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A Distributed Gateway Selection Algorithm for UAV Networks

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ABSTRACT In recent years, unmanned aerial vehicle (UAV) has been widely adopted in military and civilian applications. For small UAVs, cooperation based on communication networks can effectively expand their working area. Although the UAV networks are quite similar to the traditional mobile ad hoc networks, the special characteristics of the UAV application scenario have not been considered in the literature. In this paper, we propose a distributed gateway selection algorithm with dynamic network partition by taking into account the application characteristics of UAV networks. In the proposed algorithm, the influence of the asymmetry information phenomenon on UAVs' topology control is weakened by dividing the network into several subareas. During the operation of the network, the partition of the network can be adaptively adjusted to keep the whole network topology stable even though UAVs are moving rapidly. Meanwhile, the number of gateways can be completely controlled according to the system requirements. In particular, we define the stability of UAV networks, build a network partition model, and design a distributed gateway selection algorithm. Simulation results show using our proposed scheme that the faster the nodes move in the network, the more stable topology can be found, which is quite suitable for UAV applications.

INDEX TERMS Wireless sensor network, clustering, energy consumption analysis, segment equalization, energy efficiency.

I. INTRODUCTION

Recently, Unmanned Aerial Vehicles (UAVs) were widely used in reconnaissance, fire fighting and disaster rescue, etc. There are many kinds of UAVs, ranging from the large ones as the global hawk, which is comprehensive and loaded with a variety of functional modules, to the small ones that can take off just by manual throwing. For large UAVs, it can complete various tasks at the same time, due to its strong load capacity. While small UAVs can only achieve some simple missions because of their limited load. Connecting those small UAVs via a communication network to build multiple UAV networks, can greatly expand their ability for complex tasks [1]. As the multiple UAV cooperative scheduling strategies proposed in [1]–[5], communication network is the precondition of cooperation. As the foundation of multiple UAV coordination, further studies of UAV network are definitely expected.

The research of UAV networks has been conducted extensively, involving topology control, communication protocol, antenna design, etc. According to different objects, those studies can be divided into two categories. One series of research tried to control the placement and mobility of UAVs, to improve the performance of the network [6]–[11]. The other kind of research of UAV networks focused on how to design a suitable communication system to match the characteristics of UAVs. Note that our work falls into the second category. Since the Mobile Ad Hoc Network (MANET) is featured with non-centralized architecture, it is quite appropriate for UAV networks. Most studies of the second category tried to improve the traditional MANET to satisfy the requirement of UAVs. In [8], [12], and [13], the researchers proposed some new protocols of MANET to reduce the affection of UAV's flight altitude on UAV network with the addition of a directional antenna. In [14], an adaptive beamforming antenna scheme was presented to minimize the interference in a UAV network. In [15], a MAC layer protocol named C-ICAMA was proposed for ground backbone nodes to access UAVs to solve the highly asymmetric data traffic in ground-UAV networks. In the work presented in [16] and [17], the stability of UAV networks was improved by adding the link state information into the routing protocol.

All those existing works only considered how to use or avoid the affection of UAV's flying characteristics on the network. However, the difference of communication requirements between UAV network and other MANET has not been taken into account. Since a UAV is a kind of special communication terminal, its application scenario is also quite different from other MANETs. Considering this problem, in this paper, we focus on the characteristics of UAV group application scenario and its distinctive communication requirements. According to that, we propose a distributed gateway selection algorithm to choose a certain number of superior UAVs as gateways for the others.

According to the existing applications of UAV, there are four kinds of main communication requirements as follows:

- Sending back the sensor data.
- Receiving the control commands.
- Cooperative trajectory planning.
- Dynamic task assignments.

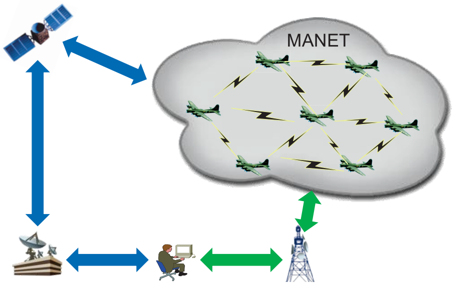


FIGURE 1. **The communication structure of UAV network.**

The first two communications happen between the MANET and the external network. While the last two communications are essentially the same with those existing ones in a usual MANET. Thus, the network structure of a UAV group can be illustrated as shown in Fig. 1. Inside the network, each UAV communicates with each other through the MANET. Meanwhile, every UAV in the network can also connect the command center via remote communications. Due to the long distance between a UAV and the command center, these remote connections are usually supported by high-power wireless communication, such as satellite. In such a case, the number of these remote connections should be controlled meticulously to avoid serious interference and satisfy the restriction of limited resources. Therefore, some superior nodes in the UAV network should act as gateways, so that other nodes in the network can connect the command center through them rather than to establish a remote connection. In this paper, we focus on how to dynamically select UAV gateway to ensure the network stability, as well as the reliable communications between a UAV network and a command center.

The selection of gateway in a UAV network is quite similar to the selection of a cluster head in an Ad Hoc network. However, the existing works regarding Ad Hoc clustering have not considered the movement of nodes when selecting the cluster head. For instance, Max-Min heuristic approach [18] assumed that the topology of the network is stable while exchanging their information. However, when nodes are in a highly dynamic state as in UAV networks, this assumption cannot be satisfied. In some other algorithms, the cluster selection is based on each node's local information, which is not global optimized. Like the Lowest ID algorithm [19] (one of the most famous clustering algorithm) and the CONID algorithm [20] (an extension to the Lowest ID), nodes decide whether to become a cluster head or not through comparing the asymmetric local information it obtained. Therefore, the selection may not be the optimal, and the system may not be stable when nodes move rapidly. Moreover, these clustering algorithms cannot accurately control the number of the cluster heads, which, however, is also an important requirement in UAV networks.

To meet the requirement of UAV networks, our objective is to develop a distributed algorithm that can dynamically select a certain number of superior nodes acting as gateways. Meanwhile, the algorithm should be adaptive to match the rapid change of the UAV network's topology. In summary, the contribution of this paper can be summarized as follows. To the best of our knowledge, this is an early work in UAV networks, therefore, we have some assumptions in our modeling, and we will address them in the near future.

