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A Data Gathering Approach for Wireless Sensor Network with Quadrotor-based Mobile Sink Node

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Abstract

In this paper, we use a quadrotor-based mobile sink to gather sensor data from the terrestrial deployed wireless sensor network. By analyzing the flight features of the mobile sink node, we theoretically study the flight constraints of height, velocity, and trajectory of the mobile sink node so as to communicate with the terrestrial wireless sensor network. Moreover, we analyze the data amount which the mobile sink can send when it satisfies these flight constraints. Based on these analysis results, we propose a data acquisition approach for the mobile sink node, which is discussed detailed in terms of network performance such as the transmission delay, packet loss rate, sojourning time and mobile trajectory when given the flying speed and height of the mobile sink node. Extensive simulation results validate the efficiency of the proposed scheme.

Keywords: Mobile sink node; sensor terrestrail network; data acquisition; sojourning time; packet loss rate

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1. Introduction

Wireless sensor network (WSN) includes the gathering of distributed information, the transmission of data and the processing of information. The purpose is to effectively sense, acquire and transmit data from sensor nodes. Such networks can be widely used in national defense, security, environmental monitoring, traffic management, health care, manufacturing and anti-terrorism disaster and etc.. As the wireless sensor nodes are powered with batteries, the energy constrains their wide applications. Herein mobile sink nodes are added to WSN not only in order to enchance the data gathering, but also to improve the energy efficiency and prolonging the network lifetime [1][2][3]. In such scenario, one or more mobile sink nodes travel in a statically deployed network, where one-hop data transmission simplies data gathering, Additinally it results in other advantages such as no special concerning on the network connectivity, low cost for deployment, and high reliability [4][5].

Previous research about data acquisition of mobile sink node focuses on the node discovery, data forwarding[6], routing algorithms[7] and movement control[8][9]. Howerver, the movement pattern such as movement trajactory and speed of mobile sink node affects the data gathering efficiency. The greatest effect of mobile feature is the controllability, i.e. whether the mobile sink nod is controllable [8] or uncontrollable [9]. The controllable mobile sink node may change the location by controlling of travel trajectory and the speed, which might simplify some problems during data acquisition. For example, the mobile sink node is controlled to access some sensor nodes in specific time, which simplifies the node discovery procedure. In addition, as the mobile sink node can be controlled to soujern in the communication range of a sensor node, the connection with this sensor node become easy too. However, a new challenge appears, e.g. how to control the mobile sink node for data gathering so as to improve the enery efficiency while satisfying the specific quality of service [10]

For the trajectory controllability of mobile sink node, it is divided into two categories: the static controllability [11] and the dynamic controllability [12][17]. In the static controllability, the travel path of mobile sink node does not change with time. In the dynamic controllability, the mobile trajectory may change so as to satisfy some constraints, e.g. delay. For those mobile sink nodes whose speeds are controllable, they use stop-and-communicate approach. Specifically, the mobile sink node moves according to the predefined trajectory. When it enters the communication range of a sensor node, it decides whether this sensor node has data to send. If so, it stops and collecting data from this sensor node untill all data are gathererd [13][18]. In [14], a linear programming problem is proposed in 2-demision uniform grid network by controlling the mobile routine and speed of mobile sink node. There the mobile sink node starts from a specific sensor node, and uses stop-and-commuicate approach to collect data so as to maximize the network lifetime. In [15], the problem is extended for the non-uniform network. Besides that, the delay of routing releasing/establishing and the energy consumption are also considered. For this problem, they proposed a heuristic algorithm based on the greedy sojourning energy. In [16][17], the problem concerns about both the scheduling and routing algorithm, and solved the linear programming problem in a distribution manner.

Different from the previous studies, the mobile sink node in this paper is carried out by a quaterotor, which flies in the air. Therein, the movement pattern included not only the movement trajectory and speed, but also the flying height. In this paper, we discuss the these constraints of movment pattern, and propose a data gaterhing approach for such scenario where the mobile sink node is carried by a aircraft to gather data in the terretrial WSN.

Our main contributions on this paper are summarized as follows.

- We characterize the data gathering problem for flying mobile sink node by theoretically analyzing the flying height, velocity and pattern of mobile sink node above the terrestial sensor network.
- We propose a data gathering approach for such terrestial sensor network with a mobile sink node flying above it and to gather data from this network as much as possible when the mobile sink node flies above it.
- We demonstrate that effitiveness of our proposed scheme through extensive simulations. The simulation results confirm that the transmission time, sojourning time and packet loss are impacted by the flying height , velocity and network size significantly.

Other parts of this paper are organized as the following: Section II formulates the problem in terms of the movement speed, height, the amount of data and delay; Section III gives the data gathering approch for such network application; Section IV analyzes the performance of this approach in detail with lots of simulations such as the packet loss rate, the movement speed and flying height; The final section concludes this paper and shows the future work.

2. Problem Formulation

In this paper we will concern about the applications where the wireless sensor networks are deployed in scenarios where human are difficult to reach, such as the monitoring of marsh, forest fire, flood, and lake. In these networks, sensor nodes are divided into two categories: cluster heads and memebers. All cluster members only communicate with the nearby cluster heads, and cluster heads are in charge of transfering data to the mobile sink node. A mobile sink node is carried by a quadcopter which is controllable to fly above the deployed sensor networks. To carry the mobile sink node, we choose a quadcopter since it is more flexible than other kinds of aircrafts to move, stay, lift and descent. As the mobile sinke node might fly with different patterns in term of flying heigtht, velocity and direction, etc., to gather data from the sensor network depends on this pattern since the sensor node has limited communication range due the energy constraint. Therein, the problem becomes how to control the flight pattern of mobile sink node so that the data in the network can be gathered efficiently. .

