

A Flight Path Determination Method Considering Battery Constraints for Building a Communication Platform Using Delivery UAVs

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Abstract—In recent years, natural disasters such as heavy rainfall and earthquakes have become increasingly frequent, creating a growing demand for communication systems that can rapidly collect information from affected areas. However, communication in disaster-stricken regions may become difficult due to damage to communication infrastructure and a sudden increase in communication traffic during emergencies. To address this issue, the authors have proposed a wireless multi-hop network using delivery UAVs. In the proposed method, waypoints (WPs) are placed between the source point and disaster areas, and multiple UAVs relay data through these WPs. By shortening the communication distance between disaster areas, the number of hops required for multi-hop communication can be reduced. In this paper, in addition to the previously proposed WP placement method, a flight path design method considering battery consumption constraints is proposed. Simulation results demonstrate that the proposed method can reduce battery consumption while suppressing throughput degradation.

Index Terms—UAV, Network, Multi-hop, Waypoint.

I. INTRODUCTION

Traditionally, unmanned aerial vehicles (UAVs) have primarily been used as aerial user equipment (UE). However, with the reduction in UAV weight and the miniaturization of onboard communication devices, the deployment of multiple UAVs as a communication platform has attracted significant attention [1], [2]. UAV-based communication platforms are considered a promising solution in areas where terrestrial communication infrastructure cannot sufficiently satisfy communication demands, as well as during emergency situations. For example, UAVs are expected to provide flexible communication services in environments where urgent communication needs arise, such as smart agriculture, transportation infrastructure inspection, mountain rescue operations, and disaster response scenarios [3], [4]. In this study, we focus particularly on emergency communication scenarios during disasters.

UAV-based communication platforms can generally be classified into two categories: UAV base station systems and UAV relay systems [5]. In the base station approach, a large number of UAVs are deployed and connected to existing terrestrial base stations, allowing UAVs to function as aerial base stations within a cellular network. However, communication between

UAVs and terrestrial base stations is often based on line-of-sight (LOS) links, making UAVs more susceptible to inter-cell interference (ICI) from a wide range of neighboring cells than terrestrial UEs [6], [7]. To reduce dependence on cellular infrastructure, increasing attention has been paid to communication systems that utilize UAVs as relay nodes [5]. In such systems, UAVs operate within a dedicated communication network and therefore do not suffer from the ICI issues encountered in UAV base station systems. For this reason, this study focuses on UAV relay-based communication systems. UAV relay systems can be classified into single-UAV relay systems [8] and multi-UAV relay systems [9]. While single-UAV relay systems are relatively simple to deploy, communication may be interrupted if the relay UAV fails. In contrast, multi-UAV relay systems enable multiple UAVs to complement each other's coverage areas, thereby providing more reliable communication. Furthermore, multi-UAV relay systems can be categorized into multi-hop single-link UAV relay systems and dual-hop multi-link UAV relay systems. Although dual-hop multi-link UAV relay systems [9] may experience mutual interference among UAVs, they can establish real-time data transmission networks using multiple UAVs and extend communication coverage over a wide area. Therefore, this study adopts the dual-hop multi-link UAV relay system because it is expected to provide better communication performance than the single-link approach.

On the other hand, these relay-based systems often require a large number of UAVs to establish communication paths between source and destination nodes. In addition, the communication overhead increases with the number of hops, resulting in higher deployment costs and reduced communication throughput. Furthermore, most previous studies have focused on reducing travel distance and energy consumption through flight path optimization, while relatively few studies have jointly considered both flight performance and communication performance. To address these issues, the authors previously proposed a waypoint (WP) placement algorithm that enables efficient communication path construction using a limited number of UAVs while achieving both high throughput and

