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A Dynamic Trajectory Control Algorithm for Improving the Communication Throughput and Delay in UAV-Aided Networks

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***Abstract*—Recently, the unmanned aircraft systems (UAS) is extensively exploited for data collection from remote and dangerous or inaccessible areas. While most of its existing applications have been directed toward surveillance and monitoring tasks, the UAS can play a significant role as a communication network facilitator. For example, the UAS may effectively extend communication capability to disaster-affected people (who have lost cellular and Internet communication infrastructures on the ground) by quickly constructing a communication relay systems among a number of unmanned aerial vehicles (UAVs). However, the distance between the centers of trajectories of two neighboring UAVs, referred to as, IUD, plays an important role on the communication delay and throughput. For instance, the communication delay increases rapidly while the throughput is degraded when the IUD increases. In order to address this issue, in this article, we propose a simple yet effective dynamic trajectory control algorithm for the UAVs. Our proposed algorithm considers that the UAVs with queue occupancy above a threshold are experiencing congestion resulting in communication delay. To alleviate the congestion at the UAVs, our proposal adjusts their center coordinates and also, if needed, the radius of their trajectory. The performance of our proposal is evaluated through computer-based simulations. In addition, we conduct several field experiments in order to verify the effectiveness of UAV-aided networks.**

***Index Terms*—Disaster resilient network, UAV-aided networks, Unmanned aircraft systems (UAS), unmanned aerial vehicle (UAV).**

I. Introduction

Recently, the unmanned aircraft systems (UAS) have become a prominent choice for use in dangerous and/or repetitive missions. For example, the UAS comprising a swarm of unmanned aerial vehicles (UAVs) is being increasingly utilized in a wide range of applications such as military reconnaissance, security, environmental monitoring, crop and forest assessments, post-battle/post-disaster damage assessments, search and rescue operations, geographical mapping, and so forth [1]–[5]. Even though the UAVs have been traditionally exploited by the military and governmental agencies to conduct mission-critical surveillance and monitoring operations, they are now gradually becoming useful for civilian applications. This has become possible as a consequence of the much appreciated advances in a number of sectors including communication, computation, energy storage, networking devices and sensors, and carbon fiber-reinforced plastic materials. A typical UAV, equipped with wireless transceivers, is able to communicate with other UAVs and also with the users on the ground (referred to as "users" throughout the article). Furthermore, the recent availability of the UAVs at affordable prices has made it easy to use a swarm of collaborative UAVs as a robust communication platform.

A swarm of communication capable UAVs may be effectively deployed to construct a large communication network, and also to inter-connect separated heterogeneous networks on the ground. For example, the UAVs may effectively extend communication capability to disaster-affected people (who have lost cellular and Internet communication infrastructures on the ground) by promptly constructing a communication relay system through a number of UAVs. However, in order to provide various communication services to the users, the UAVs need to directly communicate with them. Furthermore, in emergency scenarios (e.g., after a disaster), it might be difficult to set up base stations that may communicate with the flying UAVs to cover the entire target area. As a consequence, an individual UAV may not be able to connect the users in a wide target area. Therefore, a swarm of UAVs is required to provide the connectivity to the users with a high probability. In such a swarm, each UAV can be considered to have a circular trajectory so that the swarm can cover the entire target area.

In this article, we consider a UAS composed of a swarm of UAVs, which can be remotely controlled by an UAV control station. In other words, the UAVs are supposed to be controlled by the control station in order to construct a multi-hop communication network that can reduce the end-to-end delay of communication by reducing the individual UAV's transit time. Also, we assume high mobility of the UAVs that makes it possible to provide communication service to the users (i.e., users scattered on the ground) over a significantly wide area. The users send their data to distant users through the swarm of UAVs, each of which is in flight with a circular trajectory. Thus, the UAVs construct a multi-hop network to help the users send and receive packets. In order to reduce the communication delay, an UAV needs to move close to the users on the ground. However, due to mobility and the need to connect with other UAVs, it is not always possible for a given UAV to maintain a close link with the users. As a consequence, the users are subject to experiencing long communication delays when the UAV moves away from them. Furthermore, an UAV does not only need to maintain close communication links with the users but it also needs to maintain connection with its neighboring UAVs. In other words, the UAVs also need to ensure that the links among them are stable so as to avert communication link disruption. Therefore, we demonstrate that the distance between the centers of trajectories of two neighboring UAVs, referred to as, IUD, is an important parameter in maintaining stable communication between the UAVs. If the value of IUD is small, the UAVs' capabilities are under-utilized in terms of a low coverage area. On the other hand, if the value of IUD is significantly high, the communication throughput degrades dramatically while the communication delay increases substantially.