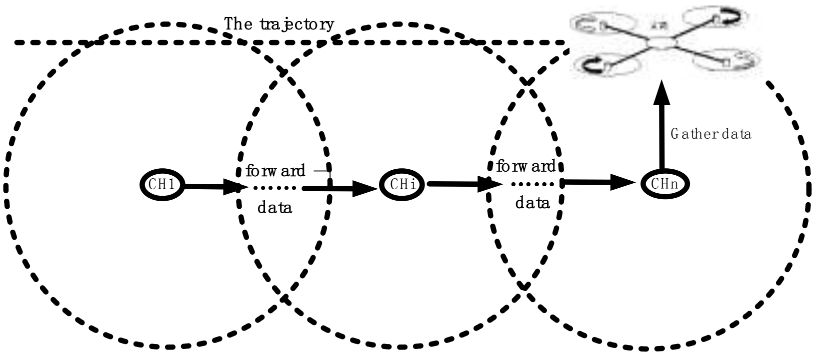

Fig. 1. Cluster Heads in Line

Fig.1 depicts the scenario in which a mobile sink node carried in a quadcopter flies above a linenar sensor network consisting of cluster heads. Here $CH_i....CH_n$ represent the *n* cluster heads, and the spherical dotted line circles are their communication ranges. Only when the mobile sink node enters into the communication ranges of the cluster heads, the mobile sink node can collect data from the related cluster head. Cluster member sensor nodes around the cluster heads send data to the cluster heads for data gathering. The adjacent cluster heads can communicate since they lay in each other’s communication range.

To combat the above problem, firstly we study the scenario where a mobile sink node communicates with one cluster head. After that we extend to the scenario where the mobile sink node can communicate with more than one cluster head.

2.1 One Cluster Head

Here we will study the features of mobile sink node such as communication duration, average data transmission delay, and the data amount in the cluster head which might be sent.

1. Communication duration

The communication duration refers to the time at which the mobile sink node can communicate with the cluster head. It starts from the moment when the mobile sink node enters the communication range of the cluster head, and ends when it leaves the communication range. Therein the communication duration depends on the flying speed, direction and height of the mobile sink node in addition to the communication range. Assume that the mobile sink node flies with a fixed speed of *v*, flight height of *h*, and communication range of the cluster head (spherical) is *D*. As a result, the maximum communication duration is

$$t_{\max} = \frac{2\sqrt{D^2 - h^2}}{v}. \tag{1}$$

This maximum commuincation duration happens when the mobile sink node flies on top of the cluster head, i.e. in the vertical plane of cluster head.

2. Transmission time

Assume that in the cluster head, there are *L* bits data waiting to send, and the transmission rate of the cluster head is *R*. If *L* bits can be transmitted continuously from the cluster head to the mobile sink node, the transmission time is t_t, i.e.

$$t_t = L/R. \tag{2}$$

If the mobile sink node does not stop during flying, Eq.2 exists only when there is $t_t < t_{\max}$.

3. Data amount

In this subsection we consider the data might be transmitted when the mobile sink node lies in the communication range without stopping. Assume the time for the mobile sink node passing through the fixed communication range is *T* without sojourning, which depends on the flying velocity. *L* is the data amount which might be transmitted. Herein we have

$$\frac{L}{R} + T_p + T_c \le T, \tag{3}$$

where T_p and T_c denote the propagation delay and processing delay. As $T_p \geq h/c$ (here h denotes the height, c denotes the propagation rate of electromagnetic wave). Hence, the maximum amount data which might be transmitted is :

$$L_{\max} = R(\frac{2D}{v} - \frac{h}{c} - T_c), \tag{4}$$

If the data amount in the cluster head is fixed, e.g. a small buffer in the sensor node, L is constant. Therein, if the mobile sink does not stop over when it flies in the communication range of the cluster head, to collect all data from the cluster head the permitted flying rate should be less than:

$$v_{\max} = \frac{2D}{L/R + h/c + T_c}. \tag{5}$$

Similarly, the maximum permitted flying height is:

$$h_{\max} = c \bullet (\frac{2D}{v} - \frac{L}{R} - T_c). \tag{6}$$

Eq.(6) gives an upper bound for the mobile sink node so as that the mobile sink node can collect data from the cluster head when it flies on the top of the sensor network. Otherwise it can not gather data from this sensor network.

2.2 Multiple Cluster Heads in Line

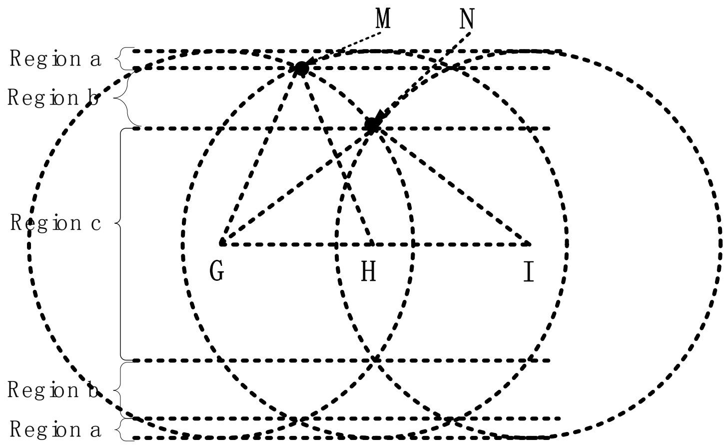

Fig. 2. Divisions of Communication Ranges

In above section, we analyze the constraints for the scenario where a mobile sink node gather data from one cluster head. Now we extend it to a scenario with more than one cluster head. In **Fig.2**, G, H and I denote the positions of the cluster heads i, (i+1) and (i+2) respectively. There are n cluster heads in line.We assume that the distance between two adjacent cluster heads is the similar, e.g. d, and all cluster heads have the same communication ranges. M is the intersection point of communication ranges of the cluster heads i and (i +1). N is the intersection point of communication range of the cluster heads i and (i +2).

