leaders of the groups and dispatch MAs to those leaders, from which MAs start their travel to collect and process data.

The rest of the paper is organized as follows. Section 2 reviews related works. In Sect. 3, the model of our proposed system is shown and challenging problems are defined. Section 4 presents our effective algorithm for data gathering. A case study of the system is discussed in Sect. 5. Section 6 shows simulation experiments and analysis of the results. We conclude the paper in Sect. 7.

2 Related work

There are many methods of data gathering and aggregation [3,4,12,15], by which the data of a sensor node in a network can be collected and computed to get the useful information. Specifically, an MA, which is a piece of program traveling the network from node to node to compute the local data to get useful global information, has attracted more researchers' interests, since they have the following features [18], comparing with the server/client (s/c) based approaches without using MAs. Also, researches on UAV assisted have lots of publications on the field [5,6].

1. More application-oriented and task-adaptive: MAs can be developed on-demand and dispatched to sensor nodes dynamically, instead of deploying the computation programs in advance.
2. More scalable: The computation and traveling among sensor nodes can be easily adapted and expended by mobile agents, though the number of sensor nodes is increased or decreased, and the connection links between nodes is changed.
3. More reliable: MAs can continue their works even though some parts of the network are damaged or disconnected, and get the final results when the network problems are fixed.
4. More energy-efficient: The traveling of the mobile agents can be dependent on the information gain and energy levels of neighboring nodes.
5. More flexible for the computation: MAs can perform a task to get a partially integrated result generated by nodes having already visited, if the partial results have already satisfied criteria for the results. This feature gives quick responses and saves energy of nodes, due to reducing the nodes to be visited.

On the other hard, UAV-based approach is proposed in [7], which has the following features, comparing with s/c methods and MAs methods.

1. Since the UAVs are used to receive the data from sensor nodes directly, communication between sensor nodes is greatly reduced, to save the energy for listening to the neighbors, which costing much energy.
2. There are free spaces between the sensor fields and the UAVs, so that the decaying of signals is slower than the decaying between sensor nodes, due to low-lying antennas of sensors.
3. The UAVs can detect weak signals, since they can be equipped with high level signal processing units and multiple antennas.

However, there are following problems in this approach.

1. There are heavy conflicts, since every sensor node directly sends its data to the UAV, which reduces the efficiency and some data may be lost due to the conflicts.
2. Because of the speed of flying servers on the UAV and conflicts mentioned above, the servers may not communicate with all sensor nodes requested, and the approach is only useful for dense networks, where data can be duplicated in neighbors. It is also assumed that the requested information can be achieved by a fraction of data due to the duplication of data.

To solve those problems, we propose a new data gathering method, which employs both the UAV and MAs. The proposed method takes the advantages of both approaches and gains the performance efficiency in terms of both execution time and energy consumption of the network.

3 Network model and problem definition

3.1 System model

Figure 1 shows the model of the system. There are a UAV, e.g. an airplane or a balloon, MAs, and a sensor network having many sensor nodes in the model.

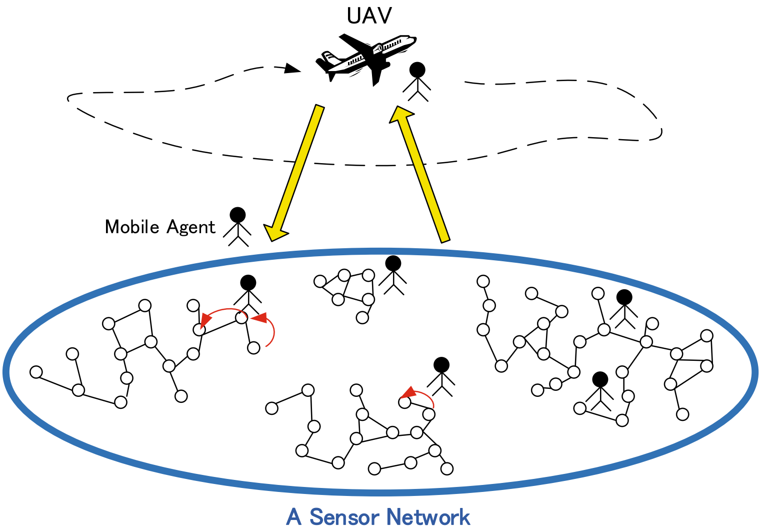


Fig. 1 Network model

If communication between a pair of sensor nodes is available, we say there is a link between nodes of the pair. We call the pair neighbors. The sensor network is a variable density network, which means some parts of the network are dense, and some parts of the network are sparse.