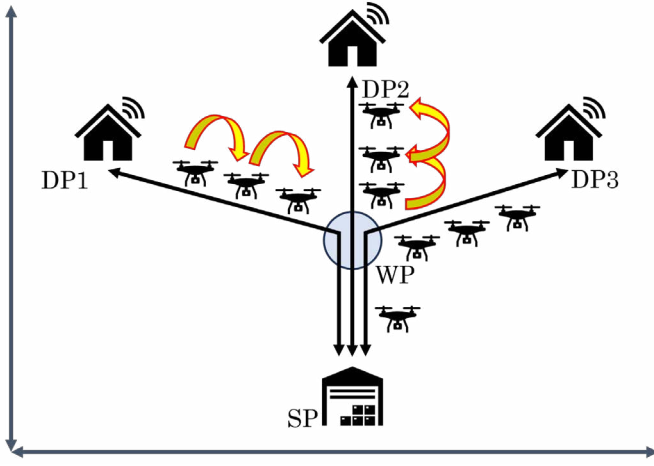


Fig. 1. UAV Flight Model

TABLE I. Simulation Parameters

Parameter	Values
Area Size	$10 \times 10 \text{ km}^2$
Number of SPs, (n_{sp})	1
Number of DPs, (n_{dp})	3
Number of WPs, (n_{wp})	3
UAV movement velocity	15 km/h
UAV operating time	8 hour
Maximum communication range of UAVs	200 m

low deployment cost [10]. Building upon the previously proposed WP placement algorithm, this study proposes a battery-aware flight path determination method. Simulation results demonstrate the trade-off between battery consumption and communication performance and clarify the effectiveness of the proposed method under different DP deployment scenarios.

II. SYSTEM MODELS

This study assumes an environment where roads are severed and ground communication base stations are non-functional during a disaster. Furthermore, it assumes multiple UAVs are operating to deliver relief supplies to the disaster area. The delivery UAVs are capable of relaying data via wireless communication. Fig. 1 shows an example of the system model within the affected area. This study defines a $10 \times 10 \text{ km}^2$ area as the flight-capable zone. Within this area, disaster response bases are designated as the UAVs departure points (SP: Source Point), and the disaster-stricken areas as their destinations (DP: Destination Point). UAVs are assumed to travel back and forth between SP and DP to deliver supplies. Furthermore, this study sets multiple DPs. Each UAV has a predetermined destination DP, and the DP does not change per delivery. UAVs take off from the SP toward each DP every minute. This study uses these delivery UAVs to collect information such as the safety status of people at each DP and the damage situation in the disaster area, transmitting the data via multipoint communication using multiple UAVs. Furthermore, it is assumed that the UAV undergoes battery replacement each time it returns to the SP. Assuming daytime flight operations, the UAV's daily operational period is set to 8 hours from dawn to dusk. If the UAV exceeds 8 hours of flight time during

Algorithm 1 Flight Path Construction

Input: $p_{cp}, p_{wp}, n_{cp}, n_{wp}$

Output: $routes_f, routes_b$

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1:  $p_{ip} \leftarrow \text{generate\_IP}(p_{cp}, p_{wp}, n_{cp}, n_{wp})$ 
2:  $nodes \leftarrow [p_{cp}, p_{wp}, p_{ip}]$ 
3:  $edge \leftarrow \text{generate\_edge}(nodes, n_{cp}, n_{wp})$ 
4:  $batterys \leftarrow []$ 
5:  $routes \leftarrow []$ 
6: for  $st \leftarrow 1$  to  $n_{cp} - 1$  do
7:    $prev \leftarrow \text{search\_path}(edge, \text{len}(nodes), st)$ 
8:    $E_t, rt \leftarrow \text{generate\_route}(nodes, prev, st, n_{cp}, n_{wp})$ 
9:    $batterys \leftarrow \text{push}(batterys, E_t)$ 
10:   $routes \leftarrow \text{push}(routes, rt)$ 
11: end for
12: if  $g(battery)$  then
13:    $routes_f, routes_b \leftarrow \text{separate\_route}(routes, n_{dp})$ 
14: else
15:    $routes_f, routes_b \leftarrow [], []$ 
16: end if
17: return  $routes_f, routes_b$ 

