IEICE Communications Express, Vol.13, No.3, 93–96

ComEX

LETTER

Integration of speed control and bandwidth allocation to enable fair uplink communications in UAV-aided aerial base stations based on Open-RAN

Shu Mitsui [1, a)] **and Hiroki Nishiyama** [1, b)]

Abstract Unmanned aerial vehicle (UAV) base stations have a variety of applications due to their ability to be quickly and freely deployed. They provide a promising solution when existing terrestrial networks are damaged during a disaster and network connectivity is lost, helping to restore connectivity in disaster-affected areas. However, moving UAVs provide unfair network connectivity for ground-based user equipment. To solve this, we need to integrate speed control and bandwidth allocation. In this paper, we give an overview of the algorithms integrating them and demonstrate how they further improve fairness. Moreover, we provide an architecture based on the Open-RAN architecture for running integrated algorithms. Finally, we use computer simulations to demonstrate its effectiveness.

Keywords: UAV, fairness, speed control, bandwidth allocation, Open-RAN, RIC

Classification: Satellite communications

1. Introduction

Unmanned aerial vehicle (UAV) base stations have a variety of applications, such as expanding coverage to the sea and air, supplying connectivity to remote areas, and augmenting network capacity during events. What makes all this feasible is the UAV's ability to be quickly and freely deployed. This makes it particularly useful when existing terrestrial networks are damaged during a disaster and network connectivity is lost, where they can be used to recover connectivity in the affected area.

The most important aspect of disaster communication is ensuring fairness. There are prior studies that have focused on the fairness issue [1, 2], two of which were conducted by us and focused on improving fairness and developing two separate algorithms [3, 4]. One is the speed control algorithm, which addresses the unfairness caused by an uneven spatial distribution of user equipment (UEs) and the other is the bandwidth allocation algorithm, which addresses the unfairness caused by differences in the communication time and the communication distance. However, both of these sources of unfairness can occur simultaneously, so we need to be able to use these algorithms at the same time. In this paper, we present a method for integrating these algorithms. Moreover, we introduce an architecture based on the Open-RAN architecture, which handles the information to run our algorithms and enables their implementation. This architecture can be used when aspects of the UAV's mobility, such as the trajectory, flying speed, and hovering position, are optimized to improve network performance.

Our contributions in this paper can be summarized as follows.

- We formulate the optimization problem for the UAV's flying speed and bandwidth allocation, and propose integrated algorithms that performs speed control and bandwidth allocation, which solves the unfairness issues.
- We provide an example of an Open-RAN architecture that implements our integrated algorithms, which can be used to determine the UAV's mobility to then improve communication performance.
- We perform a computer simulation and analyze the performance of our integrated algorithms.

The rest of this paper is organized as follows. In Section 2, we provide an overview of the UAV-assisted communication system and present the formulation of the objective function. In Section 3, we elaborate on our algorithms, which optimize the UAV's flying speed and bandwidth allocation to enhance fairness. Furthermore, we propose an example architecture that can implement our algorithms. In Section 4, we conduct simulations to assess the performance of our technique. Finally, in Section 5, we present our conclusions.

2. System model

2.1 Model of a circling UAV

As shown in Fig. 1, we assume a situation in which a UAV-aided base station is flying in a circular trajectory and collecting data from K_{tot} ground-based UEs. The radius of the service area, R, is determined some parameters such as the transmission power and antenna radiation patterns. The location of each UE, denoted as $\mathbf{L_k} = (r_{\mathrm{UE}_k}, \theta_{\mathrm{UE}_k}, 0)$, is fixed, which the UAV knows in advance from its previous passage along the flight trajectory. The UAV flies at a fixed radius

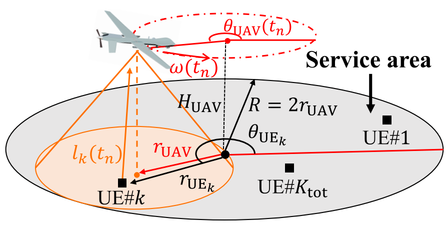

Fig. 1 System model.

