A Dynamic Trajectory Control Algorithm for Improving the Probability of End-to-End Link Connection in Unmanned Aerial Vehicle Networks

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Abstract. *Recently,* the Unmanned Aircraft Systems (UASs) have attracted great attention to provide various services. However, the Unmanned Aeria Vehicle (UAV) network which is constructed with multiple UAVs is prone to frequent disconnection. This is why the UAV-to-UAV links are constructed with two UAVs with high mobility. In such a disconnected network, ground-nodes cannot communicate with other ground-nodes with End-to-End link and the communication failure. Because the UAVs fly along with a commanded trajectory, the trajectories are the most important to decide UAV network performance. In this paper, we propose a effective UAVs' trajectory decision scheme.

Keywords: Unmanned Aircraft System (UAS) · Unmanned Aerial Vehicle (UAV) · End-to-End link connection

1 Introduction

Recent advances in wireless communication technologies and autonomous control technologies have made the Unmanned Aircraft System (UAS) applications feasible. UAS is a system made up of multiple Unmanned Aerial Vehicles (UAVs), which are small aircraft vehicles equipped with sensors, video camera, and wireless communication modules. UAV flies over the ground with propeller empowered by equipped battery, and use equipment to gather the information. Gathered information by UAVs are transmitted to ground-nodes (e.g. mobile phones, Access Points (APs), sensors and so forth) by using wireless communication modules. Generally, these UAVs are controlled by a control station located on the ground. UAVs receive the trajectory command from the remote control station, and travel along with transmitted trajectory. These UAVs can be classified into fixed-wing UAVs and rotor-propelled UAVs. Fixed-wing UAVs can fly with a higher speed than rotor-propelled UAVs. Moreover, fixed-wing UAVs can fly longer distance than rotor-propelled UAVs but cannot stay stationary at a

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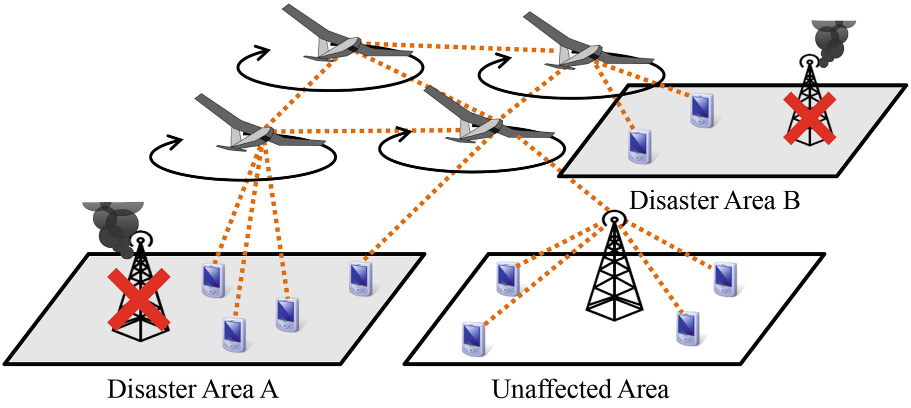

Fig. 1. Multi-hop data communication employing UAV network.

location. Therefore, it is clear that fixed-wing UAVs can better to provide the applications in large areas (e.g. urban area, mountains, islands and so forth) with its high mobility. On the other hand rotor-propelled UAVs can provide the applications such as fixed point observations by hovering objectives. The applications made possible by UAVs include scouting hazardous areas [1,2], collect data from mobile sensors [3], environmental observation [4–6], and so forth. Additionally, the UAVs trajectories can be dynamically changed in real-time by the control station to achieve these applications' objectives. Hereafter, we refer to a fixed-winged UAV as a UAV for brevity because our objective is to provide the services in wide area.