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a delivery, it will terminate the delivery and automatically return to the SP. For this study, flight path deviations due to disturbances like wind are not considered. The UAV's flight velocity is set to 15 km/h, maintaining a constant velocity throughout its movement. This study assumes a scenario where one SP ($n_{sp} = 1$) is set, and supplies are transported to three Distribution Points ($n_{dp} = 3$) while building a network. Furthermore, to enable efficient data transmission, UAV flight Waypoints (WPs) are established. The number of WPs is set to $n_{wp} = 3$. In this study, the SP is positioned at the edge of the area as shown in Fig. 1, and no DPs are set outside the area. The UAVs fly along flight paths determined by the algorithm described later, performing both material transport and data communication. The UAVs fly in formation, conducting data communication via relay transmission between them. Here, the maximum communication distance between UAVs is set to 200 m, and relay transmission is performed with the farthest UAV within the maximum communication distance. Furthermore, the throughput used for evaluation in this paper is defined as follows:

$$C_{hop}(i, j) = \frac{C_{max}}{N_{hop}(i, j)}, \quad (1)$$

where $C_{hop}(i, j)$ is the throughput between DP_i and DP_j , $N_{hop}(i, j)$ is the number of hops between DP_i and DP_j , and C_{max} is the maximum throughput. Here, C_{max} was set to 200 Mbps. Simulation parameters are summarized in Table. I.

III. ALGORITHM

This chapter describes a UAV flight path setting method using WPs determined by the WP placement algorithm [10]. Algorithm. 1 sets the UAV flight path using the p_{wp} determined by the WP placement determination method. The flight path is determined to ensure the shortest communication path between DP points while keeping the battery consumption

of all UAVs below the threshold. Battery consumption is calculated using the following equations.

$$t_f = \frac{l_f}{v}, t_b = \frac{l_b}{v}, e_f = p_f t_f, e_b = p_b t_b, \quad (2)$$

$$E_t = e_f + e_b = p_f \frac{l_f}{v} + p_b \frac{l_b}{v}, \quad (3)$$

$$E_t(i) = p_f \frac{l_f(i)}{v} + p_b \frac{l_b(i)}{v}, \quad (4)$$

$$g(\mathbf{E}_t) = \text{all } E_t(i) \leq E_c, \forall i \in \{1, 2, \dots, n_{dp}\}, \quad (5)$$

where n_{dp} is the number of destination points, E_c is the battery threshold, p_f and p_b are the power consumptions during outbound and return flights, respectively, and l_f, l_b, t_f, t_b, e_f , and e_b denote the flight distance, flight time, and energy consumption. Furthermore, when constructing the flight path, each outbound/return leg passes through at most one WP. In Algorithm. 1, let p_{cp} denote the coordinate array for SP and DP, and p_{wp} denote the coordinate array for pre-calculated WPs. At this point, the number of elements in p_{cp} and p_{wp} is the total number of SP/DP points $n_{cp}(= n_{sp} + n_{dp})$ and the number of WPs n_{wp} . The first line generates intersection points (IP) composed of SP/DP points and WPs. The second line groups each Point into a Node. The third line constructs candidate paths (Edge) composed of these Nodes. Lines 4 and 5 allocate empty arrays to store the battery consumption and round-trip paths for flights from SP to each DP. Lines 6 to 11 calculate the flight paths to each DP and the corresponding battery consumption. Lines 12 to 16 determine whether the battery constraint condition ($g(\mathbf{E}_t)$) is satisfied. Here, if $g(\mathbf{E}_t)$ is not satisfied, it is considered that no flight path exists, and an empty array is returned. If satisfied, the WP used for the outbound/return leg is returned. At this time, if the WP is not passed through on the outbound/return leg, -1 is returned.