The UAV has strong signal processing functions and multi-antennas. The UAV can send signals to a sensor node directly. It can also receive signals from the node, if the node has a certain level of power for sending the signal. We assume not all nodes can have enough power to send the signals reaching to the server directly.

MAs are created by the UAV, depending on a request of application and have a task based on the request. The MAs are dispatched to some sensor nodes and start their work on arriving at the sensor nodes, and travel other sensor nodes to perform their tasks, i.e. run the program on the visited nodes.

A sensor node has its local data obtained by sensors and stored in a simple DB or memory. The data are changing with the time reflecting the change of the physical conditions of environments. The sensor node is simple and has limited memory. The energy of the sensor node is consumed for its sensing, communication, and other operations. The remaining of energy is different for different nodes. We assume a sensor node can have several modes such as the strong power mode for sending signal to the UAV, the normal mode for communication between neighbors, and the sleep mode for saving the energy. In the sleep mode, the node can only receive a simple one-bit message to change its mode.

3.2 Problem definition

Under the model mentioned in last subsection, we challenge the following problems in this paper.

1. How does the UAV dispatch the MAs to sensor nodes.
   a. How many MAs are dispatched to the sensor network?
   b. To which sensor nodes, the MAs will be dispatched?
   c. With what kind of order, are those MAs dispatched?
2. How do the MAs work in the sensor network?
   a. What itinerary should an MA follow?
   b. How does an MA interact with a sensor node?
   c. How to make a group consisting of sensor nodes for reducing the cost of MAs?
   d. How to elect the leader of a group, and change the leader for load balancing?
   e. How do the MAs collaborate with each other?
   f. How does the MA collaborate with the UAV?
3. How does an MA return back to the UAV?
   a. From which node, should an MA return.
   b. What kind of information, should the MA carry with it.
   c. What kind actions should the UAV take after an MA return back?

4 UAV-assisted data gathering

4.1 Basic idea

The following scenario is considered to conserve energy of sensor nodes and also to avoid network traffic conflicts in communication between the UAV and sensor nodes.

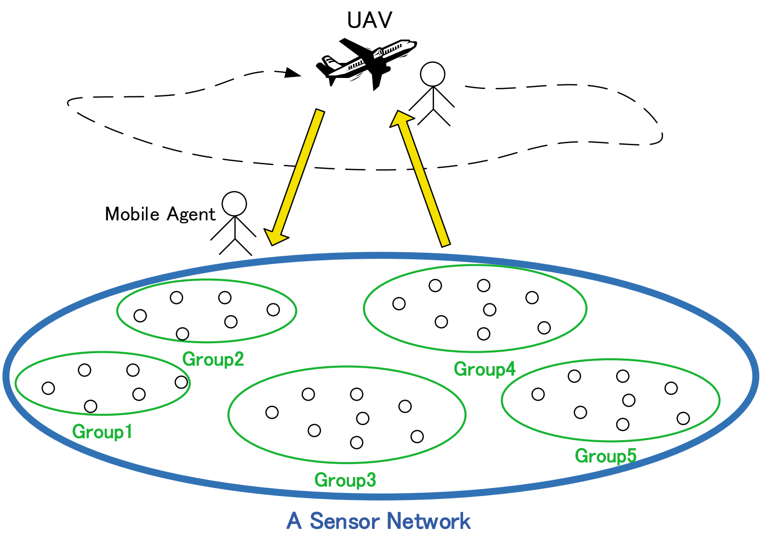
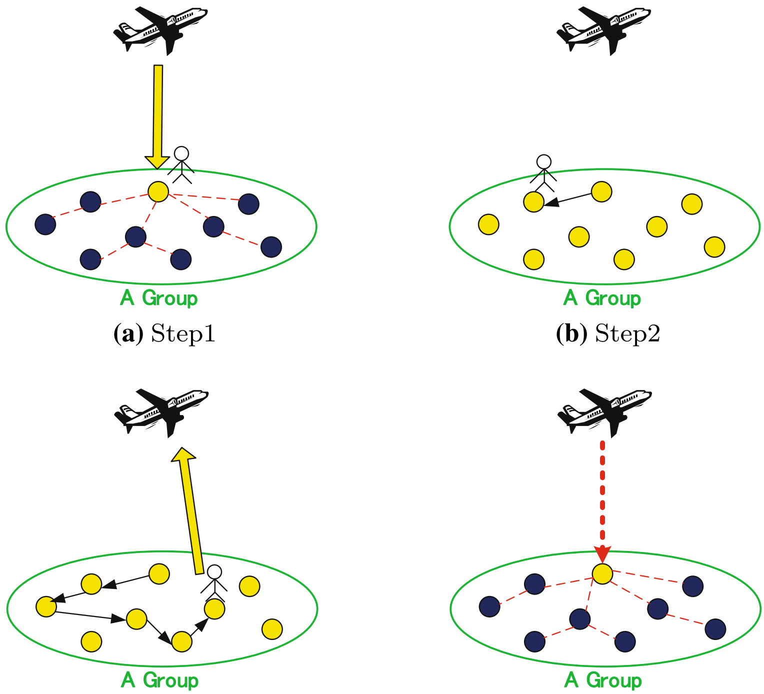