We consider the situation where the mobile sink node flies in the communication range of cluster heads. According to the flying height, three sub-regions: a, b and c are defined. In sub-region *a*, the mobile sink node can only communicate with one cluster; in sub-region *b*, the mobile sink node might communicate with two cluster heads; in sub-region *c*, the mobile sink node might communicate with three cluster heads.

According to above assumption, there are $MG=MH=NG=NI=D$, $GH=HI=d$, $GI=2d$. Here *H*, *D*, *R* and *v* are explained in above. Therefore the heights of points *M* and *N* follow:

$$M_h = \sqrt{D^2 - \frac{d^2}{4}} \tag{7}$$

$$N_h = \sqrt{D^2 - d^2} \tag{8}$$

According to the above analysis, the sub-region *a* has $M_h<h<D$, the sub-region *b* has $N_h<h<M_h$, and the sub-region *c* has $0<h<N_h$. In the following we will discuss the data amount which might be sent in these three sub-regions.

- Sub-region *a* ($M_h<h<D$)

In sub-region *a*, the mobile sink node can communicate with one cluster head. Now for the cluster head, the data amount which can be sent depends on the communication time, i.e. the duration in which the mobile sink node stays in the communication range of the cluster head. Theorem 1 gives the data amount which can be transmitted for this cluster head.

Theorem 1: When a mobile sink node in sub-region *a* flies with a height of *h* and with a uniform speed of *v*, the maximum data amount can be transmitted for the cluster head is

$$L_1 = R \bullet (\frac{2\sqrt{D^2 - h^2}}{v} - T_a), \tag{9}$$

where T_a denotes the sum of the processing and propagation delay, and *R* is the data transmission rate.

Proof: In sub-region *a*, the duration in which the mobile sink node stays in the communication range of cluster head is *T*, i.e.

$$T = \frac{2\sqrt{D^2 - h^2}}{v}. \tag{10}$$

Consider the delay of data transmission, propagation and processing delay, we obtain Eq.9. Herein **Theorem 1** is proved. ■

- Sub-Region *b* ($N_h<h<M_h$)

Data gathering procedure in sub-region *b* can be divided into two phases. In phase 1, the mobile sink node can only communicate with one cluster head; in phase 2, the mobile sink node might communicate with two cluster heads. Herein, the data amount to be transmitted should contain these two phases. Theorem 2 shows the maximum data amount which can be gathered in this sub-region.

Theorem 2: For several cluster heads in line with equal distance, when a mobile sink node flies in the region *b* without stopping, the maximum data amount which the mobile sink node might gather from the first cluster head and last cluster head is

$$L_2 = \frac{R}{2} \bullet (\frac{2\sqrt{D^2 - h^2} + d}{v} - T_a) \tag{11}$$

For other cluster heads, the maximum data amount which the mobile sink node might gather is:

$$L_2 = R \bullet (\frac{d}{v} - T_a) \tag{12}$$

Proof: **Fig.3** depicts the crossing point of communication ranges for three ajacent cluster heads in sub-region *b*. When the mobile sink node flies on *PQ* or *ST* segment, it can communicate with two cluster heads. When the mobile sink node flies on *OP* or *QS* segment, it can only communicate with one cluster head. According to the plane geometry principle, we have

$$\text{QS} = 2d - 2\sqrt{D^2 - h^2} \tag{13}$$

Here *d* is the distance of two cluster heads, e,g. *GH*=d; *D* is the communication range of cluster head, e.g. *GO=PH=GQ=HT=D*, and *h* is flying height, i.e. the vertical distance between the segment *OT* and *GH*.

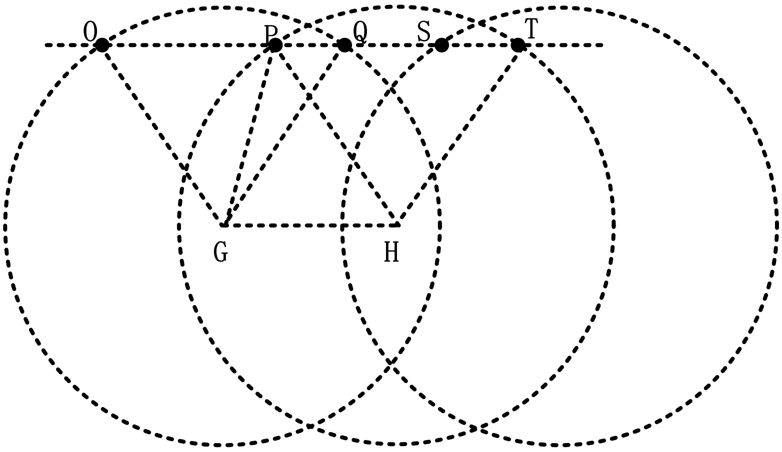

Fig. 3. The Plane Diagram for Sub-region *b*

Firstly, we prove Eq. (11). In this sub-region when the mobile sink node communicates with a single node, i.e. the mobile sink node locates in the *OP* section, the data amount might be transmitted as

$$L_2' = R \bullet (\frac{d}{v} - T_a'), \tag{14}$$

where T_a' contains the processing delay and propagation delay, L_2' denotes the data amount which might be transmitted. Then we compute the data amount in this region when the mobile sink node communicates with either of two sensor nodes, i.e. the mobile sink node locates in the *PQ* section. In this scenario, from the considration of fairness, we let each cluster head have the same opportinuity to transmit data. Then the total data amount from these two cluster heads which can be collected is

$$L_2'' = \frac{R}{2} \bullet \left(\frac{2\sqrt{D^2 - h^2} - d}{v} - T_a'' \right) \tag{15}$$