[1] Department of Communications Engineering, Graduate School of Engineering, Tohoku University, Sendai, Japan

a) shu.mitsui.t8@dc.tohoku.ac.jp

b) hiroki.nishiyama.1983@ieee.org

DOI: 10.23919/comex.2023XBL0178
Received December 19, 2023
Accepted December 26, 2023
Publicized January 15, 2024
Copyedited March 1, 2024

of r_{UAV}, altitude of H_{UAV}, and turn period of T. Its position is represented by (r_{UAV}, θ_{UAV}, H_{UAV}). To cover the whole service area with one circle, $r_{\mathrm{UAV}} = R/2$. We introduce discretized time points, denoted as t_n, where $n \in \{0, 1, \ldots, N\}$ and $t_N = T$, and the set of UEs accommodated by the UAV at time t_n is denoted as $\mathcal{K}_n$, with $|\mathcal{K}_n| = K(t_n)$. The UAV uses orthogonal frequency division multiple access (OFDMA), and the total available bandwidth is denoted as B. In this system, the bandwidth is divided into N_{B} subchannels, each with a bandwidth of b. The length of each time frame is represented by δ_t.

The angular velocity of the UAV at a time between t_n and t_{n+1} is given by $\omega(t_n)$, and the control interval of the angular velocity is denoted by δ_ω. With these variables defined, we can write

$$\begin{gathered}\omega(t_k) = \omega(t_{k+1}) = \ldots = \omega(t_{k+M-1}),\\ k = Mk'(k' = 0, 1, 2, \ldots),\end{gathered} \tag{1}$$

where $M = \delta_\omega/\delta_t$ is the number of slots that meet the control interval of the angular velocity δ_ω.

Moreover, we define $\mathbf{w} = (\omega(t_0), \ldots \omega(t_{N-1}))$, which is the vector of angular velocities at all times. The relationship between the angular velocity of the UAV and its turn angle is given by

$$\theta_{\mathrm{UAV}}(t_n) = \begin{cases} 0, & n = 0 \\ \delta_t \sum_{i=0}^{n-1} \omega(t_i), & n \geq 1. \end{cases} \tag{2}$$

2.2 Formulation of the optimization problem for integrated speed control and bandwidth allocation

We use the free-space pass loss model as our propagation model, so the k-th UE uses one subchannel in the n-th time frame. The signal-to-noise ratio (SNR), $\gamma_k(t_n)$, can be expressed as

$$\gamma_k(t_n) = \frac{p_{\mathrm{UE}}}{bN_0}\left(\frac{\lambda}{4\pi l_k(t_n)}\right)^2, \tag{3}$$

where λ denotes the wavelength of the carrier wave with frequency f, p_{UE} denotes the transmit power of the UEs, N_0 represents the spectral density of the additive white Gaussian noise at the UAV, and $l_k(t_n)$ is the distance between the UAV and the k-th UE in the n-th time frame.

Then, the transmission rate, $r_k(t_n)$, derived from the Shannon–Hartley theorem, can be expressed as

$$r_k(t_n) = b \log_2\left(1 + \gamma_k(t_n)\right). \tag{4}$$

Next, we introduce $u_k(t_n)$, which indicates how many subchannels the k-th UE uses, and we assume that all the subchannels suffer from the same propagation loss. Therefore, the amount of transmitted data for the k-th UE, d_k, is given by

$$d_k = \delta_t \sum_{n=N_k^{\mathrm{S}}(\mathbf{w},\mathbf{L_k})}^{N_k^{\mathrm{E}}(\mathbf{w},\mathbf{L_k})} u_k(t_n) r_k(t_n), \tag{5}$$

where $N_k^{\mathrm{S}}(\cdot)$ is the sequential number of the time frame when the k-th UE starts to transmit to the UAV and $N_k^{\mathrm{E}}(\cdot)$ is the sequential number of the last time frame that the k-th UE transmits to the UAV.