Relaying the data from ground-nodes to other ground-nodes is one of the anticipated UAS applications. This kind of application is especially useful when deployed over the disaster areas where conventional networks (e.g., antennas, ground base stations, network cables, etc.) are damaged and stopped. In such disaster area, conventional network infrastructures loses ability to provide the network connectivity. UAV network, which is constructed with multiple UAVs, can provide the connectivity to the ground-nodes which is distributed on those areas by using equipped communication module. The transmitted data from ground-nodes is received by flying UAV over the ground-nodes. The received data are transmitted to the destination ground-nodes in a multi-hop fashion by employing the UAV network. An overview of network construction is shown in Fig. 1. In Fig. 1, UAV networks can relay the data among the areas by connecting the wireless communication link to the each ground-node. Generated data in disaster areas are transmitted to the base station in the non-affected area.

However, UAV network's relay communication is not always successful because of the distance limitation of wireless communication. In the case that the distance between communicating nodes are larger than the limitation of wireless communication, the communication fails. Therefore, the ground-nodes cannot send the data when there are no UAVs inside of communication range. The link disconnections is more critical in the UAV-to-UAV communication because both of these two UAVs fly with high speed and easily move outside of communication range. If one or more of the UAV-to-UAV links between source and destination is disconnected, the ground-nodes cannot communicate with each other. Even if a large number of UAVs are deployed, we still need to consider the UAVs' trajectory to connect End-to-End link. If the UAVs' trajectory are decided without considering about network environment, End-to-End links are not established.

In this paper, firstly, we calculate the effect of UAV's trajectories on UAV-to-UAV links connection. Based on the analysis, we propose UAV's trajectory decision scheme to enhance the probability of End-to-End link connection. The proposal scheme calculates the each nodes' trajectory by using volume of flowed packet to provide the End-to-End link connection to many users. Although, there are so many parameter (e.g., shape of UAV's trajectory, altitude, speed, and so forth), we suppose that all of UAV have circular trajectories. The center position vector and the radius of circular trajectory can be changed by the control station. This is a reasonable assumption that UAV need to cover users who are around damaged base station while operation in the disaster situation.

The remainder of the paper is organized as follows. Section 2 reviews some related works and presents our research motivation. In Sect. 3, we show our ground node aware clustering algorithm. Performance evaluation is presented in Sect. 4. Finally, Sect. 5 concludes the paper.

2 Related Works and Our Motivations

The network construction with vehicles studied in some areas [7,8]. Mobile sink is the one of the network construction by using a vehicle. In the Mobile sink scheme, movable sink (e.g., vehicle, Unmanned Aerial Vehicle and so on) patrols the Wireless Sensor Networks (WSNs). As the sink node moves around the network area, the sensor nodes send data to the sink node when the sink node comes in their proximity. Thus, energy consumption can be decreased by reducing the amount of relays in the WSN. However, mobile sink make the big delay because the mobile sink moves to proximity of sensor nodes. In [9,10], the authors proposed the data aggregation method within limited period or limited buffer. The minimizing sum of required energy for data aggregation with a mobile sink are proposed in [11].

In [12], the authors proposed a Message Ferrying (MF) scheme. Message Ferry (MF) scheme is a approach for routing in disconnected ad hoc networks. It address the disconnection problem by introducing MF's mobility. In the MF scheme, the some rendezvous points are calculated beforehand to connect the all of disconnected ad hoc networks. MF schemes are resemble to mobile sink schemes and UAV networks. In [13], the author propose the hierarchical structure of message ferry data transmission to improve the network capacity. Although the MF scheme connect between disconnected ad hoc networks, these researches do not consider the End-to-End link connection. All of the received data are carried with MF's mobility.

The UAVs' trajectory decision scheme was proposed in [14,15]. In [14], the authors proposed the real-time environment sensing scheme with multiple UAVs. The proposed scheme is a role based trajectory decision scheme and effective for sensing all field. This scheme, however, do not consider the frequent sensing. Moreover, the destination gathered by UAVs is a fixed.

In this paper, we present how to decide the UAVs' trajectory to provide the End-to-End connectivity to ground-users by using multiple UAVs. Based on a communication performance analysis between UAVs, we propose the simple UAV's trajectory decision scheme.

3 UAV's Trajectory Decision Scheme

UAVs' trajectory is one of the most important factors that decide the probability of End-to-End link connection in UAV networks. In this section, we first show how the UAV-to-UAV link performance affected by the UAVs' trajectory. Based on the UAV-to-UAV link performance analysis affected by UAVs trajectory, we propose a UAVs trajectory decision scheme to improve the probability of End-to-End link connection.