Fig. 2 Big picture of the idea



(a) Step1 **(b)** Step2

(c) Step3 **(d)** Step4

Fig. 3 Interaction between the UAV and a sensor group in the WSN

Figure 2 shows a big picture of the idea and has some elements. First, a wireless sensor network (WSN) consists of some sensor nodes, which are grouped into Group1, Group2, and so on. Each group has a leader, which has the strongest power remaining in the group and can send the signal using the strong power mode. We suppose that the WSN is sparse as a whole, but partially dense. This means the WSN is composed of some dense and small WSNs. Second, the UAV moves/flies over the WSN to find the leaders of groups and dispatches MAs to those leaders. The number of MAs dispatched to a leader depends on the density of the group, which is known by the group leader. The MA migrates from node to node to perform the task requested by the UAV, and collaborates with each other to reduce the duplicated visiting. After finishing the tasks to get the requested results, based on environmental data sensed by sensor nodes, the MAs return back to the UAV with integrated results.

How to save energy of nodes are shown as follows. We focus on a group in the WSN and every group works in the same way as we will mention below.

Figure 3 roughly depicts how the MAs are dispatched from the UAV, travel around sensors in the group, and are sent back to the UAV. First of all, each group has a leader node which has the most energy in the group and also has a good channel to the UAV. Then, the following steps are taken for each group.

Step1 (Fig. 3a): Before the UAV sends an MA to the group, every node in the group is in the sleep mode to conserve energy except for the leader node. Therefore, the

leader node can receive the MA from the UAV when the UAV comes over the group. If the leader node gets the MA, it sends a beacon message to all other nodes to wake them up by flooding.
Step2 (Fig. 3b): After every node in the group wakes up, the MA starts to migrating from node to node and collect environmental data sensed by each sensor node.
Step3 (Fig. 3c): After the MA finishes its itinerary for data gathering, it comes back to the UAV with aggregated data. If a node, which is the MA's last stop, has enough energy to contact with the UAV, the node can send the MA directly to the UAV. If not, the MA returns its itinerary to find a node having sufficient power for accessing the MA.
Step4 (Fig. 3d): After the UAV gets back the MA with collected data, it sends a shortmessage to the leader node to inform success of receiving the MA. Then, the leader broadcasts a message to make all other nodes change into the sleep mode.

4.2 How can nodes make groups in one network?

Every node sends a massage showing its level of energy remaining. We assume energy remaining of nodes is not uniform but variable. If a node find there is all nodes around has lower level of energy remaining, the node becomes a leader. If there are some nodes having the same level, a unique identification can be used to break the tie. If a node can not be a leader, it will select a neighbor who has the biggest level of energy remaining in all neighbors, as its father node (which will be the leader or directed to the leader). So forest will be constructed, such that local maximal node is the leader.

During above computation, every node also sends its degree of density (i.e. how many neighbors the node has) to its father node, which will compute the average of the density. Finally, the leader will compute the average density of the group. This density information will be used for deciding routing algorithm for MA (discussed later).

This grouping procedure would be taken periodically. If we keep using the current leader as an access point for the UAV, it consumes energy quickly more than the other nodes in the group. Therefore, the leader must be changed periodically and, at the same time, the group should be reconstructed. The current leader sends a beacon message to wake the other all nodes and inform them to reorganize the group.