We formulate the optimization problem for the UAV's flying speed and bandwidth allocation as

$$\underset{\mathbf{w}, u_k(t_n)}{\text{maximize}} \quad \min_k d_k, \tag{6a}$$

$$\text{s.t.} \quad \frac{1}{N}\sum_{n=0}^{N-1} \omega(t_n) = \frac{2\pi}{T}, \tag{6b}$$

$$\omega_{\min} \leq \omega(t_n) \leq \omega_{\max}, \quad \forall n \in \{0, 1, \ldots, N\}, \tag{6c}$$

$$\sum_{k=1}^{K_{\mathrm{tot}}} u_k(t_n) = N_{\mathrm{B}}, \quad \forall n \in \{0, 1, \ldots, N\}. \tag{6d}$$

(6b) specifies that the turn period of the UAV is constant, and (6c) places bounds on the speed of the UAV. (6d) specifies that all N_B subchannels should be allocated at all times.

3. Proposed integrated algorithms

In this section, we give an overview of how our algorithms in [3] and [4] are integrated. We then provide an outline for each algorithm and an example architecture based on Open-RAN to implement them.

3.1 Integration strategy

Although there are only two variables in the optimization problem (6a), it is difficult to control both simultaneously since changing the UAV's speed also changes the UEs entering the coverage area at each time (i.e., the UEs to which bandwidth can be allocated). Therefore, we first set the speed of the UAV, and then we determine bandwidth allocation.

Firstly, we use the speed control algorithm. This algorithm is input as $\mathbf{L_k}$, and the algorithm outputs $\mathbf{w}$. Then, we use the bandwidth allocation algorithm. This takes $\mathbf{w}$ and $\mathbf{L_k}$ as inputs, and the algorithm outputs $u_k(t_n)$. As a result, we get $\mathbf{w}$ and $u_k(t_n)$.

3.2 Speed control algorithm

We will now summarize the steps involved in the speed control algorithm [3]. We make two assumptions to simplify the analysis of unfairness caused by uneven spatial density: we assume that the size of the communication range is a constant value $(N^{\mathrm{R}})^*$ for all UEs and that the frequency utilization efficiency for each UE is equal to the average value at each turn angle. Based on these assumptions, the amount of data transmitted by each UE depends solely on the sequential number for the turn angle at which the k-th UE begins transmitting to the UAV, $(N_k^{\mathrm{S}})^*(\cdot)$. The equation for the amount of transmitted data can be reformulated as

$$d_k = B\delta_\theta \sum_{n=(N_k^{\mathrm{S}})^*(\mathbf{L_k})}^{(N_k^{\mathrm{S}})^*(\mathbf{L_k})+(N^{\mathrm{R}})^*} \frac{\overline{\log_2(1+\gamma_k(\theta_n))}}{\omega_\theta(\theta_n)K(\theta_n)}, \tag{7}$$

where δ_θ is the discretized interval of the turn angle, θ_n represents the discretized turn angle of the UAV, $\gamma_k(\theta_n)$ is the SNR for the k-th UE at the n-th discretized turn angle when subchannels are allocated equally, the numerator is the frequency utilization efficiency averaged over the UEs in the coverage area, $\omega_\theta(\theta_n)$ is the angular velocity at each turn angle of the UAV, and $K(\theta_n)$ is the number of UEs that the UAV accommodates at turn angle θ_n. We define $f(\theta_n)$ and $I(\theta_n)$ as

$$f(\theta_n) = \frac{\overline{\log_2(1+\gamma_k(\theta_n))}}{K(\theta_n)}, \tag{8}$$

$$I(\theta_n) = \frac{f(\theta_n)}{\omega_\theta(\theta_n)}. \tag{9}$$

If $I(\theta_n)$ remains constant and independent of θ_n, the amount of data transmitted will be constant regardless of $(N_k^{\mathrm{S}})(\cdot)^*$. In this case, under the given assumptions, the amount of data transmitted among UEs becomes equal, ensuring fairness. However, achieving fairness in the amount of data transmitted by each UE also requires determining an angular velocity $\omega_\theta(\theta_n)$ that maintains a constant value for $I(\theta_n)$. This is the design policy for the speed control algorithm.