To deal with this issue, in this article, we propose a simple yet effective dynamic trajectory control algorithm for the UAVs in order to improve the performance of our considered UAV-aided network. Our proposed algorithm considers that the UAVs with queue occupancy above a threshold are experiencing congestion resulting in communication delay. To alleviate the congestion at the UAVs, our algorithm is executed at the control station instructs the UAVs to dynamically move their centers of trajectories based on the traffic at a crowded or "busy" communication link. The UAVs react accordingly by moving to shorten the length of the link. Furthermore, to provide sufficient coverage of the target area, the UAVs are instructed to change their radius of trajectory. The effectiveness of our proposed algorithm is evaluated through computer-based simulations. Furthermore, several field experiments are conducted to verify the effectiveness of multi-hop communication using a swarm of UAVs, and also in order to measure the effect of the distance between the user and UAV on communication.

The remainder of the article is organized as follows. Sec. II presents a survey of the relevant research works in the area of UAVs trajectory planning. Sec. III portrays an overview of our considered UAV-aided communication network. The section also discusses the challenge associated with the trajectory control of the UAVs. To address the challenge, our proposed algorithm is presented in Sec. IV. Evaluation of our proposal and field experiments are provided in Sec. V. Finally, the article is concluded in Sec. VI.

II. Related Works and Our Motivation

In this section, we provide a survey of relevant research works on trajectory planning of the UAVs. In the work in [6], an approach for real-time path planning of the UAVs was proposed. The shortest path of the UAVs was computed in the work. However, it only considered the shortest path planning of the UAVs as important due to increasing power consumption with a significantly long flight time. The impact of trajectories of UAVs on communication performance such as delay was not taken into account at all. On the other hand, the research conducted by Tisdale *et al.* revealed, through flight experiments of UAVs, the capability of the UAS to perform autonomous search and localization in a cooperative scenario by exploiting receding-horizon path planning [7]. Tisdale *et al.* aimed to find practical control strategies for a group of fixed-wing UAVs performing cooperative sensing in a de-centralized fashion. In fact, the experimental objective of their work was to employ the UAVs to locate a stationary target on the ground, and the receding-horizon path planning did not indicate any direction on how to exploit it for facilitating communication between the users on the ground. The work in [4] presented a path planning approach of an UAV by using target localization uncertainty covariances along feasible UAV paths by considering target detectability. The work, however, aimed to maximize the detection chance of a target while minimizing sunlight reflection. Therefore, it can be considered as a target localization-centric path planning instead of that for finding the best path of the UAVs for improving communication performance.

In [8], the concept of a system for rapid aerial mapping was presented that can serve as a useful asset to aid workers to respond to a natural disaster or a big accident. The system focused on the path planning capabilities of a team of multi-rotor UAVs. On the other hand, Chen *et al.* remarked in their research conducted in [9] that the path planning is of significant interest for the autonomous navigation of an UAV. In addition, in [9], they formulated a three-dimensional path-planning algorithm for the UAV under three-dimensional dynamic environments. They dealt with the path planning problem in two steps. In the first step, based upon the information from an environment map constructed *a priori*, a path that avoids static threats is planned. In the second step, when the UAV is in flight by following the path, it updates the map and corrects the path with sensor information. That particular work, although useful for constructing three-dimensional paths of a single UAV, may not be directly applicable to a swarm of UAVs that need to cooperate with each other, particularly in case of a communication network formed by the UAVs.