4.3 How to determine an MA's itinerary?

We consider two kinds of algorithms for MAs routing: ISMAP (information-driven static mobile agent planning) and IDMAP (information-driven dynamic mobile agent planning) proposed by Xu et al. [18]. It depends on a density level of each group. We apply the ISMAP if a group is a relatively sparse network. Otherwise, the IDMAP is applied to the group. This is because the ISMAP performs better if a network is sparse. We will discuss how to briefly judge whether a group is dense or sparse in Sect. 4.4.

Each leader has density information of own his group. The density information is collected in a grouping procedure as mentioned above. Therefore, a leader knows his group is a dense/sparse network. The leader informs the UAV that its group is a

Table 1 Notations used in Eq. 1

Notation	
E_{kj}	Consumed energy for transmission of an MA between node S_k and node S_j
$E_{\max}$	Maximum energy consumption for transmission of an MA between two nodes
$I_j(t)$	Information gain on node S_j at time t
$I_{\max}$	Maximum information gain on any node
$e_j(t)$	Remaining energy of node S_j at time t
$e_{\max}$	Full energy of a node

sparse/dense network before an MA is dispatched. Based on the density information, the UAV sends an MA with the ISMAP/IDMAP algorithm.

– MA with ISMAP: If the density of the group is sparse, the leader sends the UAV MA's itinerary with the density information. The itinerary is periodically updated since it is strongly affected by information gain, which is real-time and sensory data from an environment. An MA is sent to a node which is the first node of the itinerary obtained by the leader, and then the MA starts to migrate. If data collected by the MA meets a predefined threshold, the MA ends the itinerary and is sent back to the UAV. If not, the MA keeps going on the itinerary until there are no unvisited nodes anymore.
  After the UAV gets back the MA with collected data, it sends a short message to the leader node to inform success of receiving the MA. Then, the leader broadcasts a message to make all other node change into the sleep mode.
– MA with IDMAP: After an MA is dispatched to a leader node from the MA, the MA decides a next destination after collecting data from the node. Likewise, every hop is determined by the MA along the way. The itinerary is end if collected data meets the threshold as well as in the case of ISMAP. If so, the MA returns to the UAV. After that, the same procedure as the ISMAP is taken for this case.

For the dynamic itinerary, the next hop is decided based on the following cost function $C_{kj}(t)$ where an MA migrates from node S_k to node S_j at time t, based on [18]:

$$C_{kj}(t) = a\frac{E_{jk}}{E_{\max}} + b\left(1 - \frac{I_j(t)}{I_{\max}}\right) + (1-a-b)\left(1 - \frac{e_j(t)}{e_{\max}}\right) \tag{1}$$

where $0 \leq a, b \leq 1$. Notations used in Eq. 1 are summarized in Table 1. a and b are constant values to weight and make balance among the three components: the energy consumption, the information gain, and the energy remaining. Hence, the MA decides where it goes next, by calculating the cost based on these three components, and select a node for immigration with the smallest cost. Especially, the information gain depends on requests of applications and what the nodes collect from environments. To make it simple, we will have an example of an application for localizing particular people and the details will be explained in Sect. 5.

4.4 How to briefly judge whether a group is dense or sparse

The ISMAP is more suitable if the number of nodes is less than 50 where a deployment field is 20 m × 20 m. Every node was deployed like grids in the field and the same number of nodes was set in column and row. From this condition, we derive the minimum length L between nodes for a sparse network: $L = 2.86$ m. Because of a grid-like deployment of nodes, we can have the following definition with this L.

Definition:{Dense group}

A node S_i tries to find neighbor nodes in the grouping procedure. A neighbor node is called a vicinal node of S_i , if the length between the node S_i and the neighbor node is within L. Then, a group is dense if the average number of vicinal nodes found by each node in the group is more than 4. Otherwise, it is sparse.

4.5 How does the UAV communicate with the sensor networks and dispatch mobile agents

When the UAV moves/flies over the sensor network, it broadcasts a *HELLO* message to leaders of groups. When a leader receives the *HELLO* message, it will response the UAV with an *I_AM_HERE* message with the average density of the group. Depending on the density of the group, the UAV decides the routing algorithm of MAs dispatched to the group, through the leader based on the density information.

We assume that the UAV can find all leaders by flying over the sensor network and repeating *HELLO* messages. More sophistic methods will be considered in the future.

5 Case study

As an example, we apply the model to searching for disaster victims. Because of damages of a disaster like a big earthquake, it may be difficult to search victims by landed vehicles. Under this situation, air vehicles such as aircrafts and helicopters are useful to find people from the sky. However, it still might be hard to discover victims because the aircrafts could not get enough close to the land surface for the search. Also, the helicopters might not be helpful for the victims because the helicopter noise kills voices of victims crying for help. Then, if our method is applied to this situation, we can save much time for searching, so it leads to save many lives of victims.