Next, we calculate $\omega_\theta(\theta_n)$ using

$$\omega_\theta(\theta_n) = \frac{2\pi}{T}\left(\overline{\frac{f(\theta_n)}{f(\theta_n)}}\right)\frac{f(\theta_n)}{\overline{f(\theta_n)}}. \tag{10}$$

Substituting (10) into (9), $I(\theta_n)$ becomes a constant and satisfies the design policy of the speed control algorithm. Then, if $\omega_\theta(\theta_n)$ does not meet the speed limit, the speed control algorithm calculates the $\omega_\theta(\theta_n)$ that satisfies the speed limit while maintaining the relative magnitude in one cycle. Finally, the speed control algorithm converts $\omega_\theta(\theta_n)$ to $\omega(t_n)$. The algorithm performs the conversion using the function $C(\cdot)$,

$$\mathbf{w} = C(\omega_\theta(\theta_0), \omega_\theta(\theta_1), \ldots, \omega_\theta(\theta_{N-1})), \tag{11}$$

which means that once the angular velocities at all discretized turn angles have been obtained, the angular velocities at each discretized time in one lap can be calculated.

3.3 Bandwidth allocation algorithm

We will now summarize the steps involved in the bandwidth allocation algorithm [4]. Firstly, this algorithm calculates the amount of transmitted data if bandwidth is allocated equally with $\mathbf{w}$ using

$$d'_k = \delta_t \sum_{n=N_k^{\mathrm{S}}(\mathbf{w},\mathbf{L_k})}^{N_k^{\mathrm{E}}(\mathbf{w},\mathbf{L_k})} b_{\mathrm{e}}(t_n)\log_2\left(1 + \frac{p_{\mathrm{UE}}}{b_{\mathrm{e}}(t_n)N_0}\left(\frac{\lambda}{4\pi l_k(t_n)}\right)^2\right), \tag{12}$$

where $b_{\mathrm{e}}(t_n) = B/K(t_n)$ is the bandwidth when it is allocated equally at time t_n. Since d'_k reflects the unfairness resulting from the positioning of UEs in the system, and since there is an approximately linear relationship between bandwidth and transmission rate, this algorithm assigns resources to UEs within the coverage area inversely proportional to their respective d'_k values.

The bandwidth determined by the inverse ratio of d'_k is given by

$$b'_k(t_n) = B\frac{d_k'^{-1}}{\sum_{l\in\mathcal{K}_n} d_l'^{-1}}. \tag{13}$$

This algorithm allocates subchannels in a manner that ensures the bandwidth for each UE closely approximates $b'_k(t_n)$.

We will now explain how we calculate $u_k(t_n)$, which minimizes the gap between $b'_k(t_n)$ and the bandwidth finally allocated. We introduce $b''_k(t_n)$, which represents the gap between $b'_k(t_n)$ and the allocated bandwidth when subchannels are allocated by the quotient of $b'_k(t_n)$ divided by b. $b''_k(t_n)$ is given by

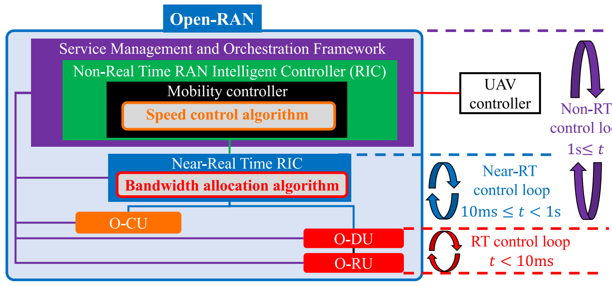

Fig. 2 Example architecture based on Open-RAN.

$$b''_k(t_n) = b'_k(t_n) - b\lfloor b'_k(t_n)/b\rfloor. \tag{14}$$

Furthermore, we count the number of remaining subchannels once they are allocated by the quotient of $b'_k(t_n)$ divided by b, denoted as N_{r}. This can be expressed as

$$N_{\mathrm{r}} = N_{\mathrm{B}} - \sum_{k\in\mathcal{K}_n}\lfloor b'_k(t_n)/b\rfloor. \tag{15}$$