3.1 Network Model

In this paper, we consider a network that consists of a ground node (e.g., mobile sensors, mobile phones, Access Points (APs)) spreads within a limited field and UAVs are deployed over the field. The Wi-Fi technology can be easily deployed on UAVs and ground nodes. Regardless of being a ground nodes or UAVs, a node has a Wi-Fi's limited communication range r, and communication is always successful if it is conducted within r.

The ground-nodes are densely distributed in some areas, which iclude refuge sites in disaster struck areas. These ground nodes are supposed to transmit the data to other grounds nodes in refuge sites. Generally, these nodes communicate with the base station to transmit the data to the destination ground-nodes. And the base station transfers the data to base station by employing wired cables. However, in some networks such as those deployed in disaster areas, islands and so forth, base stations are not always connected with each other. Due to physical factor, ground-nodes cannot communicate with the destination. If the End-to-End link between ground-nodes and the destination is disconnected, communication fails.

UAV networks, which consist of several UAVs deployed over the field. These UAVs travel along a circular trajectory to provide network service to a certain area. By communicating with each other, UAVs can transfer the data in a multi-hop fashion. All of the UAVs' trajectories (which consist of the center position of trajectory, and the radius of trajectory) are determined and controlled by a control station. A control station deployed on the field, communicates with all of the UAVs and transmit the UAVs' position vectors, and receive data directed to UAV in real-time. UAVs control their own trajectories by comparing with information from GPS and the information sent from the control station. UAV fly along the commanded trajectory paths. The data from the ground-nodes are relayed to the destination ground node through multiple UAVs.

3.2 UAV-to-UAV Link Performance Analysis

In the UAV-to-UAV link composed of two UAVs having circular trajectory, the UAV link performance is affected by the center position vector of the circle and radius of the circle. When the distance between two UAVs is smaller than communication range, r, a communication link is established and the communication link is disconnected when the distance is larger than r. And also the phases of circle is one of the determinants of the link performance. However, we deal with the phases as the means to get to know how trajectory's shape affects the UAV network's performance. Figure 2 shows the UAV-to-UAV link factors. $\mathrm{UAV_i}$ has the circle trajectory with the radius of R_i and center position vector of $\mathbf{X_i}(\mathbf{x_i}, \mathbf{y_i})$. Each UAV has a limited communication range, r, and communication is successful if it is executed within r.

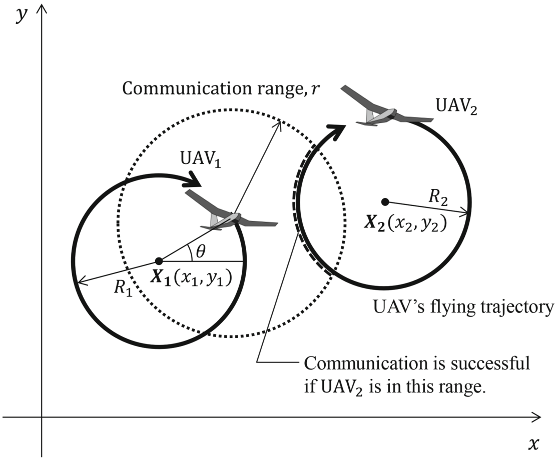

Fig. 2. The parameters of UAV-to-UAV link.

As shown in Fig. 2, when $\mathrm{UAV_i}$ is on trajectory with phase of θ, the successful communication probability is the ratio of length of lapped circle to length of circumference, $p(\theta)$, is shown as follows,

$$p(\theta) = \frac{1}{\pi} \arccos\left(\frac{R_2^2 + d^2 - r^2}{2R_2 d}\right), \tag{1}$$

where d is the distance between $\mathrm{UAV_1}$ and center of $\mathrm{UAV_2}$s circular trajectory,

$$d = \sqrt{(x_2 - x_1 + R_1 \cos\theta)^2 + (y_2 - y_1 + R_1 \sin\theta)^2} \tag{2}$$