IV. RESULT

In this section, the throughput between DPs and the battery consumption are evaluated under three different DP placement scenarios, with and without battery constraints. The flight paths are determined using the WP configuration method described in Section III. Since the WP placement algorithm generates different WP coordinates depending on the randomly initialized positions, a preliminary study was conducted in which the initial WP placement was randomly changed ten times. Simulation results obtained from these ten WP placement patterns were averaged, and it was confirmed that the influence of variations caused by the initial WP placement could be sufficiently reduced. Therefore, in this study, the initial WP placement is also randomly changed ten times for each SP and DP configuration. Throughput and battery consumption are calculated for each simulation run, and the average values of the ten simulation results are used to evaluate the performance of the proposed method. The battery threshold used for the battery-aware flight path determination is set to $E_c = 3970$ Wh. E_c was determined based on the battery capacity of the delivery UAV assumed in this study. Case 1

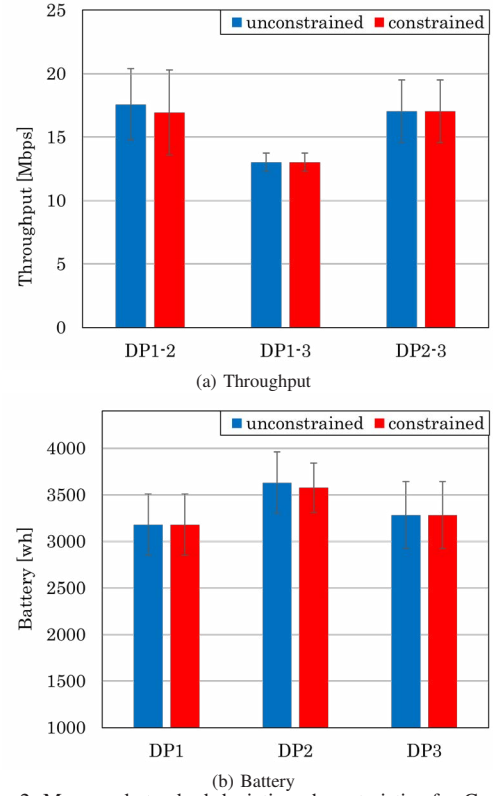


Fig. 2. Mean and standard deviation characteristics for Case 1.

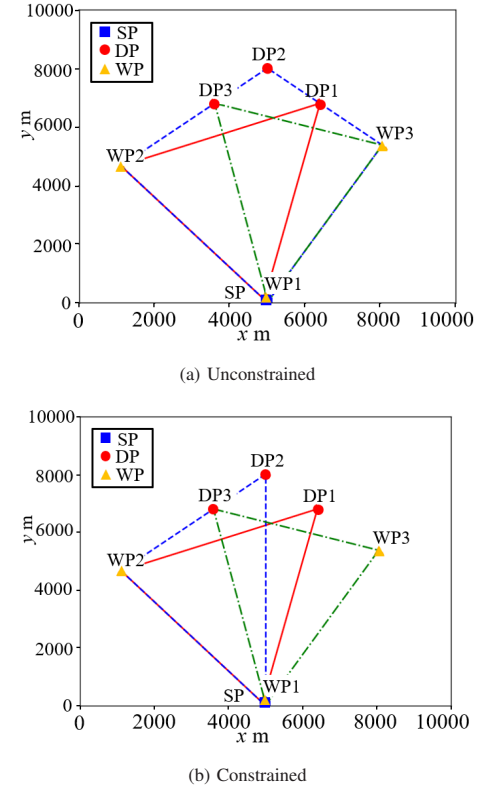


Fig. 3. UAV flight routing for Case 1.

evaluates a scenario in which all three DPs are located close to each other. As shown in Fig. 2 (a), the throughput between DP1 and DP2 decreases by approximately 0.6 Mbps in the constrained case compared with the unconstrained case. In