In these previous researches, the UAVs were employed for achieving various objectives without considering the effect of their trajectory on communication. One of the leading works in introducing the UAVs as a means to facilitate communication appeared recently in [10], [11]. Particularly, it could be understood that in the UAV-to-UAV communication and UAV-to-users communication, the mobility of the UAVs leads to the disruption of the wireless links. As a consequence, we need to consider the effect of trajectory on communication in order to construct an effective UAV-aided communication network. In the work in [12], the researchers conducted field experiments to measure the effect of trajectory on communication performance for an individual UAV in flight. However, to the best of our knowledge, the effect of trajectories of the multiple UAVs in a swarm was not studied in the earlier research works.

III. Overview of the UAV-Aided Communication Network and its Challenges

A. Overview of the Considered UAV

Here, we present the overview of an UAV and briefly describe the functionality of the equipment on board the UAV. Usually, each UAV is equipped with two wireless transceivers.

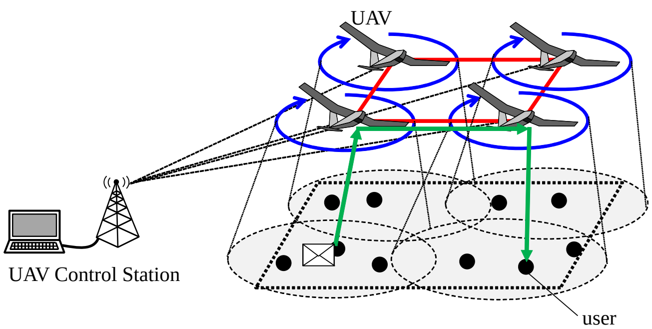

Fig. 1. Considered communication network constructed using a swarm of UAVs.

These transceivers are physically separated for ensuring secure flight. One of the transceivers is used for communicating with the UAV control station. The other transceiver is employed for data communication. The latter can perform two modes of operation when required, i.e., as UAV-to-UAV wireless transceiver and UAV-to-users wireless transceiver.

In the UAV-to-control-station communication, the UAV sends a number of parameters to the control station, namely, Global Positioning System (GPS) coordinates, flying speed, accelerometer, remaining battery, and the queue occupancy information. On the other hand, the control station is assumed to be able to decide or change the trajectory of the UAV based on the parameters received from all of the UAVs in the swarm. This interaction between the control station and the UAVs is portrayed in Fig. 1.

B. UAV-aided Data Communication

The use of non-military frequencies and civil communication technologies are rapidly gaining precedence for exploiting UAVs for communication in civilian areas, and network planners and engineers are mainly concentrating on accommodating the UAV-aided network communication through the already limited frequency pool [13]. While researchers are mainly focusing on solving the frequency reuse issues in the UAV-aided networks, in order to fully leverage the capabilities of the UAVs, it is important to adopt efficient methods for planning their trajectories and cooperative paths.

The adaptive modulation scheme may support any of the following modes, e.g., no transmit, phase-shift keying (PSK), quadrature phase-shift keying (QPSK), 16-quadrature amplitude modulation (QAM), and 64-QAM. By utilizing these modulation schemes, respectively, the users are able to transmit, to the UAV, a higher number of bits per symbol [3]. In other words, when the distance between a user and the UAV is the sufficiently small, the user may use 64-QAM to send as much data as possible in a time-slot. On the other hand, when the UAV moves along its trajectory and becomes distant from the user, the user switches to one of the lower modulation schemes. As the signal transmitted from the user to the UAV significantly degrades due to a large distance, the user stops transmitting data to the UAV, and waits for the next opportunity to transmit. To allow the users to transmit data in a real-time manner, the UAV needs to follow a specific flight trajectory, which can be either circular or elliptical. Unless otherwise stated, we assume circular trajectory of the UAV in the remainder of this article.

Now that we have described the data communication links, we introduce our multi-hop-UAVs based communication architecture through an example shown Fig. 1. In this figure, a UAS comprising four UAVs is depicted. Each UAV has a number of users that it can cover while flying along its circular trajectory. Note that the coverage areas of the different UAVs do not necessarily comprise the same number of users. In other words, the distribution of users on the ground is non-homogeneous. As shown in the figure, a user in the area covered by one of the UAVs is attempting to communicate with another user in a distant region. By this way, the network constructed by the four UAVs can provide a communication facility for users in such areas.