1) We analyze the asymmetry of the information obtained by different nodes in a non-centralized UAV network, and propose a quantifiable network partition method to ameliorate the influence of asymmetric phenomenon on the dynamic topology control. The network partition method is quite practical for the UAV networks, where their missions and targets are usually distributed in some dispersive areas.
2) Based on the network partition model, we give a formal definition of stability with focus on the affection of the network boundary on UAV's stability, and construct an optimization mathematical model to equalize the stability of different subareas. This equalization is rather important in UAV networks, since all the missions and targets should be equally treated and completed.
3) With the optimal gateway selection model, we further propose an adaptive gateway selection algorithm based on a dynamic network partition. The algorithm can

adaptively adjust the partition of the network to match the change of the network's topology, which is proved to be feasible and better than existing solutions by simulation.

The rest of this paper is organized as follows. The system model is described in Section 2. Then, we present the proposed UAV network partition model in Section 3, discuss the network stability in Section 4 and design the distributed gateway selection algorithm in Section 5, respectively. The simulation results are shown in Section 6 and the conclusion is drawn in Section 7.

II. SYSTEM MODEL

As described in Section 1, a UAV network is a special MANET network with high-mobility nodes and rapidly changing topology. In a UAV network, there is no center node which can obtain the topology information of the entire network at any time. In such a case, if we want to choose some nodes to be gateways, the selection algorithm should be distributed and adaptive to the dynamic topology in time. In order to weaken the influence of the dynamic topology on communication, those selected gateways should be relatively stable. Meanwhile, the number of these gateways should be completely controlled, because of the limited remote communication recourses in a UAV network.

Let S_i denote the stability of node i, U denote the set of nodes in a network, and U_g denote the set of gateways. If one wants to select P gateways in a network with n nodes, we have

$$\{S_k > S_j | k \subset U_g, j \subset U - U_g\}, \quad \text{where } \left\|U_g\right\| = P. \tag{1}$$

In order to obtain U_g in a distributed way, every node in the network should compute the stability of itself, and then compare it with its neighbors. But this comparison is asymmetrical. As shown in Fig. 2, because of the lack of a center node in the UAV network, every node can only obtain the local topology information from its one hop away neighbor, i.e., they have no access to the entire topology structure in time. In Fig. 2, the two dotted circles represent the communication range of UAV 3 and 6, respectively. Because of the limited communication distance, the two UAVs can only obtain the local information of different location in the network, which leads to the fact that they can only compute their stability with that the local information. Since the local information is asymmetric, the stabilities they compute are also asymmetric. Apparently, the selection based on those asymmetric metrics is not an optimized result. On the other hand, if we let the information spread through the whole network in a diffusion fashion to ensure every node could obtain the information of the network, it cannot match the fast changes of topology in time. We can see that the asymmetric information of each node and the global optima quickly selection is a pair of contradiction. In the following paper, we target on finding appropriate approaches to solve this contradiction.

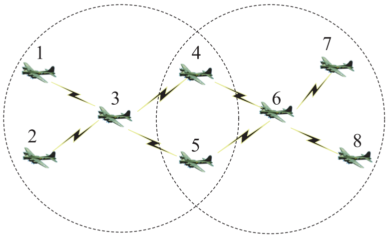


FIGURE 2. The asymmetric of local information.

III. UAV NETWORK PARTITION

In UAV networks, the movement of one UAV is usually motivated by its missions. Most of the UAV's tasks are associated with positions on the ground. For instance, for the mission of military surveillance, the targets are usually uniformly distributed; while for the mission of a fire attack, the UAV would fly around some special targets. For a practical consideration, we can divide the UAV network into several sub-areas according to their missions. The size of each sub-area can be adjusted to match the distribution of the targets, which are involved in this region. By dividing the network, the assignment of tasks among a UAV group will be simplified and more reasonable. Meanwhile, the aforementioned asymmetric problem can be ameliorated in a partition network. With such partition mechanism, the topology information can be diffused in a small range by adding the UAV node's one hop neighbor list in the heartbeat packet periodically sent by each UAV node. In such a case, the information obtained by the UAV nodes, which are in the same sub-area, can be limited in the same range. Then, the UAVs within the same region can fairly select the most stable node to be gateway in a distributed way.

In order to meet the application characteristics of UAV networks, and also improve the consistency of the node information, we developed a split method to divide the network, as shown in Fig. 3. If $P \leq 3$, the network can be just split into P fan areas by omitting the sub-area 1 in Fig. 3. With this partition method, all the sub-areas can completely cover the entire network without any overlap. Note that every sub-area has a tuning parameter to adjust its size. Through dividing the whole mission area by this method, the partition of the network can also match the assignment of the UAV group's mission. In this paper, we focus on the scenario where the UAV's mission targets are uniformly distributed in the area, as shown by the partition in Fig. 3. Note that the model and algorithm proposed in this paper can also be applied in the scenario with some special targets, e.g., fire attack. More importantly, the number of gateways in this partition network can be completely controlled. In the following, we will discuss how to improve the stability of the network by optimally configuring the parameters of each sub-area. The partition method shown in Fig. 3 can be represented by a vector ω

$$\omega = (r, \theta_2, \ldots, \theta_P), \tag{2}$$

where r is the radius of the central circular sub-area, $\theta_2, \ldots, \theta_P$ are the angles of other $P - 1$ fan sub-areas.

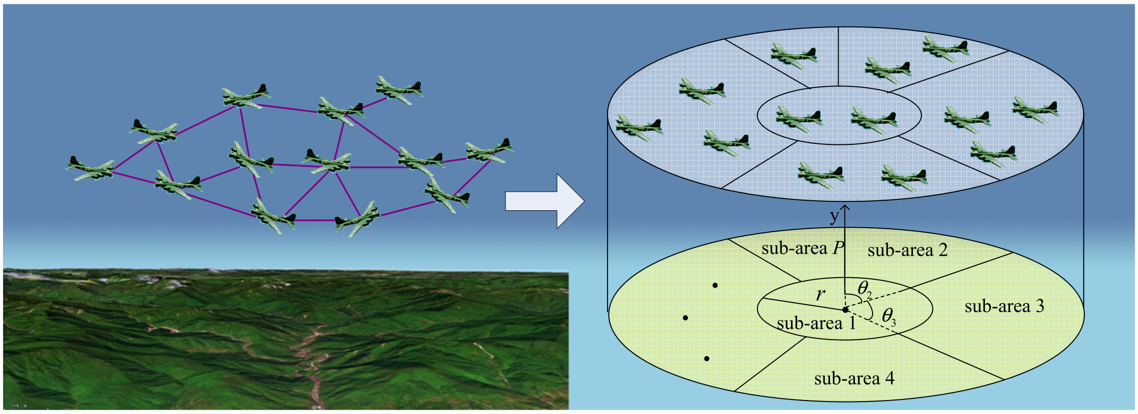


FIGURE 3. The network partition method.