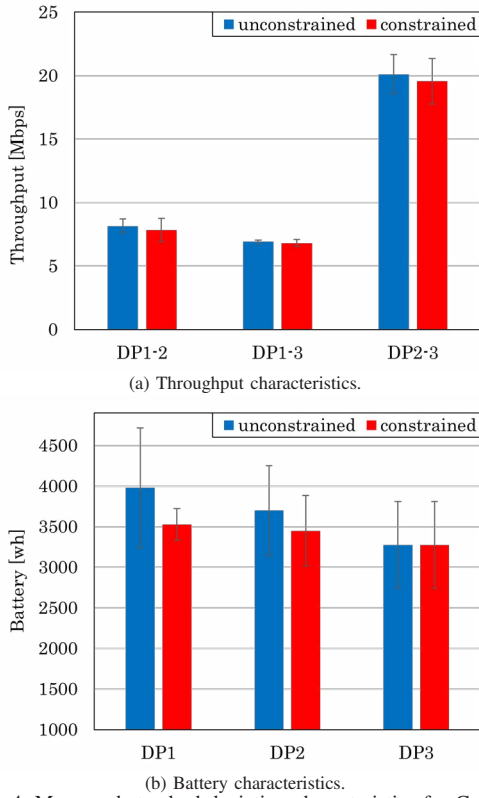


Fig. 4. Mean and standard deviation characteristics for Case 2.

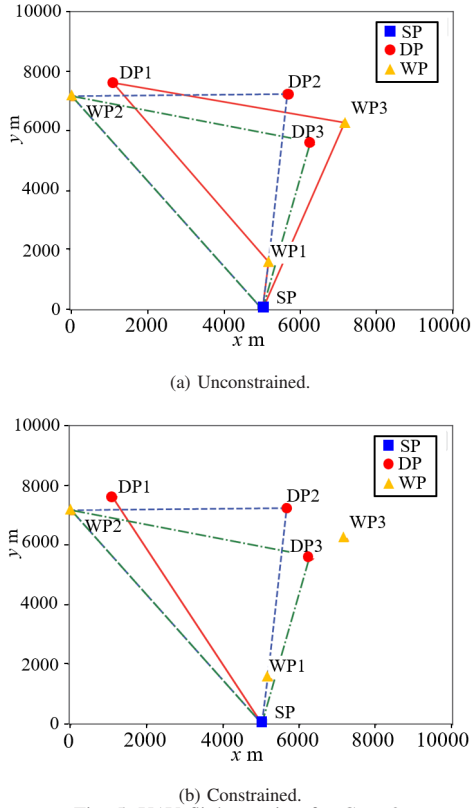


Fig. 5. UAV flight routing for Case 2.

contrast, no significant differences are observed in the throughput between DP2 and DP3 or between DP1 and DP3. Fig. 2 (b) indicates that the battery consumption of the UAV traveling

to DP2 is reduced by approximately 54 Wh in the constrained case. On the other hand, the battery consumption of the UAVs traveling to DP1 and DP3 remains almost unchanged. The reason for this result can be explained using Fig. 3. In the unconstrained case, the flight path to DP2 passes through both DP1 and DP3. In contrast, in the constrained case, the route is modified to pass only through DP3. As a result, the travel distance to DP2 is shortened, leading to a reduction in battery consumption. Although the throughput slightly decreases due to the change in the communication route, both changes are relatively small. Therefore, the impact of the battery constraint is limited in this scenario. Case 2 evaluates a scenario in which two of the three DPs are located close to each other. According to Fig. 4 (a), the average throughput in the constrained case is lower than that in the unconstrained case for all DP pairs. However, the reduction is relatively small, amounting to approximately 0.4 Mbps between DP1 and DP2, 0.2 Mbps between DP1 and DP3, and 0.7 Mbps between DP2 and DP3. The overall average reduction is approximately 0.4 Mbps. On the other hand, Fig. 4 (b) shows that battery consumption is reduced in the constrained case. Specifically, reductions of approximately 460 Wh and 270 Wh are achieved for DP1 and DP2, respectively, while the overall average reduction is approximately 243 Wh. In particular, the battery consumption for DP1 is reduced by 11.41% compared with the unconstrained case. These results indicate that the introduction of battery constraints can effectively reduce battery consumption while maintaining only a minor degradation in throughput. The reason can be explained by comparing the routes shown in Fig. 5. In the unconstrained case, the flight path to DP1 passes through WP1 and WP3. In contrast, the constrained case selects a route that does not pass through any WP. This occurs because the battery constraint prioritizes shorter flight paths over longer routes that involve WPs. Consequently, the travel distance to DP1 is reduced, resulting in lower battery consumption.