C. Challenge of UAV-based Communication Network

In the remainder of the section, we describe a major challenge that needs to be addressed in the UAV-facilitated communication network. In the UAV communication network comprising a swarm of UAVs, each UAV has a circular trajectory and is assumed to be always flying over the ground. Therefore, the data link connection between the UAVs become disconnected frequently. This happens because the distance between the UAVs becomes longer (due to their mobility) than the maximum distance supported by the wireless communication. Then, the average successful communication ratio is decided by the inter-UAV-distance (IUD), i.e., the distance between the centers of the trajectories of a pair of UAVs. By decreasing the IUD, the probability of link connection between two UAVs can be increased. Higher successful communication probability can, in turn, reduce communication delay because each UAV would not require to carry the data for a long duration. Also, the increased probability of link connection means improved throughput. However, in terms of coverage area on the ground, a smaller value of IUD leads a smaller coverage area. Therefore, if we consider a swarm of UAVs, it is necessary to adopt a method for controlling the flight of the UAVs so as to increase the probability of end-to-end link connections while maintaining coverage of the entire target field. In the following section, we propose a trajectory control algorithm for the UAVs to effectively address this challenge.

IV. Proposed Trajectory Control Algorithm

In this section, we propose a dynamic trajectory control algorithm of the UAVs for increasing the probability of end-to-end link connections. In our proposal, the control station decides the UAVs' trajectory (i.e., the center coordinates of the trajectory and the radius of trajectory of each UAV) based on the information obtained from all the UAVs in the considered swarm. Our proposed method is shown in the steps of the Algorithm-1 carried out by the control station. The variable inputs to the algorithm are the current center-coordinates and radius. The additional inputs, namely a queue occupancy threshold Q, distance reduction factor D, and the

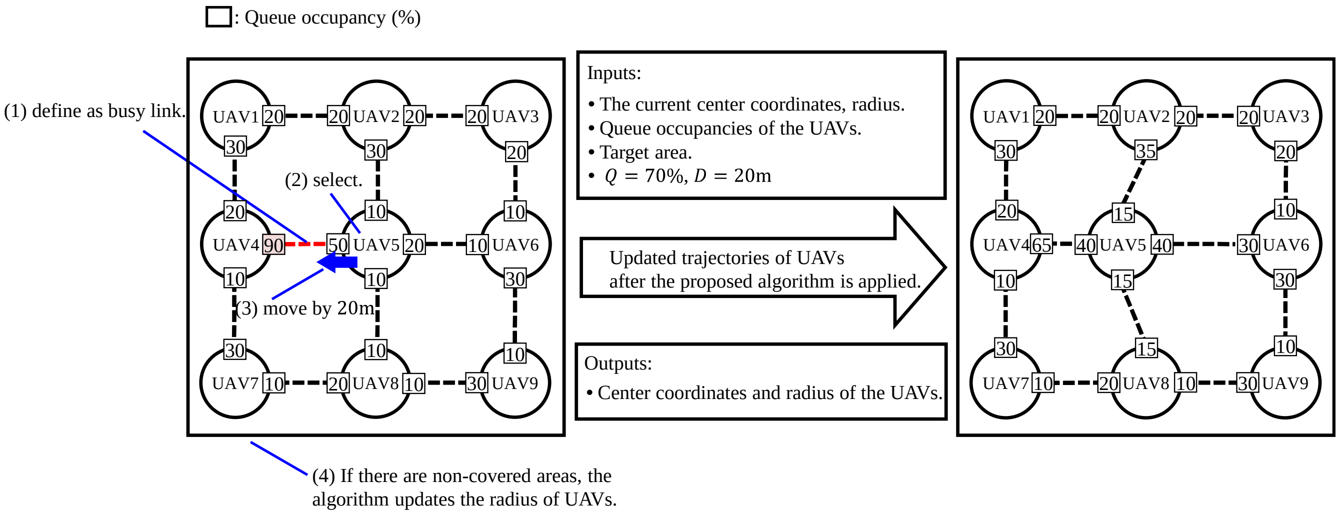

Fig. 2. A simple example of how the proposed algorithm works.