Here T_a " contains the processing delay and propagation delay too, and L_2" denotes the data amount. According to $L_2 = L_2' + L_2''$, the data amount which the mobile sink node can collect in segment *OQ* is L_2. Herein we have

$$L_2 = \frac{R}{2} \bullet \left(\frac{2\sqrt{D^2 - h^2} + d}{v} - 2T_a' - T_a'' \right) \tag{16}$$

Let $T_a = 2T_a' + T_a''$, we obtain Eq.(11).

Now we prove Eq.(12). For the non-end cluster heads, the mobile sink node will pass through three segments: *PQ*, *QS* and *ST*. On *PQ* and *ST* segments, the mobile sink node can communicate with either of two cluster heads. But within *QS* segment, only one cluster head can only communicate with it. Similarly, the data amount can be transmitted in *QS* section is

$$L_2' = R \bullet \left(\frac{2(d - \sqrt{D^2 - h^2})}{v} - T_a' \right) \tag{17}$$

The data amount can be transmitted in *PQ* or *ST* section is

$$L_2'' = \frac{R}{2} \bullet \left(\frac{2\sqrt{D^2 - h^2} - d}{v} - T_a'' \right) \tag{18}$$

According to $L_2 = L_2' + 2L_2''$, we have Eq.(12) and the theorem is proved. ■

- Sub-region ***c*** **(0<*h*<*N_h*)**

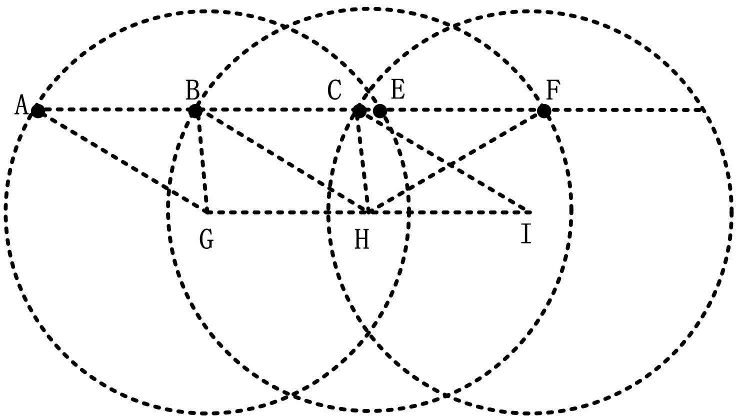

Fig. 4. The Plane Diagram for Sub-region *c*

Data communication in sub-region *c* contains three phases: in phase 1, the mobile sink nodes only communicate with one cluster head; in phase 2, the mobile sink node can communicate with two cluster heads; in phase 3 the mobile sink node can communicate with three cluster heads. Theorem 3 shows the data amount that can be sent by each cluster head nodes within communication range.

Theorem 3: When a mobile sink node in sub-region c, the data amount of the end cluster heads (the first and the last cluster head nodes) can transfer is L_3, i.e.

$$L_3 = \frac{R}{6} \bullet \left(\frac{4\sqrt{D^2 - h^2} + 5d}{v} - T_a\right) \tag{19}$$

For other cluster heads, the data amount can be transmitted as follows:

$$L_3 = \frac{R}{3} \bullet \left(\frac{2\sqrt{D^2 - h^2} + d}{v} - T_a\right) \tag{20}$$

Proof: **Fig. 4** depicts the sub-region C in detail. In this figure, *AB* denoted the segment where the mobile sink node may communicate with on cluster head; In segments *BC* and *EF*, the mobile sink node may communicate with either of two cluster head; In segment *CE*, the mobile sink node may communicate with one of three cluster heads. According to above assumpation, there is AB=BC=EF=d. Herein we obtain

$$CE = 2\sqrt{D^2 - h^2} - 2d \tag{21}$$

When the mobile sink might communicate with more than one cluster head, following the fair rule, all cluster head may transmit the same data. Therefore we can obtain data amount which might be transmitted in the sub-region c.

Firstly we prove Eq.(19). In *AB* segment, the mobile sink node can communicate with one cluster head，the data amount which might be transmitted is same as that in Eq.(14), i.e.

$$L_3{}' = R\left(\frac{d}{v} - T_a{}'\right) \tag{22}$$

In *BC* segment, the mobile sink node can communicate with either of two cluster heads. Now the data amount which might be transmitted is

$$L_3{}'' = \frac{R}{2}\left(\frac{d}{v} - T_a{}''\right) \tag{23}$$

Similarly, in CE segment there are three cluster heads which might communicate with the mobile sink node, each cluster head may transmit data as following

$$L_3{}''' = \frac{R}{3}\left(\frac{2\sqrt{D^2 - h^2} - 2d}{v} - T_a{}'''\right) \tag{24}$$

According to L_3=$L_3{}'$+ $L_3{}''$+ $L_3{}'''$, we obtain Eq.(19).