From these two values, $u_k(t_n)$ is given by

$$u_k(t_n) = \begin{cases} \lfloor b'_k(t_n)/b\rfloor + 1, & \text{The UEs up to the top } N_{\mathrm{r}}\text{-th with the largest } b''_k(t_n). \\ \lfloor b'_k(t_n)/b\rfloor, & \text{otherwise}. \end{cases} \tag{16}$$

3.4 Proposed architecture

The Open-RAN and RAN intelligent controller (RIC) were developed to intelligently manage base stations and to supply quality service [5, 6]. However, they do not have support for controlling the UAV's mobility with communication information, which prevents the implementation of the speed control algorithm. Therefore, we introduce a new component to implement our speed control algorithm and provide an example architecture based on Open-RAN.

As shown in Fig. 2, our algorithms are run on an Open-RAN-based architecture. To facilitate UAV mobility control, we introduce a new component called the "mobility controller." This controller governs various aspects of UAV mobility, including the flying speed. We assume the mobility controller is placed in the Non-Real Time RIC. It is connected to the central unit (CU), the distributed unit (DU), and the radio unit (RU), referred to as O-CU, O-DU, and O-RU in the Open-RAN specifications, respectively, to receive a variety of information, such as the location information of the UEs and the channel status of each UE. It then calculates the UAV's mobility in a Non-RT control loop and transmits the results to the Near-Real Time RIC and UAV controller, which actually operate mobile base stations. The Near-Real Time RIC calculates the radio resource allocation in a Near-RT control loop based on the determined mobility. When our algorithms are used in this architecture, the speed control algorithm is run by the mobility controller, and the bandwidth allocation algorithm is run by the Near-Real Time RIC.

4. Performance evaluation

In this section, we present the results of a MATLAB simulation that we used to evaluate the performance of our algorithms. The simulation parameters listed in Table I were

Table I Parameter settings

Parameter	Value	Parameter	Value
b	180 kHz	N_B	106
K_{tot}	40, 80, 120	f	2 GHz
p_{UE}	10 mW	δ_t	10 ms
N_0	4.14×10^{-21} W/Hz	H_{UAV}	100 m
R	130.4 m	T	60 s
ω_{min}	$1/r_{UAV}$ rad/s	δ_ω	1 s
ω_{max}	$20/r_{UAV}$ rad/s		

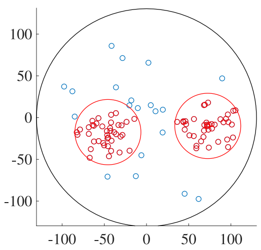

Fig. 3 Example of a UE distribution.

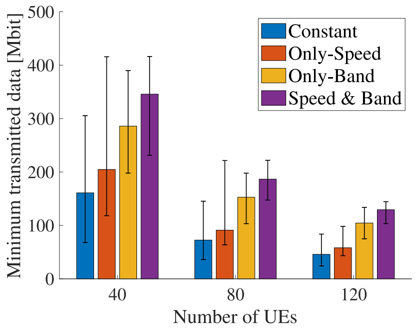

Fig. 4 Minimum amount of transmitted data.

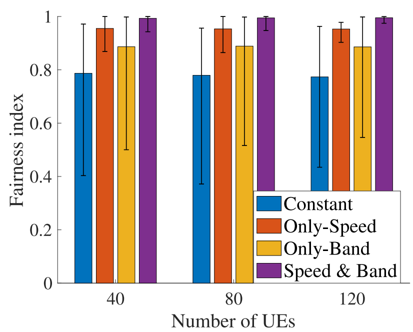

Fig. 5 Fairness in the amount of transmitted data.

determined by referencing the configuration of 5G base stations [7]. The UEs are distributed by the following model, as illustrated in Fig. 3. They are dispersed within the range of $0.05 \le r_{UE_k} \le 0.95R$. Two hotspots are randomly located in the service area, with 40% of the total UEs within each hotspot. The hotspots have a radius of $0.3r_{max}$, and the remaining UEs are located outside of them.