This method ensures that all the sub-areas cover the entire area, but each of them does not overlap with any other sub-areas. The size of each sub-area can be determined by the corresponding parameter. Since the positions of targets and missions are relatively fixed in one period, the position of each sub-area is also relatively fixed. While the size of each sub-area is needed to be adjusted because of the dynamic task assignment and resource allocation. Under such circumstances, the second sub-area's left boundary can be fixed to the positive direction to ensure there is an one-to-one relationship between ω and the partition. Thus, the optimal gateway selection problem is converted to the problem of optimizing the parameters of the partition.

Although the targets and missions are uniformly distributed in the specific area, the mobility of UAVs can lead to their non-uniform distribution in the network. On one hand, if the UAVs aggregate in some sub-areas, the load of the gateways in those areas will be extremely heavy. On the other hand, it is possible that the topology in some sub-areas are very stable, while some sub-areas may frequently change the gateway due to their weak stability, which may decrease the overall stability of the UAV network. Therefore, it is rather important to equalize each gateways' stability by dynamically adjusting the size of each sub-area. Based on this idea, we construct an iterative optimal objective function as follows.

$$\min f = \sum_{k=1}^{P} \left(S_k\left(l-1\right) A_k\left(l\right) - \frac{1}{P} \sum_{m=1}^{P} S_m\left(l-1\right) A_m\left(l\right) \right)^2, \tag{3}$$

$$A_k\left(l\right) = \begin{cases} \frac{r(l)^2}{R^2} & k = 1 \\ \frac{\theta_k(l)\left(R^2 - r(l)^2\right)}{2\pi R^2} & 2 \le k \le P, \end{cases} \tag{4}$$

subject to

$$\sum_{k=2}^{P} \theta_k\left(l\right) = 2\pi, \tag{5}$$

$$0 < r < R. \tag{6}$$

where $S_k\left(l-1\right)$ represents the stability of the gateway that belongs to sub-area k at iteration $l-1$, $r\left(l\right), \theta_2\left(l\right), \ldots, \theta_P\left(l\right)$ are the estimated parameter of the partition at iteration l, and $A_k\left(l\right)$ is the proportion of k sub-area in the entire area at iteration l. R is the radius of the network. The first term in (3) is the product of each sub-area's area ratio and its stability, and the second term is the mean of this product. Thus, (3) can be seen as the variance of this product, minimizing which can equalize the stability and all sub-areas and ensure the stability of the whole network. Moreover, The constraint described in equality (5) and inequality (6) guarantee that those P sub-areas can completely cover the entire network without overlap. The optimization problem shown in function (3) can be solved by convex optimization. The advantage of convex optimization theory is to ensure any local minimum must be a global minimum. Instead of calculating optimal ω, we can first compute $A_k\left(l\right)$ with following constraints

$$\sum_{k=2}^{P} A_k\left(l\right) = 1, \tag{7}$$

$$0 < A_k\left(l\right) < 1. \tag{8}$$

The standard convex optimization form is to find a solution to minimize a convex function in a convex set. If a function is twice continuously differentiable and its Hessian matrix is positive semi-definite, then it is a convex function. In our model, this is equivalent to $\partial^2 f / \partial x^2 \ge 0$. Thus, $\partial^2 f / \partial {A_k}^2$ can be calculated as follows

$$\frac{\partial^2 f}{\partial A_k\left(l\right)^2} = 2S_k^2\left(l-1\right)\frac{P-1}{P}. \tag{9}$$

Since $P \ge 1$, and the stability of the UAV is always positive, so it can be concluded that (3) is convex. In Section 5, we will explicitly discuss the solution to the optimization problem in (3).

IV. UAV'S STABILITY IN A BOUNDARY NETWORK

To solve the aforementioned optimization problem, the stability of each UAV needs to be calculated. In this section, we will discuss the stability of a UAV network. One of the most prominent challenges for a UAV network is the dynamic topology. While they are moving, the connection between each node would break or establish randomly, because of their limited transmission distance. The availability of the link between each node, will directly impact the topology stability of the UAV network. Therefore, how to calculate the availability is rather important, which is also a hot topic in MANET. In [21], the author defined the term link availability as the probability that a link would be continuously available from t_0 to $t_0 + t$, given that it is active at t_0. Moreover, some works also utilized this probability to predict the movement of nodes, where they represented the node's mobility as a stochastic process [21]–[23]. The velocity, moving direction and state change time are random variables, and the position of the node is a function of those variables. Apparently, the shift probability of a node's position is closely related to the node's mobility model. In the literature, random walk mobility model is commonly adopted in MANET research work. In this model, the movement of a node is composed of a series of random length interval. Nodes change their speed and direction in each interval, and this mobility model has zero pause time. The speed and direction is uniformly distributed over (v_{min}, v_{max}) and $(0, 2\pi)$. The length of the interval is an exponentially distributed random variable with mean $1/\lambda$.

In [22], there was a strong assumption in the model, i.e., the number of the changing times of the node's mobile state during the period of prediction should be very large, which is not reasonable if that period is short. The model presented in [23] was simple, however, in this model the random walk mobility model of the node was simplified as four direction random movement, which is far from reality. Through discretizing the distance between two nodes, the authors in [21] transited the random variation of distance to a Markov chain with the discrete distances between the nodes as the state space, when a node moves with a random walk mobility model. The authors first obtained the transition matrix by calculating the probability density of the distance if any one of these two nodes change its state once. Then, the transition probability of the distance in a smaller range after a period of t can be calculated with the initial distance d_0. Finally, they derived the function to calculate $L(d_0, t)$, which represents the probability that the link will be continuously available from t_0 to $t_0 + t$, given the initial distance between two nodes is d_0. Although the work in [21] was more reasonable and accurate compared with [22] and [23], the author did not consider the network boundaries, i.e., the network region is considered to be infinite.