Algorithm 1 Proposed trajectory control algorithm executed at the control station.

Input: The current center-coordinates, radius, and queue occupancies of the UAVs, threshold Q, distance reduction factor D, and the target coverage area.

STEP1: Check which UAVs have links with queue occupancy $> Q$. Select the link of that UAV having the maximum queue occupancy $> Q$. This is referred to as the "busy link".

STEP2: Select the neighboring UAV, which shares the "busy link" selected in *STEP1*.

STEP3: Calculate the physical distance (IUD) between the UAVs of the busy link. Reduce their IUD by D. This reduction is performed by moving the selected neighboring UAV in *STEP2* toward the UAV selected in *STEP1* by a distance of D.

STEP4: Check the entire target area. If the entire target area is not covered, the algorithm updates the radius of UAVs' trajectories having the nearest center coordinates from the non-covered area.

Output: Center-coordinates and radius of the UAVs.

target coverage areas, are considered to be fixed. Furthermore, the queue occupancy of each link is also used for the inputs of the algorithm. This queue occupancy shows the utilization of transmission queue of a link. At the first step, the control station determines which inter-UAV-links are currently experiencing congestion by checking their links' queue occupancy against Q. The link with maximum queue occupancy above Q is selected. This strategy is adopted based on the queue occupancy because significantly higher queue-utilization means that there is much volume of queued data, which is likely to overwhelm the outgoing link. Thus, the control station selects the severe-most congested link based on the utilization of the links' queue. In the second step, the neighboring UAV which shares the "busy link" selected in first step is selected. In the third step, to reduce the higher queue-utilization, our algorithm computes the physical distance (IUD) between the center coordinates of the UAVs' trajectories of the overwhelmed (i.e., busy) link, and then reduces that distance by moving the selected neighboring UAV in second step toward that selected in the first step by D. This is performed because the shorter physical distance between the centers of the UAVs' trajectories leads to higher probability of successful communication. In the fourth step, the algorithm verifies if the radius of the UAVs' trajectories need to be adjusted or not in order to ensure that the entire targeted area is covered. If there are non-covered areas, the algorithm updates the radius of UAVs having the nearest center coordinates from the non-covered area.

As a simple example of how our proposed algorithm works, assume an UAV-based communication network shown in Fig. 2 where nine UAVs are deployed in a square grid. The users are non-uniformly distributed on the target area. The nine UAVs are labeled as UAV1, UAV2, and so forth. The values of Q and D are considered to be 70% and 20m, respectively. The steps of the executed algorithm are shown in bracketed numbers, i.e., (1), (2), and so forth. In *STEP1*, the link between UAV4 and UAV5 in Fig. 2 is selected because it experiences the maximum queue occupancy (90%$> Q$) compared to all the other queues. This communication link having the queue with the highest queue occupancy is defined as "busy link". In *STEP2*, UAV5 is selected because it shares the "busy link" selected in *STEP1*. In *STEP3*, the center coordinates of UAV5 is moved toward UAV4 by $D = 20$m. Whether it is necessary to change the radius of trajectory of UAVs is decided in *STEP4*.

As shown in Fig. 2, the queue occupancies of several links have changed after the proposed algorithm is applied. When the trajectory of an UAV is updated (i.e., when the UAV is moved toward one of its neighbors), the IUD between the UAV and that neighbor decreases, which results in increased probability of inter-UAV link connections between these two UAVs, thereby decreasing the queue occupancy in their link. On the other hand, the IUD increases between the UAV

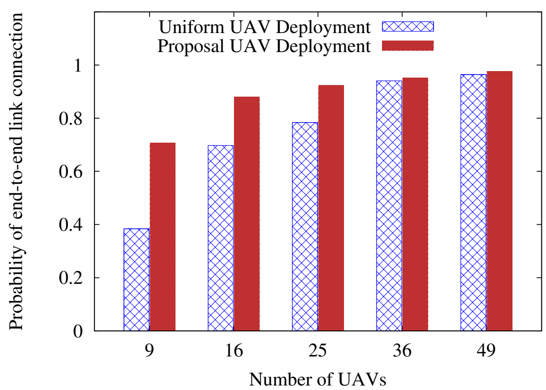

Fig. 3. Comparison of end-to-end link connection probability in uniform and proposed UAV deployments for increasing numbers of UAVs.