We use the following four methods for performance comparison.

- **Constant**: Flying at a constant speed and allocating subchannels equally. If any subchannels are left, they are allocated randomly.
- **Only-Speed**: Using the speed control algorithm proposed in [3] and allocating subchannels equally.
- **Only-Band**: Flying at a constant speed and using the bandwidth allocation algorithm proposed in [4].
- **Speed & Band**: Using the proposed scheme integrating the speed control algorithm [3] and the bandwidth allocation algorithm [4].

Figures 4 and 5 show the minimum amount of transmitted data and the fairness index [8] at different values for the total number of UEs, $K_{tot} = \{40, 80, 120\}$. The results show that the integrated algorithms have the best performance in both indexes, which indicates it can resolve the unfairness caused by uneven spatial distribution, differences in communication time, and differences in communication distance.

5. Conclusion

In this paper, we aimed to reduce the unfairness that arises in data transmission capabilities when a cycling UAV is providing network connectivity in a disaster-affected area. We demonstrated a method for integrating both a speed control algorithm and a bandwidth allocation algorithm. Moreover, we provided an overview of the architecture that enables our algorithms to run, which is based on the Open-RAN architecture. Finally, we demonstrated through computer simulations that our technique does improve fairness among UEs in terms of the amount of transmitted data. This work was supported in part by the Japan Society for the Promotion of Science KAKENHI under Grant No. JP20K11785.

References

[1] J. Kang, K. Kim, H. Lee, and J.-H. Kim, "Lyapunov optimization-based online positioning in UAV-assisted emergency communications," *IEEE Access*, vol. 11, pp. 60835–60843, June 2023. DOI: 10.1109/access.2023.3286038

[2] Z. Qin, Z. Liu, G. Han, C. Lin, L. Guo, and L. Xie, "Distributed UAV-BSs trajectory optimization for user-level fair communication service with multi-agent deep reinforcement learning," *IEEE Trans. Veh. Technol.*, vol. 70, no. 12, pp. 12290–12301, Dec. 2021. DOI: 10.1109/tvt.2021.3117792

[3] S. Mitsui and H. Nishiyama, "Speed-control technique for achieving fair uplink communications with a UAV-aided flying base station," *IEEE Access*, vol. 11, pp. 21332–21344, March 2023. DOI: 10.1109/access.2023.3251580

[4] S. Mitsui and H. Nishiyama, "A bandwidth allocation algorithm mitigating unfairness issues in a UAV-aided flying base station used for disaster recovery," *2023 IEEE 98th Vehicular Technology Conference (VTC2023-Fall)*, Hong Kong, China, pp. 1–6, Oct. 2023. DOI: 10.1109/vtc2023-fall60731.2023.10333709

[5] M. Polese, L. Bonati, S. D'Oro, S. Basagni, and T. Melodia, "Understanding O-RAN: Architecture, interfaces, algorithms, security, and research challenges," *IEEE Commun. Surveys Tuts.*, vol. 25, no. 2, pp. 1376–1411, 2023. DOI: 10.1109/comst.2023.3239220

[6] B. Balasubramanian, E.S. Daniels, M. Hiltunen, R. Jana, K. Joshi, R. Sivaraj, T.X. Tran, and C. Wang, "RIC: A RAN intelligent controller platform for AI-enabled cellular networks," *IEEE Internet Comput.*, vol. 25, no. 2, pp. 7–17, March-April 2021. DOI: 10.1109/mic.2021.3062487

[7] E. Dahlman, S. Parkvall, and J. Skold, *5G NR: The Next Generation Wireless Access Technology*, 1st ed., Academic Press, FL, USA, 2018. DOI: 10.1016/b978-0-12-814323-0.00005-3

[8] R. Jain, D. Chiu, and W. Hawe, "A quantitative measure of fairness and discrimination for resource allocation in shared systems," Digital Equipment Corporation, Tech. Rep., DEC-TR-301, Sept. 1984.