In our model, the network is partitioned into several sub-areas, i.e., there are multiple boundaries in the network. If a UAV moves across the boundary from one sub-area into another sub-area, it will select the gateway in the new sub-area to acquire relay service. Although it is possible that the UAV is stll in the range of the old gateway's communication distance, but the connection between the UAV and the old gateway has already been broken. Therefore, we have to consider the influence of link availability with those boundaries, when calculating the stability of UAV. To further emphasize the importance of considering boundaries, we simulate the movements of UAV nodes in a bounded disk with the random walk model. In this simulation, the center of the disk is set as $(0, 0)$, and the link between these two nodes will be broken in two cases, i.e., the distance of these nodes is longer than the transmission distance or one of them leaves the disk. The simulation parameters are shown in Table 1 and the statistics of the link's availability are shown in Fig. 4. Note that each simulated curve in Fig. 4 is a result of $100,000$ independent experiments. The three curves in Fig. 4 indicate the availabilities of the link between these two UAVs in different initial positions. In these three cases, the initial distances of the two UAVs all are 200m. Although the initial distances are the same, it can be seen that availability of the link drops more quickly, if the nodes are closer to the edge.

TABLE 1. **Simulation parameters.**

parameter	value
Radius of the disk	1000m
Transmission distance	1000m
speed	[20,30]v/s
Mean epoch length	60s

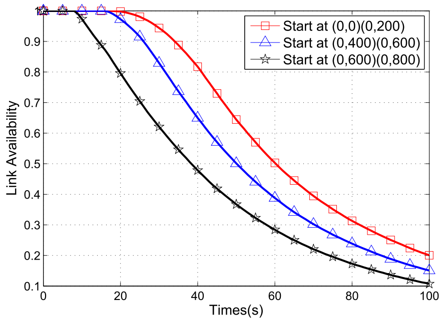


FIGURE 4. **Simulation result of the link's availability in a bounded disk.**

In order to calculate the stability of UAV, we have to quantify the effect of the stability caused by the network's boundaries. Let us consider a circular boundary area, which is the simplest shape, as shown in Fig. 5. R is it's radius. A mobile node starts at point A. Assume that the angle between the moving direction of the node and the positive direction of the x axis is θ. According to the trigonometry, we can obtain

$$a = \sqrt{R^2 - d^2 \sin^2\theta} - d\cos\theta. \tag{10}$$

Let L indicate the event that node a stays in this area after moving a distance c. Let B indicate the impact factors of a UAV's stability caused by the network's boundaries. If θ is uniform distributed in $[0, 2\pi]$, and c is uniform distributed in

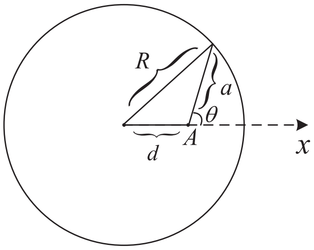


FIGURE 5. **Circular boundary area.**

$[0, 2R]$ then B can be approximately represented as follows:

$$B \approx \Pr(L) = 1 - \iint\limits_{\substack{\sqrt{R^2 - d^2\sin^2\theta} - d\cos\theta < c \\ 0 \le \theta \le 2\pi,\, 0 \le \mathrm{c} \le 2R}} \frac{1}{4\pi d}\mathrm{d}\theta \mathrm{d}c$$

$$= 1 - \frac{1}{2\pi R}\int_{R-d}^{R+d} \arccos\frac{R^2 - d^2 - c^2}{2dc}\mathrm{d}c - \frac{R-d}{2R\pi}. \tag{11}$$

Since the shape of each sub-area of the UAV network is irregular, it is very hard to give out the accurate function of B for every sub-area. In this paper, We use (11) to approximately compute each sub-area's B. Therefore, we can give the formal definition of the stability of UAV in the network as follows.

Definition 1: Let S_i denote the stability of node i and i belongs to sub-area k, I_k denote the set of nodes, that also belong to sub-area k. Let E_i denote the set of nodes that connect to node i, and L_{ij} denote the link availability between node i and j. Suppose the distance between node i and the center of sub-area k is d_i, and the farthest distance from the sub-area's boundary to its center is D_k, then

$$S_i = B_i \sum\nolimits_{j \in I_k} L_{ij}, \quad j \in I_k \bigcap E_i, \tag{12}$$

where

$$B_i = 1 - \frac{1}{2\pi D_k}\int_{D_k - d_i}^{D_k + d_i} \arccos\frac{{D_k}^2 - {d_i}^2 - c^2}{2d_i c}\mathrm{d}c - \frac{D_k - d_i}{2D_k\pi}. \tag{13}$$

According to formula (12), the stability is composed of two factors, one is the distance between the node and the center of the sub-area. Since every node has the knowledge of the partition parameter of the network, it can compute the position of the center point of its sub-area. Nowadays the GPS system is almost the standard equipment for UAV, thus it is reasonable for UAV to be location-aware. The other factor used in formula (12) is the availability of the link $L(d_0, t)$. Since the position of the UAV is aware, so the initial distance of any two UAVs, which can connect with each other in one hop, can be calculated. They can also calculate the $L(d_0, t)$ between them by the method in [21].

In summary, with the stability definition and optimization problem (3), the optimal gateway selection in UAV network can be transformed to a problem of convex optimization by dividing it into several sub-areas. In the next section, we will describe how to select the most stable node to be a gateway for each sub-area, and how to adjust the partition parameters in an adaptive way.

Algorithm 1 Gateway Selection

```
1:  if adjust_split = true then
2:      break;
3:  else
4:      compute $S_i$;
5:      if ($S_i - S_k \ge \varepsilon$) then
6:          is_change = true
7:          switch (state_i)
8:           case: Normal_Node
9:          if (is_change) then
10:             state_i = Potential_GW
11:             wait for random short time to check again
12:         end if
13:          case: Potential_GW
14:         if (is_change) then
15:             state_i = Active_GW
16:             GW_Seq_num_k ++
17:             broadcast GWADV
18:         end if
19:          case: Active_GW
20:         bresk
21:     end if
22: end if
```

V. DISTRIBUTED GATEWAY SELECTION ALGORITHM

As described above, the procedure of our gateway selection algorithm is composed of two parts. First, the nodes in each sub-area should select a most stable node to be a gateway for their sub-area. After that, the parameters of the partition network should be optimized according to the variance of the topology. After several iterations, the state of the network can be optimized. In this section, we will present these two parts in details.