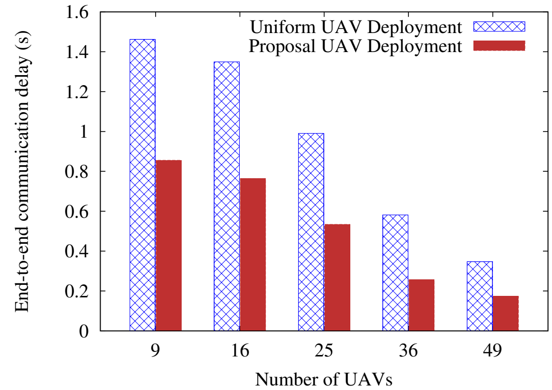

Fig. 4. Comparison of the end-to-end delays in uniform and proposed UAV deployments for increasing numbers of UAVs.

with changed trajectory and its other neighbors that results in decreased probability of inter-UAV link connections between the UAV and its neighbors, thereby increasing the queue occupancy in those links. Furthermore, if the number of users covered by an UAV is changed due to updated trajectories of an UAV, the volume of traffic flowing to the UAV and the queue occupancies of its links may change. However, because the UAV control station is not aware of the varying number of users, it may not be able to estimate how much queue occupancies of the links are caused by the varying user distribution. Therefore, the control station executes the proposed algorithm iteratively to gradually change the trajectory of an UAV with a small value of D. Without iterative execution, if the value of D is set to significantly high to change the UAV's trajectory at one-shot, the IUD as well as the number of users covered by the UAV may dramatically vary, which in turn could result in sudden change in the queue occupancy of the respective links. For future works, developing the mechanism to collect the varying user distribution and developing the trajectory decision scheme with optimum solution under the varying user distribution will be considered.

V. Performance Evaluation and Field Experiment

In this section, we evaluate the performance of our proposed algorithm through computer-based simulations. Furthermore, we conduct the field experiments to verify the effectiveness of multi-hop communication using a swarm of UAVs, and also to measure the effect of the distance between the user and UAVs on communication.

In the conducted simulations, we considered two scenarios. In the first simulation scenario, we assume that the users perform real-time data communication (e.g., voice over Internet Protocol (VoIP)) with other users. In case of the real-time data communication, the end-to-end connection is required to maintain a high level of quality of service (QoS), which is required for the users' satisfaction. On the other hand, in the second scenario, we consider that the users send non-real-time data (e.g., emails) to destination users. In the following, we provide simulation models and results of these two scenarios, respectively.

TABLE I
Considered experimental environment.

Parameter	Value
Flying speed	40km/h
Field length	1000m×1000m
Number of UAVs	Varied in a grid from 9 to 49
Initial radius of each UAV	100m
Maximum communication range	150m
Queue occupancy threshold (Q)	70%
Distance reduction factor (D)	20m
Simulation time	1 hour

Table I lists the considered simulation parameters for our first simulation scenario involving real-time communication. A swarm of 9 to 49 UAVs, deployed in a grid topology, are considered in this scenario. The coverage area is set to be 1000m×1000m. The communication range of the UAVs is supposed to be 150m. The shape of the trajectory of each UAV is assumed to be a circle, with an initial radius of 100m. The flight speed of the UAVs is set to be 40km/h. The queue occupancy threshold, Q, is set to 70%, and the distance reduction factor, D, is considered to be 20m. The simulation time is set to 1 hour. Additionally, the performance of our proposal is also evaluated with that of the conventional uniform UAVs deployment. The simulation result is demonstrated in Fig. 3 in terms of the probability of the end-to-end connection in case of the considered real-time data communication. The plot in the figure shows that for the conventional uniform UAVs deployment method, the probability of achieving end-to-end connections gradually increases with the increasing numbers of UAVs. The same trend can be seen for our proposed method. Notice that when there are many UAVs servicing the users, both the conventional and our proposed methods demonstrate high end-to-end link connections. However, our proposal exhibits much higher end-to-end link connection probability for lower numbers of UAVs. For instance, for the grid topology comprising only 9 UAVs, the conventional method can ensure end-to-end connection probability below 0.4, while our proposal's end-to-end connection probability is approximately 0.7. As a result, for low-cost deployment of fewer UAVs, our proposal can achieve much better performance than the conventional one.