We assume that the UAV drops light sensor nodes on disaster sites and victims have cell phones equipped with a special function. The special function is called only when a disaster happens and the cell phone cannot connect with any cell tower. Then, the cell phone transmits SOS signals to be sensed by nodes nearby it. These signals are periodically emitted in low power to prolong the battery life of the phone.

By using the signals from cell phones, we localize and track the victims in the disaster sites. The nodes derive the information gain from acquired signals, from which a distance from targeted-phone to a sensor node is calculated. According to [18], the information gain on node k at time t is obtained using a zero mean Gaussian as follows.

Table 2 Notations used in Eq. 3

Notation	
T_j	Time when node j is visited by the precedent MA
$T_{\max}$	Maximum time length between previous visited time and the current time
c	Constant value to weight the element of the time stamp. $0 \leq c \leq 1$

$$I_k(t) = \frac{1}{\sqrt{2\pi\sigma}} \mathrm{e}^{-\frac{||x(t)-x_k||^2}{2\sigma^2}} \tag{2}$$

where $||x(t) - x_k||^2$ is the Euclidean distance between node k and the targeted phone at time t and σ is the standard deviation. The shorter the distance between the node and the target, the more the information gain.

Since we consider searching people under such a critical situation, we should let MAs migrate to nodes evenly. Especially in IDMAP, a dispatched MA has to come back to the UAV as soon as its collected data meets a desired value. Also, it decides its itinerary from local information such as neighboring nodes data. Therefore, it is possible that the MA finds only one victim in a group and then it returns to the UAV. This causes some other victims could be trapped in dangerous places. On the other hand, in ISMAP, MA's itinerary is determined from global information including the information gain and is a set of nodes in decreasing order of the information gain. This means, the more information gain a node has, the higher priority to be visited the node is given.

To solve the above problem in IDMAP, the UAV dispatches a successive MA if the time limit is over. The basic idea is the successive MA migrates to nodes unsearched by the precedent MA by referring the cache information of the nodes. A node saves time stamp into its cache whenever any MA is visited. The UAV dispatches the successive MA to a node where the precedent MA is sent. Therefore, the successive MA can start its itinerary from that node.

By adding the concept of the time stamp, the cost function in Eq. 1 needs the new forth component: time stamp. Then, we reconstructed Eq. 1 as follows:

$$C_{kj}(t) = a\frac{E_{jk}}{E_{\max}} + b\left(1 - \frac{I_j(t)}{I_{\max}}\right) + (1-a-b-c)\left(1 - \frac{e_j(t)}{e_{\max}}\right) + c\left(1 + \frac{t-T_j}{T_{\max}}\right) \tag{3}$$

where $0 < t - T_j \leq T_{\max}$. Equation 3 is applied only if node j is visited before by any precedent node. Otherwise, Eq. 1 is used to calculate the cost for migration. Then, the MA compares the result of the cost functions and it selects a node having the smallest cost. New notations appeared in Eq. 3 are explained in Table 2. $T_{\max}$ is supposed to be enough long for searching people in one group. If MAs get some problems to search during this period $T_{\max}$, a rescue team takes necessary measures such as dispatching more sensor nodes for this area to obtain more accurate information.

6 Simulation analysis

We had simulation experiments using a multi-agent simulator, Netlogo [17]. We dealt with simple conditions of the case study mentioned in the previous section, such as there is only one victim to be found and the victim does not move and stays in the same location. A targeted network is assumed to consist of one group, so the MA dispatched from the UAV is also only one. Under this condition, using the ISMAP is trivial because the targeted victim does not move from start to finish. This means the MA would find the victim as soon as the MA is dispatched. Therefore, we only considered the IDMAP in dense networks.

We selected the execution time and energy consumption of sensor nodes as evaluation metrics of the simulation. The execution time is the time from when the MA is dispatched from the UAV until when the MA returns to the UAV with collected data. The energy consumption is the total energy consumed by every sensor node in the network during the execution time. We used equations and values of parameters given in [18] to estimate the execution time and the energy consumption. For simplicity, the execution time is supposed to be the time spent by nodes to transfer, receive, and process data. Likewise, the energy consumption is the energy used by nodes in the same way. Main parameters are set in the experiments as follows: the size of MA is 1 KB, the overhead of MA (time spent for reading/writing data on a node) is 0.05 s, the network transfer rate is 2 Mbps, and data processing rate is 100 Mbps.