A. GATEWAY SELECTION

According to the analysis in Section 3, the consistency of the UAV nodes' information in each sub-area is improved in this partition network. Thus, the UAVs within the same sub-area can fairly select the most stable node to be the gateway for this region in a distributed way. The process of gateway selection is shown in Algorithm 1. In the 5th line, ε is a preset threshold. In order to compute each UAV's stability described above, we add some information into the HELLO packet, which is send by every node in the UAV network periodically. The major information contained in this HELLO packet is shown in Table 2, where *Seq_num* is the sequence number of the HELLO packet, *Sender_pos* is the position information of the sender of the HELLO packet, *One_hop_neighbor_list* is the one hop neighbor list of the sender, which contains those neighbor's stability and position, and *GW_list* is a list of the gateways, which is maintained by the sender UAV. In our algorithm, each UAV node in the network should maintain three tables. The first one is its one hop neighbor list, the second is its two hop neighbor list, and the third is the list of all the gateways in the network. Once a UAV receives a HELLO packet from its neighbor, it will check the

TABLE 2. **The structure of HELLO packet.**

Seq_num	*Sender_pos*	*stability*	*One_hop _list*	*GW_list*

information carried in this packet. The UAV will update neighbors' information in the first two table according to the neighbors' *Seq_num*, and update the gateway's information in the third table according to the gateway's *GW_Seq_num*.

TABLE 3. **The structure of GWADV packet.**

GW_Seq_num	*Sender_pos*	*stability*

This method expands the scope of information gained by each UAV node in the network via adding the list of one hop neighbor. Every UAV can obtain all the nodes' information within two hop range of it. So a UAV can calculate its stability within two hop range of it. For example, if UAV 1 is a two-hop neighbor of UAV 3 via UAV 2, the link availability between UAV 1 and 3 is the product of the two links' availability between them, $L_{13} = L_{12}L_{23}$. The information of each sub-area's gateway can be diffused rapidly through the network via *GW_list* carried by HELLO packet. Such a mechanism ensures that the node can find the right gateway to communicate immediately when its moved cross the boundary of sub-areas. Notice that there is a random delay mechanism in the new gateway generation process, and GWADV (Gateway Advertisement, its structure is shown in Table 3) only be retransmitted in the sub-area it belongs to. Those two implements ensure that if there are more than one nodes become *Potential_GW*, they will not send GWADV at the same time, i.e., guaranteeing that there is always a unique gateway in one sub-area.

In order to ensure the information of each gateway can be diffused accurately, every node in the same sub-area maintains the same *GW_Seq_num* in its gateway list. And *GW_Seq_num* only can be added by the gateway in this sub-area. When a node becomes the gateway of its sub-area, it will increase *GW_Seq_num* and then broadcast a GWADV packet to announce its information to the nodes within the sub-area. Then, it will increase *GW_Seq_num*, when it sends HELLO packet periodically. In such a case, every other node can update the information of this gateway in time.

B. DYNAMIC ADJUSTMENT OF THE PARTITION

As described in section 2, we have transited the optimization of gateway selection to the optimization of the parameter ω. The solution of optimizing the network partition parameter, is to find ω^* to minimize the $f(\omega)$. As shown in (5), it requires the stability of every sub-area to compute $f(\omega)$. Since there is no center in the UAV network, adaptive network [24] is a feasible and efficient solution for the partition parameter adjustment, considering the fact that the adjustment should be fast and adaptive to the rapidly changes of the network topology. The distributed incremental adaptive strategy presented in [25] was based on an adaptive network. The basic idea of an adaptive network is to build an optimization objective function with some parameters of the network and some metrics that can be observed, where each node measures those metrics in real time. According to the objective function, each node estimates the optimal parameter via cooperation with each other, and then utilizes the estimated parameter to adjust the network. After several rounds of coordination, the network will converge to the optimal state. For the problem of the UAV gateway selection presented in this paper, the tuning parameter is ω, and the state of the network to be observed is the stability of the gateway in each sub-area. So the cooperation of nodes within a same sub-area is needed. Usually, there are three kinds of ways for nodes to cooperate in such distributed network, as shown in Fig. 6 [25].

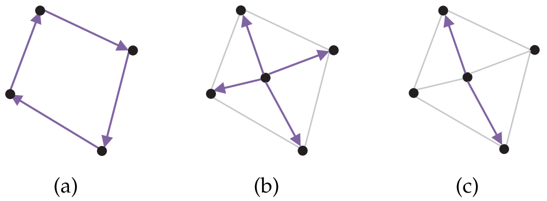


FIGURE 6. **Three modes of cooperation. (a) incremental, (b) diffusion, (c) probabilistic diffusion.**

In those three modes, the communication overhead of the diffusion way is the largest compared with the other two, while it is also with the highest efficiency for information diffusion and network state convergence. In the UAV network scenario, only the gateways in all sub-areas are required to cooperatively exchange their stability. In our implementation, the central sub-area acts as the server in the partition network, i.e., the sub-area 1 in Fig. 3. That is, each time the gateway of the central sub-area computes the system parameter ω, and then the outside $P - 1$ sub-areas can select their gateways respectively, according to the partition solution ω. After that, the selected gateways will report their stability information to the gateway of central sub-area. Based on the collected stability information from each sub-area, the gateway of the central sub-area can calculate the new ω, and then diffuse it to all other gateways. Through such an iterative way, the final stable partition solution ω can be found and the corresponding stability is also optimal according to (3). Because of the limited number of gateways, the overhead of diffusion and converge among these gateways would not be very high. Considering this circumstance, in this paper, the diffusion mode of cooperation is used to compute the optimized split parameter.