Now we proof Eq.(20). In this case, there are two cluster heads which might communicate with the mobile sensor nodes. Now the data amount which might be transmitted is same as that in Eq.(15). According to $L_3=2L_3'+L_3''$, we obtain Eq.(20). Herein theorem is proved. ■

3. Data Gathering Approach

After analyzing the flying features of mobile sink node, in this section we design a data gathering approach for the wireless sensor network so as that the mobile sink node can gather data efficiently. Assume the mobile sink node flies above the sensor network with a constant speed. The terrestrial wireless sensor netwrok is organized into clusters, and all cluster members communicated only with their own cluster heads. Cluster heads are in charge of collecting data from the cluster members and transfering to the mobile sink node. On the top of the last cluster head the mobile sink node will soujourn for a short time till all of data are acquired. When the mobile sink node flies over the sensor network, it advertises own identification periodically. After the cluster head on the ground receives this advertisement, it acknowledges and starts to transmit data to the mobile sink node. If the cluster head can not complete all data transmission during the communication time, other data will be forwarded by the terrestrial routing algorithm to the last cluster head. The last cluster head is in charge of transferring not only the data from its own cluster, but also the data from other cluster heads to the mobile sink node.

This data gathering approach transmits data as much as possible to the mobile sink node, and therein few data will be sent through the terrestrial network to the last cluster head node, which could save the energy of each sensor node, hence prolong the network lifetime. In the following, we give a detailed description of the data gathering procedure which including data gathering from the cluser heads and data transmission to the cluster heads from member sensor nodes. Firstly, we describe the session between cluster head and mobile sink node for data transmission.

3.1 Advertisement from Mobile Sink Node

To gather data from cluster head, a session should be set up before data transmission. Firstly, the mobile sink node periodically advertises its position to the cluster heads. Due to the constraints of communication range, flying speed and hight of the mobile sink node, the advertisement period should be chosen carefully. It can not be set too short otherwise most network bandwidth will be used for such adversitment message. Also this period can not be set too long othersice the node can not receive enough information from the mobile sink node to predict the direction of movement and the amount of data the sink node can be transmitted.

We assume the mobile sink node knows its flying vleocity and height since the mobile sink node is carried by a contronable quatorator. Advertisement message from the mobile sink node contains flying velocity(velocicy vector) and height of the mobile sink node as in **Fig. 5.** If a cluster head receives this advertisment message from the mobile sink node and has data waiting to sent, it immediately responses with a message as in **Fig. 6** so that the mobile sink node may prepare to receive data.

Velocity vector （v_x,v_y）	height

Fig. 5. Advertisement Message

Node ID	Response message

Fig. 6. Response Message

After the cluster head sends response messages to the mobile sink node, it broadcasts to the adjacent cluster heads so that the routing table could be updated which will be used to forward the remaining data in each cluster head. **Fig.7** gives the broadcast message format. The source node ID field is used to tell all receivers that from which cluster head the broadcast message is sent out. Also from it the location of mobile sink node is possible to deduce if the sensor network is static deployment and the positons of all cluster heads are predefined. The field of mobile sink velocity vector and height information will be used for other cluster heads to decide whether the mobile sink node will pass their communication range.

For an exmple, assume the current cluster head communicating with the mobile sink node has a position of (x, y), and the adjacent cluster head has a position of (x', y'). According to the previous assumption that all cluster heads are deployed in line, there is $y = y'$. Herein, if $(x - x') * v_x > 0$, the adjacent cluster head can decide that the mobile sink node will pass by its own communication range. When the mobile sink node passes by this adjacent cluster head, this adjacent cluster head floods the message after modifying the source node ID, otherwise it descards the received packet.

The source node ID	Mobile sink node velocity vector (v_x,v_y) and height information

Fig. 7. Broadcast message

3.2 Data Acquisition for Linear Network

After the session is setup, data will be transmitted. In this section we will analyze the data acquisition scheme for a linear network. Firstly we need to determine the duration in which the ground cluster head may send data directly when the mobile sink node enters its communication range. If during this duration, data in the cluster head may be transmitted completely, there is no need to forward data by terrestrial routing algorithm. Otherwise, the remaining data will be forwarded to the last cluster head node by the terrestrial routing algorithm. When the mobile sink node flies on the top of the last cluster head, it will soujern for a while till all data in the network are collected.

When the mobile sink node flies over the sensor network, the closest cluster head in the network computes data amount which might be sent directly to the mobile sink node according to the adverstisment information. If the data amount is too short (less than a threshold), all data in this cluster head will be forwarded by the terrestial routing algorithm to the last cluster head, where they are collected by the mobile sink node. Otherwise, the data in the cluster head will be tranmistted to the mobile sink node according to the following procedure:

Assume there are L bits in the cluster head waiting to be sent :

(1) When the mobile sink node ranges in sub-region a, if $L \le L_1$ (Eq.(9) in Theorem 1), the cluster head can transmit all data within time of T without forwarding by terrestrial routing algorithm. If $L > L_1$, the cluster head sends L_1 bits to the mobile sink node directly, the other part of $(L- L_1)$ bits will be forwarded to the final cluster head via the routing algorithm.

(2) When the mobile sink node ranges in sub-region b, if $L \le L_2$ (Eq.(11-12) in Theorem 2), the cluster head can transmit all data to the mobile sink node directly. If $L > L_2$, the cluster head sends L_2 bits to the mobile sink node, the remaining data of $(L- L_2)$ bits will be forwarded to the final cluster head via the routing algorithm.