In experiments, we changed the number of nodes from 25 to 100. These two metrics depend on the distance between a leader node and the targeted victim, e.g. if the targeted victim is close to the leader, it would be found by the MA in a short period. Therefore, CDFs of the execution time and the energy consumption are obtained from 100 trials in each number of nodes. Figures 4 and 5 show the results of the experiments: the execution time and the energy consumption respectively. As we can see the figures, the proposed method is less affected by the number of nodes in terms of time and energy. This means, the bigger the scale of the network, the more efficient our proposed model. The MA can efficiently find the victim wherever the victim is in the network although the network is large.

7 Conclusion

This paper proposed an algorithm for data gathering in wireless sensor networks by employing two technologies: mobile agents and a UAV. We take advantages of each technology to save time and energy of sensor nodes. In addition, we focused on the density of a network where the mobile agents are dispatched by the UAV. The mobile agent's itinerary is changed according to the density such as a sparse network or a dense network. To relate proposed algorithm to a reality scenario, we used a case study of searching people in a disaster like an earthquake. Our algorithm is beneficial for gathering data not only in situations of the case study, but also in many other applications in the real world. We considered both dynamic and static itinerary for the mobile agents. However, the itinerary is considered only one mobile agent migrates to nodes at once. In some cases, multiple agents walking around nodes are preferred for

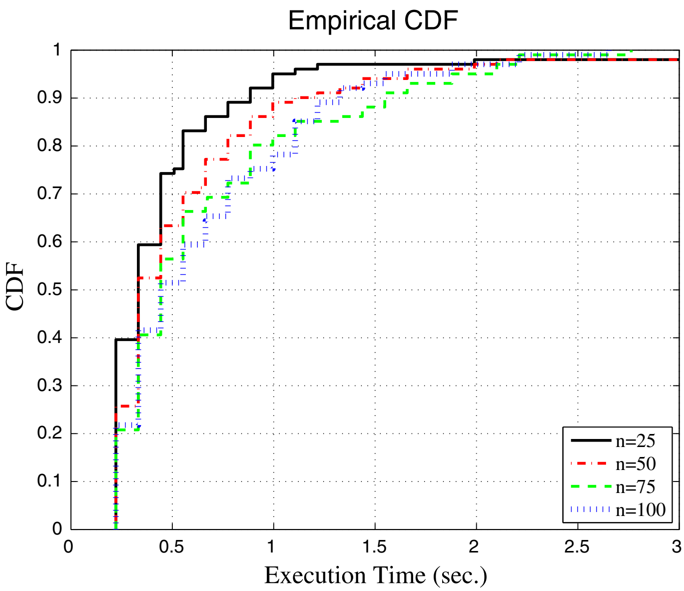


Fig. 4 Energy time vs. the number of nodes

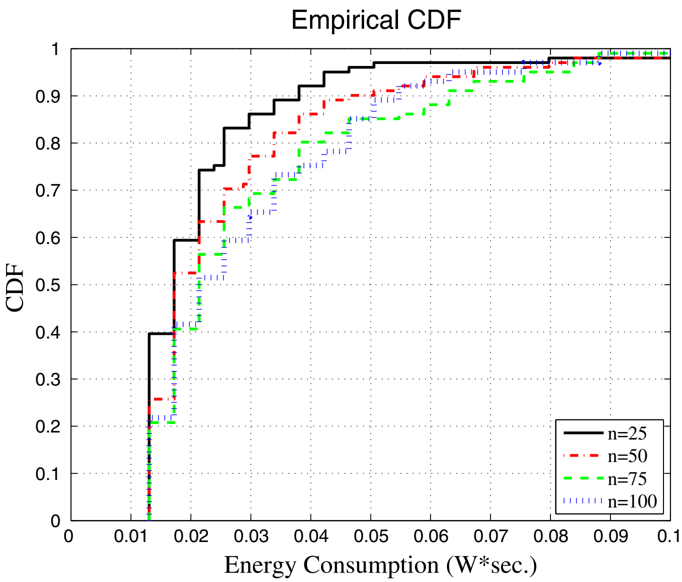


Fig. 5 Energy consumption vs. the number of nodes

saving time more and more. To utilize mobile agents' ability of parallel processing, planning itinerary for multiple agents is important and needs to be considered as our future work.

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