Algorithm 2 described the process of the partition adjustment, which is implemented by the gateway of the central sub-area. Since the gateways' information can be diffused through

Algorithm 2 Partition Adjustment

```
compute var $(S)$
if $is\_adjusting == 0$ then
    if var$(S) \geq \tau$ then
        compute the predicted $\omega^*$
        $\Delta\omega = (\omega^* - \omega)/h$
        $\omega^* = \omega + \Delta\omega$
        send $\omega^*$ to every other gateway
        $is\_adjusting++$
    end if
else
    if $0 < is\_adjusting \leq h$ then
        if var$(S) \leq \tau$ then
            $is\_adjusting = 0$
        else
            $\omega^* = \omega + \Delta\omega$
            send $\omega^*$to every other gateway
            $is\_adjusting++$
        end if
    end if
end if
```

the network rapidly, the gateway of the central sub-area is also aware of all other gateways' information. Thus, it can compute the metrics used in Algorithm 2 periodically to decide whether it is necessary to adjust the partition parameter. In the algorithm, var (S) is the variance of all the gateway's stabilities and τ is a pre-fixed threshold. If var (S) is larger than τ, then the gateway of the central sub-area will send the adjust packet to other gateways to trigger the partition adjustment. In order to control the size of each adjustment of the partition, every iteration is divided into several stages and h is the maximum number of those stages. $\Delta\omega$ is the variation of ω in each stage. Once the variance of all the sub-area's stabilities is smaller than τ in one of these stages, the adjustment of this iteration will be stopped. Once the other gateway received a new ω^* from the central gateway, it will broadcast it to all the nodes within the same sub-area.

As described in this section, the processes of the gateway selection are the iteration of Algorithm 1 and Algorithm 2. During the operation of the network, the stability of the gateways will be improved by repeating these two algorithms. The convergence of this solution will be discussed in the following section.

VI. PERFORMANCE EVALUATION

In this section, we will analyze the convergence of the gateway selection algorithm through many simulations. We will compare the algorithm proposed by us with the CONID clustering algorithm to evaluate its performance. In all the simulations, there are 100 nodes randomly located within a circular region of radius 5000m. In every simulation, the network is evenly divided at the beginning. The parameters used in this section are listed in Table 4.

A. ANALYSIS OF THE CONVERGENCE

TABLE 4. Simulation parameters.

Parameter	Value
Network Radius	5000m
Mobility Model	Random Walk
Transmit Distance	1000m
Number of UAVs	100
Speed	[0, 10], [10, 20] or [20, 30]m/s
Simulation Time	3600s
ε	0.2

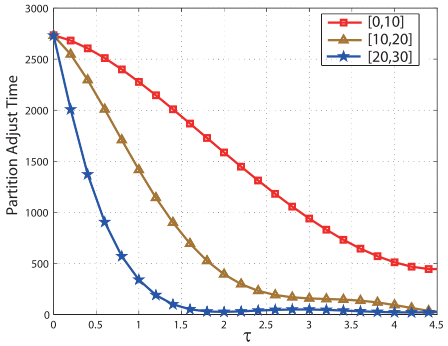


FIGURE 7. Partition adjust time.

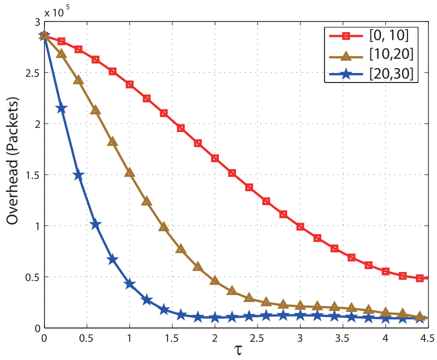


FIGURE 8. Overhead of the solution.

The convergence speed of the solution will affect the performance of this solution directly, which is directly related with the value of τ. On one hand, if τ is too small, the network would be adjusted too many times until var$(S) \leq \tau$ is satisfied, and the overhead of the adjustment will also be too high. On the other hand, if τ is too large, the network partition performance will be impaired regarding the equalization of the sub-areas' stability. Fig. 7 shows the partition adjustment times of three speed schemes: [0, 10], [10, 20], [20, 30], while Fig. 8 shows this solution's overhead of these three speed schemes correspondingly. Overall, we can see the adjustment times and overhead decreases as τ increasing due to the loose constraint. Meanwhile, it can be seen that for a same τ, the nodes move faster, the adjust time is fewer and the overhead is less. This phenomenon means that the dynamic partition mechanism would be more efficient, i.e., less convergence time and overhead, if the speed of the UAV node is faster. That is because in our solution, the adjustment affects more on those UVA nodes near the boundary than the nodes near the gateway, as shown in Fig. 9. Meanwhile, the stability defined in this paper is computed with the information within

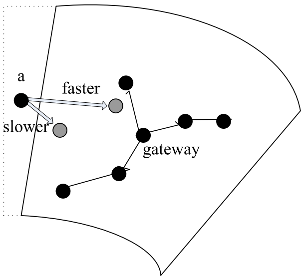


FIGURE 9. Partition adjustment range.

two hops of the gateway. In such a case, when the speed of the UAV nodes is slow, the probability of a boundary UAV moving into the two-hop distance from the gateway is also low, and thus the stability changes slowly in a short interval under the adjustment. On the contrary, if the UAV nodes move quickly, there is a higher probability that the boundary UAV node would move into the two hops of the gateway in a short interval. Therefore, our proposed dynamic adjustment mechanism is more suitable for the scenario where the nodes are moving quickly, which is just the characteristics of the UAVs.

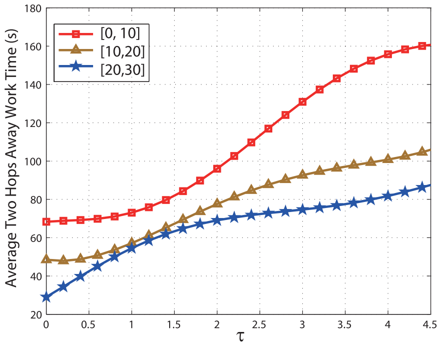


FIGURE 10. Average two hop away working time.

As mentioned earlier, the optimal target of our proposed solution is to equalize the stability of each sub-area. A large τ means that the final difference of each gateway's stability is also very large, i.e., there are more nodes working two hops away from their gateways. In order to illustrate the stability of this hierarchical network, we defined a metric called average two hops away working time, which is the average time for each UAV to work two hops away from their gateway. Fig. 10 shows the average two hops away working time of all the nodes, from which it can be seen that the time declines when the threshold τ declines. This is consistent with our analysis that more adjustment times (a small threshold τ) can lead to a more stable topology. Similarly, when the speed of the UAV nodes is slow, i.e., the entire UAV network topology is relatively stable, the probability that the boundary nodes staying two hops away from its gateway is also much higher. Therefore, as the UAVs' speed increases, the average two hops away working time decreases, i.e., the stability of the UAV network is enhanced. To summarize, the value of τ is rather important when configuring the UAV network, which should be determined according to the practical application scenarios of the UAV network. If the overhead is required to be fewer, τ should be set larger. Otherwise, the value of τ should be reduced.