(3) When the mobile sink node in sub-region *c*, if $L \leq L_3$ (Eq.(19-20) in Theorem 3), the cluster head node can transmit all data within time of T without forwarding. If $L > L_3$, the cluster head sends L_3 bits to the mobile sink node directly, the other part of $(L - L_3)$ bits will be forwarded to the final cluster head following the routing algorithm.

3.3 Terrestrial Routing Algorithms

We have analyzed the data gathering approach by the mobile sink node from cluster heads. If the mobile sink node can not collect all data in the cluster head during the short time, the remaining data will be forwarded to the last cluster head by the terrestrial routing algorithm. The last cluster head is in charge of transmitting the data to the mobile sink node including not only its own cluster, but also from other cluster heads. Since all cluster heads are in line, a cluster head routing algorithm such as LEACH [19] might be used here. In addition to the routing algorithm for cluster heads, there is a routing algorithm for the cluster members to transmit data to the cluster head as they are not one-hop communication.

Without loss of gererality, these member sensor nodes are distributed randomly in the cluster and due to the energy constraints or processing capability some of them can not communicate with cluster head directly. That is to say, they has relay other nodes to transmit information to the cluster head. Herein, we give a light routing algorithm for them.

- Routing Table

In each cluster, the non-cluster node keeps a routing table to record the path to the cluster head. The routing table entry is depicted in **Fig.8**, which includes the field of distance to the cluster head and the next hop field. When one message arrives this sensor node searchs the tiny route table and finds the best route to the cluster head, then transmits this message following the chosen routing.

The distance to the cluster head node	Next Hop

Fig. 8. Routing Table Entry

The distance to the cluster head means the number of hops between the sensor node and the cluster head. The initial value is ∞, which means unreachable. The next hop refers to the next node ID on the path from the sensor node to the cluster head. The initial value is NULL.

- Routing Updating

1) Initially, the cluster head broadcasts message to all adjacent cluster member sensor nodes including its identification. All sensor nodes receive such message will keep this identification and broadcast to other sensor nodes. Using this flooding pattern, all sensor nodes in the cluster will receive such identification message. If one node knows more than one cluster head, it chooses the one with the shortest distance or the strongest signal to be its own cluster head.

2) Within a cluster, each node broadcasts routing notification message which contains the node ID and the routing broadcast initialization message. If the cluster head can receive the packet, it sends the acknowledgment message. Therefore, these nodes become the first hop nodes and set the routing table entry of distance as 1, and the next hop is empty.

3) After broadcasting routing initialization information, if non-first-hop nodes do not receive a acknowledgment message in a short while, they do not send routing messages any longer and wait for other messages.

4) The one-hop nodes send routing message including distance, ID flag and the cluster head information. **Fig.9** gives the routing message.

5) After adjacent nodes receiving routing message, they choose the path which has the minimum distance to update their routing tables. If the distance is the same, choose the node with strongest signal strength to act as a next hop routing address. The nodes broadcast routing message to other nodes until all nodes in the cluster build their own routing tables.

Distance	Node ID	Cluster head information

Fig. 9. Routing Message

3.4 Cluster Heads in Grid Network

In above section, we have analyzed the data gathering for a linear network, here we extend the the network to a more typical scenario where all cluster heads are deployed on a grid network, and member sensor nodes are deployed randomly. In such situation, we divide the entire area into sub-areas with equal size. All senor nodes in each sub-area form a cluster. The cluster head is assumed to locate in the grid. **Fig.10** gives an example of 12 sub-areas. Here the sensor network consists several linear networks. The cluster heads in different rows can not communicate with each other. In our example, 12 cluster heads are divided into three rows and four columns. In each row there are four cluster heads.

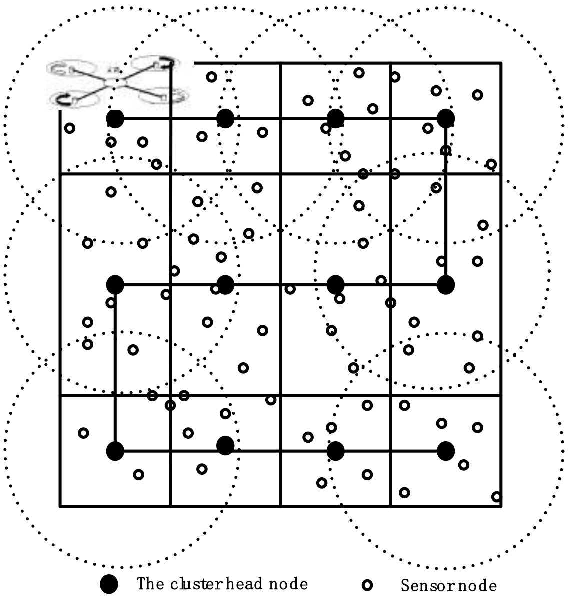

Fig. 10. Grid Sensor Network

On this sensor network, the mobile sink node moves with a constant speed and gather data from cluster heads shown in Fig.10. When the mobile sink node flies in the above of the last cluster head, the mobile sink node sojourns for some while till all data in the network are gathered. This scheme makes it possible for the mobile sink node to gather data from the cluster heads as much as possible, which herein reducing the data transmission in the terrestrial network and might save the energy.

4. Performance Analysis

Here we use simulations to evaluate the proposed data gathering approach. Simulations are performed on the platform of Omnet++[20] with Intel (R) Core (TM) 2 Duo CPU P7350@2.00GHz using Windows XP.