In case of the second simulation scenario, we consider the same simulation parameters as described for the first scenario. For this scenario, the users are supposed to communicate with one another using non-real-time data communication (e.g., email exchange) by exploiting the UAVs, numbers of which are varied from 9 to 49 in the grid topology. The comparative result is demonstrated in Fig. 4 in terms of end-to-end delays experienced by our proposal and the conventional UAVs deployment method during the entire course of the simulation. In case of both the uniform UAV deployment and our proposal, the end-to-end communication delay decreases consistently with increasing numbers of UAVs. Notice that there is a large contrast between the end-to-end delays of the 9 and 49-UAVs scenarios that are 1.4s and 0.4s, respectively, for the conventional uniform UAV deployment. On the other hand, the end-to-end delays for these two scenarios in case of our proposal are 0.8s and only 0.2s, respectively. The results, therefore, demonstrate that our proposed algorithm updates the center-coordinates and radius of the UAVs in such a way that the busy links are alleviated resulting in lower end-to-end delays.

Additionally, we have conducted two field experiments with UAVs. The objective of the first field experiments is to verify the effectiveness of relay communication between two UAVs using Wi-Fi. A smartphone acting as a Wi-Fi communication module was attached to each UAV. Then, the UAV had the ability to communicate with both the users on the ground and its neighboring UAVs. In the experiment demonstrated in Fig. 5(a), the user in area 2 sends the non-real-time data packets (i.e., e-mail) to a user in area 1. The distance of these two areas was measured to be approximately 700m. The sent packets from area 2 were received by the UAV2 which flew back and forth to area 1. Thereafter, the data were relayed to the UAV1, and in turn, the UAV1 relayed the data to the user in area 1. By this way, in the first experiment, we confirmed the effectiveness of relay communication between two UAVs.

On the other hand, Fig. 5(b) demonstrates our conducted second field experiment using a fixed-wing UAV. The objective of the experiment is to measure the effect of the distance between the user and UAV on the communication. The same as the first experiment, the smartphone acting as a Wi-Fi communication module is attached to the UAV. During the field experiment, the UAV was in flight with a circular trajectory with a height of 100m and radius of 100m. As a result, the transmitted packets from a user were successfully received by the smartphone attached to the UAV when the linear distance between the flying UAV and user is lower than approximately 170m. On the other hand, almost all transmissions were failed when the linear distance was above 170m. By this way, in the second experiment, we obtained the effect of the distance on the communication.

VI. Conclusion

In this article, we argued that while most of the unmanned aircraft system applications in the existing literature are exploited for surveillance and monitoring missions, the UAVs can play a significant role as a communication network facilaitator for users in specific areas which suffer from heavy traffic congestion, lack of communication infrastructure due to disaster, remote location, and so forth. In this vein, we considered an UAV-based network to construct a multi-hop communication system. However, the trajectories of the UAVs have a notable impact on the communication delay. Particularly, the effect of congestion at the UAVs with fixed circular trajectory covering a large number of users increases the communication delay. In order to address this issue, in this article, we proposed an algorithm to dynamically adjust the center-coordinates and radius of the UAVs. Through computer-based simulations, we demonstrated that our proposal improves the communication performance in UAVs-based communication networks in terms of end-to-end link connection probability and end-to-end communication delay. Furthermore, in the field experiments, we verified the effectiveness of relay communication using two UAVs. And also, we measured the effect of the distance between the UAV and users on communication.

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(a) Field experiment with rotor-based UAV.

(b) Field experiment with fixed-wing UAV.

Fig. 5. Field experiments conducted with rotor-based and fixed-wing UAVs.

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