B. PERFORMANCE OF PARTITION ADJUSTMENT

The algorithm proposed in this paper is to equalize the stability of each gateway in the network by adjusting the size of each sub-area adaptively. Therefore, the dynamic adjustment of partition is the key of this optimal solution. In order to evaluate the performance of the partition adjustment, we simulate the network not only with dynamic partition adjustment but also without this adjustment mechanism as a comparison. The variance of each gateway's stability at the same time under the two cases is shown in Fig. 11. The blue curve in the top of Fig. 11 is the simulation result without dynamic partition adjustment, while the blue curve in the bottom of Fig. 11 is the simulation result of with dynamic partition adjustment, where τ is set as 0.8 in this simulation and the brown straight line is the mean of the variance. We can see that the variance of each gateway's stability without dynamic partition adjustment is much higher than that with this adjustment mechanism, i.e., almost twice. With the dynamic partition adjustment, the variance can be reduced to be below τ immediately, when it is higher than the threshold τ. Therefore, it can be concluded that the dynamic partition adjustment can equalize the stability of each gateway efficiently.

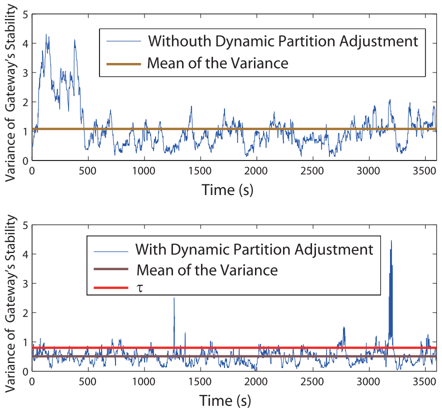


FIGURE 11. Variance of each Gateways stability.

C. COMPARISON WITH CONID

In order to evaluate the performance of the proposed solution, we also compared it with the traditional scheme CONID. To ensure a fair comparison and evaluate the performance of the limited gateways topology, we set the number of gateways in CONID and our dynamic partition solution to be the same, i.e., six gateways in total. Meanwhile, we also set the UAV nodes to be aware of two hop information in CONID as in our solution. The speed of nodes is a key factor to affect the performance of the gateway selection algorithm. We simulated both algorithms in five cases of speed distribution, [0, 10], [5, 15], [10, 20], [15, 25] and [20, 30]. In order to indicate the stability of the gateway, we defined a metric named average stable time of gateway's two-hop topology, which is the average time for each gateway's two-hop topology being the same. Fig. 12 and Fig. 13 show the average gateway duration and average stable time of gateway's two-hop topology with different speed distributions, respectively. Overall, we can see that our proposed dynamic partition algorithm always perform better than CONID in terms of both metrics. Moreover, when the speed of UAV nodes increase, the performance of CONID decreases dramatically, while our proposed algorithm is more robust. This is because, in CONID, all UAV nodes in the network get involved in the competition of gateway selection together, which leads to the fact that their local information is rather asymmetrical. Such an asymmetry would be amplified as the speed of a UAV increases, and thus the gateway would also change quickly. While in our algorithm, the gateway candidates are restricted in one sub-area, and the information they used to compare are less asymmetrical. Therefore, the partition of the network helps to reduce the asymmetry of the nodes' information if they are in the same sub-area, and the UAV network becomes more stable.

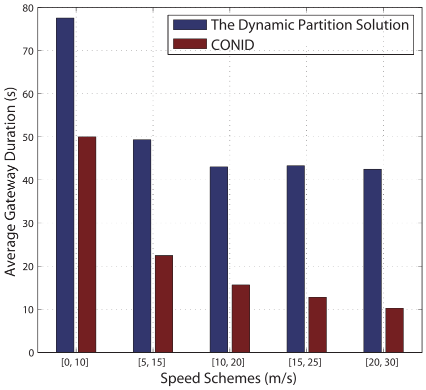


FIGURE 12. **Average gateway duration.**

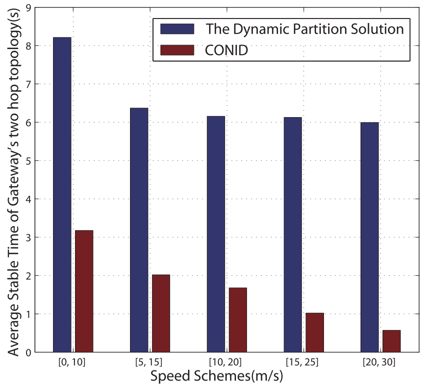


FIGURE 13. **Average stable time of gateway's two-hop topology.**

VII. CONCLUSION AND FUTURE DIRECTIONS

In this paper, the communication requirements of a UAV group was first analyzed. According to its application characteristics, a distributed gateway selection solution based on a dynamic network partition was proposed. The mathematical model of the gateway selection problem in a UAV network was also analyzed. In the process, we defined the stability of a UAV node in such a partition network. Finally, we analyzed the convergence of this solution by simulation, as well as the condition of convergence. Through the comparison with CONID, a traditional clustering algorithm in Ad Hoc networks, the performance and efficiency of our proposed solution were evaluated, the results of which showed that our solution is superior to CONID in terms of keeping the gateway stable.

In the future, there are still many problems worth studying about the gateway selection of UAV networks. For example, whether there is a better method to divide the network than that in this paper; whether we can optimize the starting boundary of the fan-shaped sub-area, which is assumed to be fixed to the positive direction in this paper; and the topology in each sub-area could be optimized by the transmission power adjustment to improve the performance of the network, etc. We plan to study these problems in the near future. We also plan to make the model more general and more practical for UAV networks. In particular, we will try to model this problem more generally considering asymmetric links.

REFERENCES

[1] A. E. Gil, K. M. Passino, S. Ganapathy, and A. Sparks, "Cooperative task scheduling for networked uninhabited air vehicles," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 44, no. 2, pp. 561–581, Apr. 2008.