Case 3 evaluates a scenario in which all three DPs are concentrated in an area satisfying $x > 5000$ and $y > 5000$. As shown in Fig. 6 (a), the throughput degradation in the constrained case is less than 1 Mbps for both the DP1–DP2 and DP2–DP3 pairs compared with the unconstrained case. However, the throughput between DP1 and DP3 decreases significantly by approximately 6.6 Mbps. Fig. 6 (b) shows that the battery consumption of the UAV traveling to DP3 is reduced by approximately 750 Wh when battery constraints are applied. In contrast, little difference is observed in the battery consumption of the UAVs traveling to DP1 and DP2. These results indicate that battery constraints can reduce battery consumption for some routes; however, throughput degradation also occurs in this scenario. The reason can be explained using Fig. 7. Since the WP placement algorithm does not consider battery constraints, the generated WPs are distributed throughout the entire area. Consequently, in the constrained case, the number of WPs satisfying the battery constraint becomes limited, and only WP2 is available. As a result, the communication route between DP1 and DP3 be-

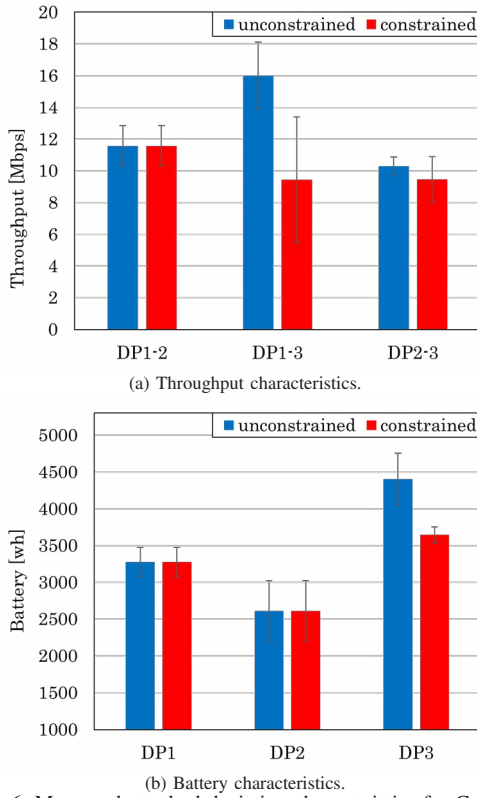


Fig. 6. Mean and standard deviation characteristics for Case 3.

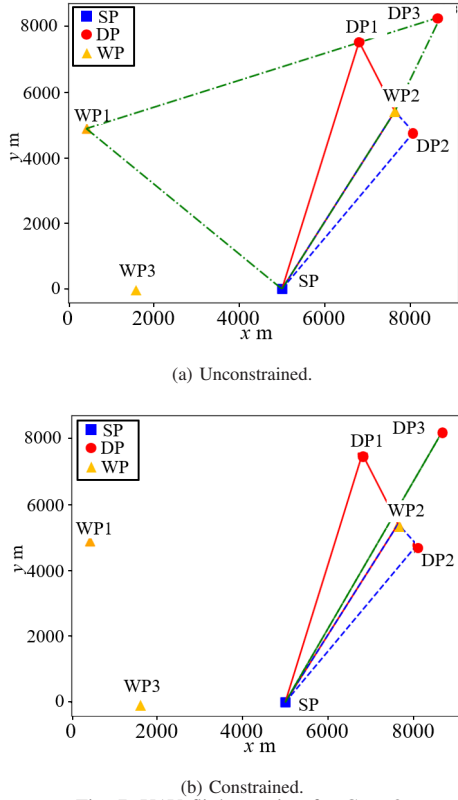


Fig. 7. UAV flight routing for Case 3.

comes longer and requires additional relay hops. This increase in the number of hops significantly reduces the throughput between DP1 and DP3.