Therefore the average successful communication probability, $P_{1,2}$ (x_1, x_2, R_1, R_2), is shown as follows,

$$P_{1,2}\left(x_1, x_2, R_1, R_2,\right) = \oint_{UAV_1} p\left(\theta\right). \tag{3}$$

According to 3, the radius of trajectory, R, and the center position vector of the circular trajectory, $\mathbf{X}$, affect the network performance. $P_{1,2}$ decrease with $||\mathbf{X_2} - \mathbf{X_1}||$. And $P_{1,2}$ decrease with R_i and R_j in some $||\mathbf{X_2} - \mathbf{X_1}||$.

3.3 Proposed UAVs' Trajectory Decision Scheme

In this subsection, we propose a effective UAVs' trajectory decision scheme. Our objective is to improve End-to-End connection probability. The proposed scheme dynamically and recursively changes the UAVs' trajectory based on the UAV-to-UAV link performance analysis.

In the assumed network environment, a control station controls the trajectory path of all of the UAVs by using allocated frequency bands for controlling the UAV. The allocated frequency bands is to communicate between control station and UAVs. General data transmissions on this bands are prohibited. Such remote trajectory controls are executed in real-time. According to the UAV-to-UAV link performance analysis, the center position vectors and the radius affect the UAV-to-UAV link's connection probability. UAV-to-UAV link's average connection probability can be increased by decreasing the radius of the circular trajectory and decreasing distance between two UAVs trajectories. The average link connection probability is not always a strict monotonic function of trajectory's parameters which include distance between UAV's trajectory and the radius of circular trajectory. However, we address the radius and the distance between UAV's trajectory while the average link probability is monotonically function, which means algorithm will stop when the average connection probability becomes a non monotonic function. An overview of our algorithm is shown in Algorithm 1.

At first, control station calculates the expected amount of successful communication in each link. Average link connection probability is calculated by 3 based on the UAV's trajectory information. After the calculation of expected number of successful communication, the algorithm selects the bottleneck link which is indicated by the link with the highest m_l.

In the selected link that has the highest value of m_l, our proposed algorithm selects the one of the $\mathrm{UAV_i}$ that has the bottleneck link. According to the link performance analysis, link's average successful communication probability can be controlled by changing UAV's trajectories. Concretely speaking, the average probability of successful End-to-End link connection increases by shortening the distance between two UAVs' center position vector of circular trajectory. And the shortening the radius of circular trajectory is also effective solution to improve the link's communication probability. Therefore, by shortening the distance between two UAVs or the radius, the average communication speed is increased. Then the successful End-to-End communication probability is also increases.

Algorithm 1. Proposed clustering algorithm

```
Set initial UAVs trajectory
while $|m_i - m_j| \leq \epsilon$ do
    Calculate the $\mathbf{m}$.
    /* Phase 1, Update the center position vector of UAS's trajectory */
    Select a bottleneck link, $l$.
    Select a $\mathrm{UAV_i}$ and $\mathrm{UAV_j}$ which compose the bottleneck link $l$
    Move the $\mathrm{UAV_i}$ and $\mathrm{UAV_j}$ to reduce the distance, $||\mathbf{X_i} - \mathbf{X_j}||$
    /* Phase 2, Update the radius of UAV's trajectory */
    Check the coverage area
    if All of network field is covered then
        Apply calculated UAV's trajectories
        $R'_i = R_i - \Delta$
        $R'_j = R_j - \Delta$
    else
        $R_k = R_k + \Delta$ for all $\mathrm{UAV_k}$
        Apply calculated UAV's trajectories
    end if
end while
```

However, we also need to consider the coverage area of UAV network in addition to communication probability. If the UAVs' trajectories are updated with consideration about the communication probability and without consideration about coverage area, some ground-nodes may become not able to connect to UAV. If the ground-nodes are outside of UAVs' communication range, the nodes' data are no longer to reach destination. To decide the UAVs' trajectory with having high communication probability and making sure the UAVs cover all of the field, our proposed algorithm checks the coverage area by using some existing schemes [16]. Only when the calculated trajectory cover all of the network field, the trajectories are applied. In case that the UAV network does not cover all of the network field, the algorithm enlarge the radius of all UAVs trajectories. Then, each UAV changes the own trajectory to received one.