On the simlation, a terrestrial wireless sensor network is defined which includes two kinds of sensor nodes: cluster heads and member sensor nodes. There are 15 cluster heads deployed on the crossing points of a grid with 3 rows and 5 columns, and 15 member sensor nodes deployed randomly in this grid sensor network. The communication range of each cluster head is assumed to be 100 meters. The communication range of member sensor node is defined to 50 m. In each sensor node there are accumulated 640 bits data waiting for transmittion. A packet has a fixed size of 128 bits or 16 bytes when it is transmitted through wireless channel. The cluster heads which are not in the same line can not communicate with each other due to the constraint of communication range. We assume that CSMA/CA is used in MAC layer. According to the previous analysis, we mainly discuss the performances such as the sojourning time, the packet loss rate, average transmission time in term of different network features, e.g. flying velocity, height of mobile sink node, and network size.

4.1 Sojourning Time and Average Transmission Time

(A) Sojourning Time

Fig. 11 gives the sojourning time of mobile sink node under different flying heights and speed. On the left of Fig.11 it can be noted that the sojourning time reduces gradually to a certain extent with the increasing of the flying speed when the flying height is constant. In such situations the mobile sink node mainly locates in sub-area *a*. When increasing the flying speed of mobile sink node, data gathered from the cluster heads directly are relatively smaller, and most of them are forwarded by the terrestrial routing to the last cluster head. Even the flying time of mobile sink node decreases, the duration while it stays on the top of the last cluster head increases. Therein, the total sojourning time of mobile sink node almost does not change. When the flying speed is fixed, the mobile sink node can collect more data from the cluster heads directly with the height decreasing, thereby reducing its sojourning time.

The right of **Fig. 11** shows the sojourning time variations when the mobile sink node flies with even lower height. It can be noted that when the sink node flying speed is less than 40 m/s, the sojourning time decreases inversely with the flying speed. When the movement speed is greater than 40 m/s, the sojourning time increases with the flying speed. Since in this scenario, the mobile sink node mainly flies in sub-area *b* and *c*, most of data in the cluster head can be transmitted directly to the mobile sink node. But when increasing of the flying speed, most of the cluster heads have less time to communicate with the mobile sink node, which results in more data transmitted by the terrestrial sensor network. With the decreasing of flying height, the mobile sink node has more time to communicate with each cluster head. Therein it is able to collect more data from each cluster head, and only a small amount of data are forwarded to the last cluster head, which reduces the total sojourning time.

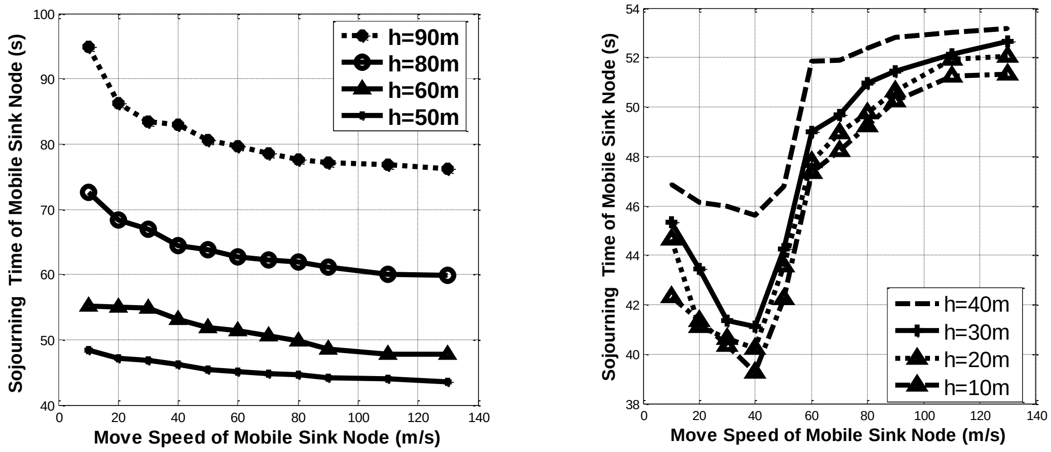

Fig. 11. Sojourning Time, Gathering Time and Mobile Rate

(B) Average Transmittion Time

Fig.12 depicts the average transmission time per packet when we change the flying speed of the mobile sink node and the network size. It is noted that changing the flying speed of the mobile sink does not reduce the average data transmission time significantly. The main problem is that when increasing the flying speed of sink node, it reduces the duration in which the mobile sink node travels through the sensor network. Therein it reduces the communication time between cluster heads and the mobile sink node directly. Thus more time is required for the data transmission from each non-last cluster head to the last cluster head, which results in the average packet delivery delay increasing. On the other hand, when the network size increases, the average packet collection time decreases. This is due to that more sensor nodes can have more opportunities to choose the better clusters, which reduce the data forwarding delay, and improving the average packet acquisition time.