The above results confirm that the proposed flight path determination method considering battery consumption is effective in reducing UAV battery consumption. In Case 2, where two of the three DPs are located close to each other, battery consumption can be reduced while maintaining only a slight decrease in throughput. In contrast, in Case 3, where all three DPs are concentrated within the same area, the battery consumption of the UAV traveling to DP3 is reduced; however, the throughput between DP1 and DP3 decreases significantly. These results indicate that a trade-off exists between battery consumption reduction and communication performance in the proposed method. This is because battery consumption is not considered during WP placement, and throughput is not directly used as an evaluation metric in the flight path determination process. Consequently, routes that prioritize battery consumption reduction are selected, resulting in an increase in the number of relay hops and communication distance, which ultimately leads to throughput degradation.

V. SUMMARY

We propose a method for deploying WPs with battery constraints in UAV multi-hop communication using delivery UAVs. Simulations demonstrate that, in some cases, battery efficiency improves without reducing throughput. However, we also found that depending on the placement of WPs, suppressing battery consumption can lead to reduced throughput between WPs. Furthermore, we observed that the proposed position determination method produces significantly different coordinate placements depending on the initial values.

- [1] S. Sekander, H. Tabassum and E. Hossain, "Multi-Tier Drone Architecture for 5G/B5G Cellular Networks: Challenges, Trends, and Prospects," in *IEEE Communications Magazine*, vol. 56, no. 3, pp. 96-103, March 2018.
- [2] B. Li, Z. Fei and Y. Zhang, "UAV Communications for 5G and Beyond: Recent Advances and Future Trends," in *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 2241-2263, April 2019.
- [3] J. Bae, K. Y. Sohn, H. Lee, H. Lee and H. Lee, "Structure of UAV-based Emergency Mobile Communication Infrastructure," 2021 International Conference on Information and Communication Technology Convergence (ICTC), Jeju Island, Korea, Republic of, 2021, pp. 634-636.
- [4] Abubakar, A. I., Mollel, M. S., Onireti, O., Ozturk, M., Ahmad, I., Asad, S. M., Sambo, Y., Zoha, A., Hussain, S., Imran, M. A., "Coverage and throughput analysis of an energy efficient UAV base station positioning scheme," *Computer Networks*, Vol. 232, 2023, Art. no. 109854.
- [5] G. Zhang, H. Yan, Y. Zeng, M. Cui and Y. Liu, "Trajectory Optimization and Power Allocation for Multi-Hop UAV Relaying Communications," in *IEEE Access*, vol. 6, pp. 48566-48576, 2018.
- [6] A. S. Hamza, S. S. Khalifa, H. S. Hamza, and K. Elsayed, "A survey on inter-cell interference coordination techniques in OFDMA-based cellular networks," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 4, pp. 1642-1670, 2013.
- [7] H. So, "Evaluation of radio interference areas by flight path and antenna directivity of UAV in urban area," in *Proc. VTC2024-Fall*, Washington, DC, USA, Oct. 2024, pp. 1-6.
- [8] Y. Chen, W. Feng, and G. Zheng, "Optimum placement of UAV as relays," *IEEE Communications Letters*, vol. 22, no. 2, pp. 248-251, 2018.
- [9] M. Horiuchi, H. Nishiyama, N. Kato, F. Ono, and R. Miura, "Throughput maximization for long-distance real-time data transmission over multiple UAVs," in *Proc. IEEE International Conference on Communications (ICC)*, Kuala Lumpur, Malaysia, May 2016, pp. 1-6.
- [10] H. Soya, K. Inagaki, and H. So, "A flight route design method considering multi-hop communication using delivery UAVs," *Drones*, vol. 9, no. 11, Art. no. 751, 2025.