4 Performance Analysis

In this section, we measure the performance of the UAV network and evaluate the performance of the proposed UAV trajectory decision scheme through extensive computer simulations. The simulation scenario was configured with the parameters summarized in Table 1. The nodes (e.g. UAVs and ground-nodes) use 2.4 GHz Wi-Fi band to connect with each other without additional base stations. We set Wi-Fi communication range, r, as 150 m and communication is successful if it is conducted within r. We assume that ground-nodes are distributed in some area such as refuges, schools, studiums, and so forth.

UAV networks are constructed over the ground to provide network connectivity to all ground-users. These UAVs have circular trajectory and each trajectory can be controlled by the control station.

Table 1. Environment of experiment

Number of users	100
User distribution	Even Gaussian Mixture
Number of UAVs, N	3–10
Speed of UAVs, v	40 km/h, 80 km/h
Communication range, r	150 m
Length of one side of field	1000 m

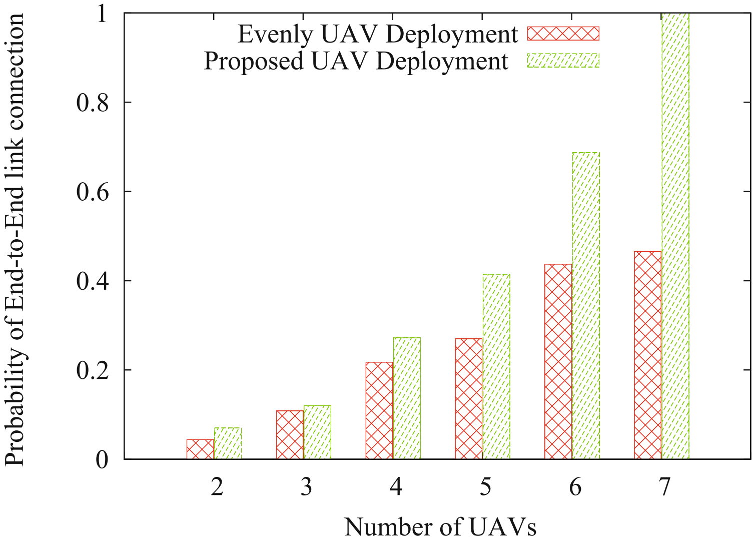

Fig. 3. Effect of the UAV's trajectory decision scheme.

We compare our UAV's trajectory decision scheme with even UAV deployment. The even UAV deployment is one where all of the UAVs have the same radius and the position vector of circular trajectories are uniformly deployed. On the other hand, the proposed scheme has the initial placement which is decided by even UAV deployment. Then proposed algorithm gradually change the UAV's deployment with UAV's speed.

4.1 End-to-End Link Connection Probability

In this experiment, we measure the End-to-End link connection probability from ground user to another ground user to evaluate our proposed algorithm in comparison to other trajectory decision schemes. Figure 3 shows average End-to-End link connection probability. As the graph shows the proposed algorithm can achieve higher End-to-End probability compared to uniform UAV deployment.

Since the proposed UAVs' trajectory decision scheme dynamically changes the trajectory to improve link connection probability based on UAV-to-UAV link's traffic load, a much larger ground-users can successfully send the data by using End-to-End link. In case of the relatively higher number of ground-nodes in a UAV Network, the proposed trajectory decision scheme changes the radius of circular trajectory unlike the even UAV trajectory deployment.

4.2 Convergence Speed and End-to-End Link Connection Probability

In this experiment, we measure the convergence speed of the proposed scheme. In the simulation, we set the nodes distribution according to the uniform, gaussian cluster distributions. The gaussian cluster distribution is the one that occurs in disaster areas where nodes gather in clusters. This behavior is in accordance with people gathering in refuge areas. We assume that the calculation of trajectory by control station takes 0.5 s. Figure 4 shows the convergence of proposed algorithm and the End-to-End link connection probability. In our proposed scheme, from the initial UAVs' trajectories which is evenly distributed, UAVs change the trajectory, which is assigned by the control station, with value of flying speed, v. Therefore, the UAVs' flying speed is one factor that influences convergence speed. Moreover, according to Fig. 4, we can get to know maximum End-to-End connection probability is changed with the nodes' distribution.