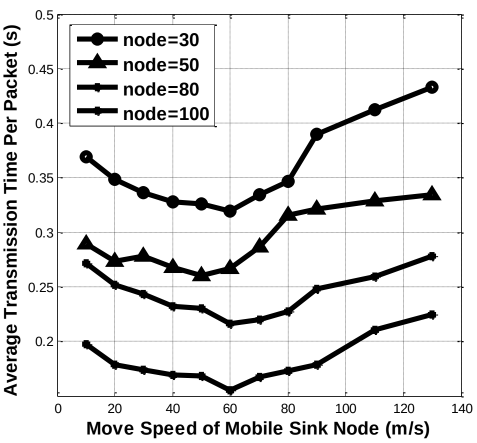

Fig. 12. Average transmission time

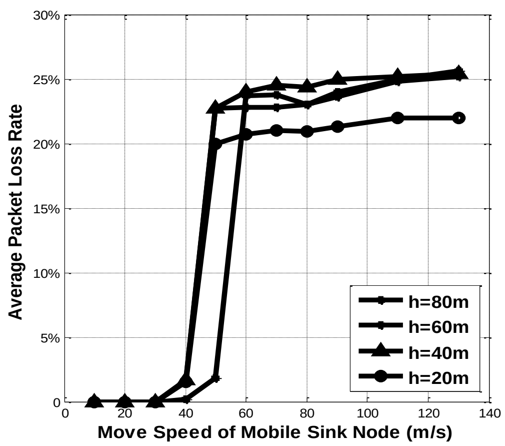

Fig.13. Average Packet Loss Rate

4.2 Average Packet Loss Rate

Here we analyze the packet loss rate when the flying speed of mobile sink node, data amount in each sensor node, and network size are changed.

(A) Flying Speed and Height

Fig.13 depicts the average packet loss rate when the flying speed and height of the mobile sink node are changed. It is noted that when the flying speed is greater than 40 m/s, the average packet loss rate suddenly increases. This is due to that the mobile sink node flies too fast, only few data in the cluster heads might be transmitted to the sink node directly. And the other data have to be transferred to the end of the cluster head node by the terrestial routing algorithm. If the forwarded packets do not reach the last cluster head, while packets in the last cluster head have completed transmission to the mobile sink node, the mobile sink node belives that all data in this network have been gathered. Therefore it will fly away even some packets are still on the routing to the last cluster head, i.e. middle cluster heads. As a result, the packet loss rate increases substantially. From this point, the flying height of the mobile sink node has little effect on the packet loss rate.

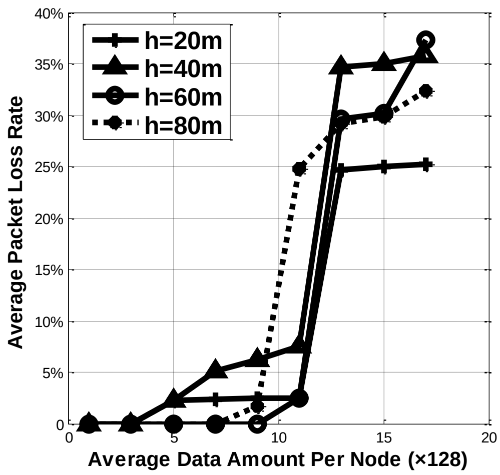

Fig. 13. Average Packet Loss Rate

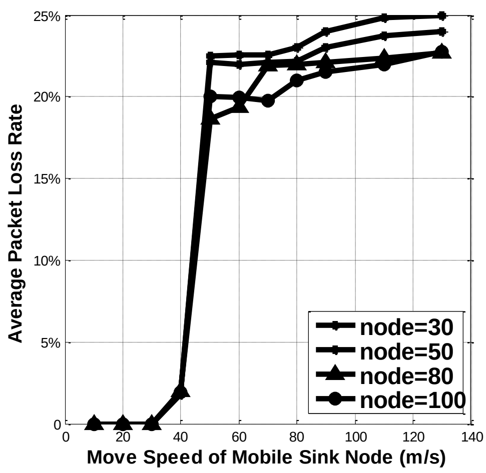

Fig.15. Average Packet Loss Rate

(B) **Average Data Amount Per Node**

Fig.14 shows the packet loss rate when the data amount in each node are different in terms of flying heights. It can be noted that when the data amount in each node is greater than (9 × 128) bits, the average packet loss rate increases significantly. When the flying speed and height of the mobile sink node do not vary, we can compute the data amount of each cluster head which can be delivered directly to the mobile sink node following Theorem (1-3). When each node sends few data, most or all of the packets are sent to the sink node directly. After the data amount is greater than the threshold, it results in most of the data have to be transferred by the terrestrial routing algorithm. Even the mobile sink node completes collecting the data in the last cluster head, in fact, there are some data in the relay cluster headers, which increases the packet loss rate significantly. On the other hand, from the figure it can be found that the flying height of sink node has little effect on the packet loss rate.

(C) Move speed and the network size

Fig.15 gives the packet loss rate in terms of mobile sink flying speed. It can be seen that there is a sharp increasing of the average packet loss rate when the speed of mobile sink node is greater than 40m/s. The main reason is that the mobile sink node moves too fast, which result in that the transmisstion time for each cluste head and the mobile sink node decreases , and only part of the packet in each cluster head can be transmitted to the mobile sink node. The data which has not been transmitted will be forwarded to the last cluster head following the terrestrial routing algorithm. If the forwarded packet does not reach the last node and the mobile sink node has finished the data gathering in the last node, the mobile sink node will fly away. It will result in the packet loss rate increasing. On the other hand, the network size has a little effect on the packet loss rate.

5. Conclusion

In this paper, a new problem is defined for the terrestrial wireless sensor network with a controllable mobile sink node carried in quadrotor. The movement features such as flying trajectory, height, velocity of mobile sink node are explicitly analyzed together with the data amount accumulated in each cluster head waiting for transmission. A data gathering method is proposed for such applications where the mobile sink node is carried in the aircraft. Simulation results show that the main features under this approach such as sojourning time, average transmission time per packet, packet loss rate, etc. in terms of flying speed, height, and network size. In future work, we will extend the data gathering strategy further from the point of energy efficiency, to control the movement trajectory, speed and altitude of mobile sink node, so as to prolong the network lifetime.

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