[2] R. W. Beard, T. W. McLain, D. B. Nelson, D. Kingston, and D. Johanson, "Decentralized cooperative aerial surveillance using fixed-wing miniature UAVs," *Proc. IEEE*, vol. 94, no. 7, pp. 1306–1324, Jul. 2006.

[3] Y. Ben-Asher, S. Feldman, P. Gurfil, and M. Feldman, "Distributed decision and control for cooperative UAVs using ad hoc communication," *IEEE Trans. Control Syst. Technol.*, vol. 16, no. 3, pp. 511–516, May 2008.

[4] R. W. Beard, T. W. McLain, M. A. Goodrich, and E. P. Anderson, "Coordinated target assignment and intercept for unmanned air vehicles," *IEEE Trans. Robot. Autom.*, vol. 18, no. 6, pp. 911–922, Dec. 2002.

[5] D. W. Casbeer, D. B. Kingston, R. W. Beard, T. W. McLain, S.-M. Li, and R. Mehra, "Cooperative forest fire surveillance using a team of small unmanned air vehicles," *Int. J. Syst. Sci.*, vol. 37, no. 6, pp. 351–360, 2006.

[6] S.-W. Kim and S.-W. Seo, "Cooperative unmanned autonomous vehicle control for spatially secure group communications," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 5, pp. 870–882, Jun. 2012.

[7] Z. Han, A. L. Swindlehurst, and K. Liu, "Optimization of MANET connectivity via smart deployment/movement of unmanned air vehicles," *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3533–3546, Sep. 2009.

[8] A. I. Alshbatat and L. Dong, "Adaptive MAC protocol for UAV communication networks using directional antennas," in *Proc. Int. Conf. Netw., Sens. Control (ICNSC)*, Apr. 2010, pp. 598–603.

[9] I. Jawhar, N. Mohamed, J. Al-Jaroodi, and S. Zhang, "A framework for using unmanned aerial vehicles for data collection in linear wireless sensor networks," *J. Intell. Robot. Syst.*, vol. 74, nos. 1–2, pp. 437–453, Apr. 2014.

[10] F. Jiang and A. L. Swindlehurst, "Optimization of UAV heading for the ground-to-air uplink," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 5, pp. 993–1005, Jun. 2012.

[11] J. Huo, Z. Xu, Y. Zhang, and X. Shan, "A UAV mobile strategy in mobile ad hoc networks," in *Proc. Int. Conf. Electron., Commun. Control (ICECC)*, Sep. 2011, pp. 686–690.

[12] A. I. Alshabtat, L. Dong, J. Li, and F. Yang, "Low latency routing algorithm for unmanned aerial vehicles ad-hoc networks," *Int. J. Elect. Comput. Eng.*, vol. 6, no. 1, pp. 48–54, 2010.

[13] A. I. Alshbatat and L. Dong, "Cross layer design for mobile ad-hoc unmanned aerial vehicle communication networks," in *Proc. Int. Conf. Netw., Sens. Control (ICNSC)*, Apr. 2010, pp. 331–336.

[14] S. H. Kim, B. H. Jung, and D. K. Sung, "Adaptive beamforming antenna scheme to minimize the interference in a unmanned aerial vehicle (UAV) MANET," in *Proc. IEEE 20th Int. Symp. Pers., Indoor Mobile Radio Commun.*, Sep. 2009, pp. 813–817.

[15] D. L. Gu, H. Ly, X. Hong, M. Gerla, G. Pei, and Y.-Z. Lee, "C-ICAMA, a centralized intelligent channel assigned multiple access for multi-layer ad-hoc wireless networks with UAVs," in *Proc. IEEE Wireless Commun. Netw. Conf. (WCNC)*, vol. 2. Sep. 2000, pp. 879–884.

[16] S. Rosati, K. Kruzelecki, L. Traynard, and B. Rimoldi, "Speed-aware routing for UAV ad-hoc networks," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2013, pp. 1367–1373.

[17] L. Lin, Q. Sun, S. Wang, and F. Yang, "A geographic mobility prediction routing protocol for ad hoc UAV network," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Dec. 2012, pp. 1597–1602.

[18] A. D. Amis, R. Prakash, T. H. P. Vuong, and D. T. Huynh, "Max-min d-cluster formation in wireless ad hoc networks," in *Proc. 19th Annu. Joint Conf. IEEE Comput. Commun. Soc. (INFOCOM)*, vol. 1. Mar. 2000, pp. 32–41.

[19] C. R. Lin and M. Gerla, "Adaptive clustering for mobile wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 15, no. 7, pp. 1265–1275, Sep. 1997.

[20] G. Chen, F. Garcia Nocetti, J. S. Gonzalez, and I. Stojmenovic, "Connectivity based k-hop clustering in wireless networks," in *Proc. 35th Annu. Hawaii Int. Conf. Syst. Sci. (HICSS)*, Jan. 2002, pp. 2450–2459.

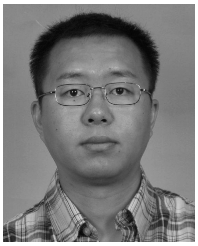
[21] Q. Han, Y. Bai, L. Gong, and W. Wu, "Link availability prediction-based reliable routing for mobile ad hoc networks," *IET Commun.*, vol. 5, no. 16, pp. 2291–2300, Nov. 2011.

[22] A. B. McDonald and T. F. Znati, "A mobility-based framework for adaptive clustering in wireless ad hoc networks," *IEEE J. Sel. Areas Commun.*, vol. 17, no. 8, pp. 1466–1487, Aug. 1999.

[23] B. L. Xiao, W. Guo, J. Liu, and S.-L. Zhu, "Pseudo gossip routing algorithm based link stability in mobile ad hoc networks," *J. Commun.*, vol. 29, no. 6, pp. 26–33, 2008.

[24] T. Miyazaki and K. Iwashita, "Towards adaptive networking," in *Proc. 7th IEEE Int. Symp. High Assurance Syst. Eng.*, Oct. 2002, pp. 151–158.

[25] C. G. Lopes and A. H. Sayed, "Incremental adaptive strategies over distributed networks," *IEEE Trans. Signal Process.*, vol. 55, no. 8, pp. 4064–4077, Aug. 2007.



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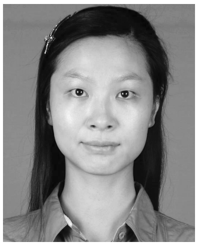

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