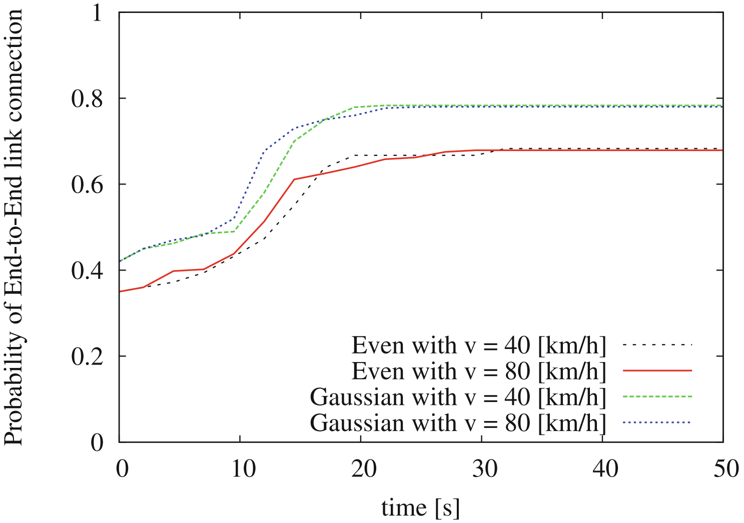

Fig. 4. Convergence speed of proposed UAV's trajectory decision scheme.

4.3 End-to-End Link Disconnection Duration

In this experiment, we measure the End-to-End link disconnection duration. To get know the character of link disconnection, we adopt an even UAV deployment scheme. Figure 5 shows the average End-to-End link disconnection duration. As shown in Fig. 5, the duration from link disconnection to link connection is related to UAV's speed and the number of UAVs. Moreover, it is considered that the radius also affects the End-to-End link disconnection duration. We need to take into consideration about the disconnection duration depending on the applications. This metric is most important when small delay is required application such as VoIP.

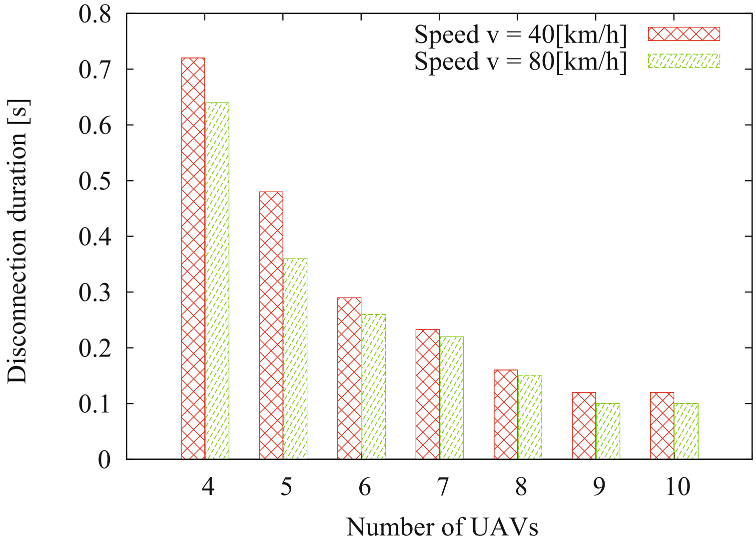

Fig. 5. Effect on the duration of disconnect.

5 Conclusion

In this paper, we proposed the UAV's trajectory decision scheme to improve the probability of End-to-End connection. At first, we evaluate the UAV-to-UAV link performance affected by UAVs' circular trajectory. Proposed UAVs' trajectory decision scheme change the center position vectors of circular trajectory and the radius of circular trajectory by using evaluated metric. Additionally, the proposed scheme decide to not make user outside UAV network. From the results, we confirmed that the proposed scheme achieves the low End-to-End delay trajectory.

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