3D Trajectory and Transmit Power Optimization for Blockage-Aware UAV Monitoring Systems

Kanghyun Heo, Gitae Park, Chaeyeon Kim, Seungeun Lee, and Kisong Lee, *Senior Member, IEEE*

***Abstract*—In this paper, we investigate a system in which an unmanned aerial vehicle (UAV) monitors multiple points of interest (POIs) and transmits collected data to a central monitoring unit (CMU) in an environment with blockages. In this system, the UAV needs to satisfy three necessary constraints during its flight. First, it must ensure a line-of-sight (LoS) condition with the POIs for accurate monitoring. Second, it must establish a LoS channel with the CMU for efficient information transmission. Lastly, the UAV must avoid blockages to perform its tasks stably without collisions. These constraints are generally non-convex sets, which are hard to solve. We replace these three constraints with linear inequalities using the separating hyperplane theorem and explain the principle. Based on successive convex approximation, the trajectory and transmit power of the UAV are optimized with the goal of maximizing the minimum rate during flight time. The simulation shows that the proposed method satisfies the constraints and outperforms existing methods.**

***Index Terms*—Unmanned aerial vehicle, monitoring, LoS channel, NFZ, convex optimization, separating hyperplane theorem.**

I. Introduction

Recently, unmanned aerial vehicles (UAVs) have attracted attention in many fields based on their low cost and mobility. There is no initial installation cost, so it can be deployed immediately. It can also perform tasks across various locations. Therefore, UAVs are used in fields such as communications, military, surveillance, and delivery [1], [2]. Accordingly, numerous studies have been conducted in the field of communication due to the advantage of enabling efficient communication by getting closer to the receiver and ensuring a line-of-sight (LoS) channel.

In particular, research has been conducted on UAV relay to service nodes outside the coverage of the base station [3]. Additionally, optimization of data dissemination using multiple UAVs [4] and energy harvesting using UAVs were studied [5]. In these studies, the channel of the UAVs was assumed to follow simplified channel models, such as a LoS channel or a small-scale fading channel model. In order to perform optimization that reflects real-world scenarios, studies have been conducted to optimize the communication task of UAVs by determining channels considering actual blockages. UAV communication optimization, which includes the constraint that service nodes must maintain the LoS channel in environments with existing buildings, was studied [6]. Additionally, by distinguishing between LoS and NLoS environments through building recognition, the resources of multiple UAVs were optimized for serving multiple nodes. [7]. Furthermore, optimization of service surveillance has also been studied.

Ensuring LoS is necessary not only for communication but also for surveillance and monitoring, which are other areas of use for UAVs. One study explored how a UAV could autonomously fly at a constant speed in a complex urban setting and monitor designated targets within the shortest possible time, taking into account various obstacles and environmental constraints [8]. However, flying the UAV at a constant speed significantly reduces the degrees of freedom in the optimization process. Another study was also conducted to capture surveillance areas with cameras and transmit images to the base station [9]. Nevertheless, assuming that the channel between a base station and UAV is LoS without considering blockages can lead to significant performance degradation in real-world scenarios where buildings exist.

In order to operate the practical UAV monitoring system, no-fly zones (NFZ) must be considered. The UAV must avoid areas such as military zones or structures like buildings to safely perform its mission. Circular and polygonal NFZs were considered [10], [11], and polygonal NFZs are handled through binary variables and the penalty method.

This paper considers practical UAV monitoring tasks in environments with blockages such as buildings. For efficient performance, the UAV's trajectory and transmit power allocation are optimized to maximize the minimum spectral efficiency during the flight time while maintaining LoS with the monitoring target and the central monitoring unit (CMU). There are constraints to avoid blockages for stable performance. We deal with the LoS maintenance and collision avoidance constraints with linear constraints through the separating hyperplane theorem.

The contributions of our study can be summarized as follows. First, we formulate a 3D UAV monitoring system in blockage-present environments. Here, the UAV must avoid blockages and transmit information about the monitoring target to the CMU at a high transmission rate. Constraints on collision avoidance and securing LoS for high data rates are generally non-convex. To solve this, we transform this problem into linear constraints using the separating hyperplane theorem. Then, we optimize the minimum spectral efficiency during the flight time typically used for stable information transmission. However, this can be seen as a less-optimized state from the perspective of overall performance. Therefore, we have improved both stability and performance to imple-

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (RS-2024-00343262).
The authors are with the Department of Information and Communication Engineering, Dongguk University, Seoul 04620, South Korea (e-mail: kslee851105@gmail.com).

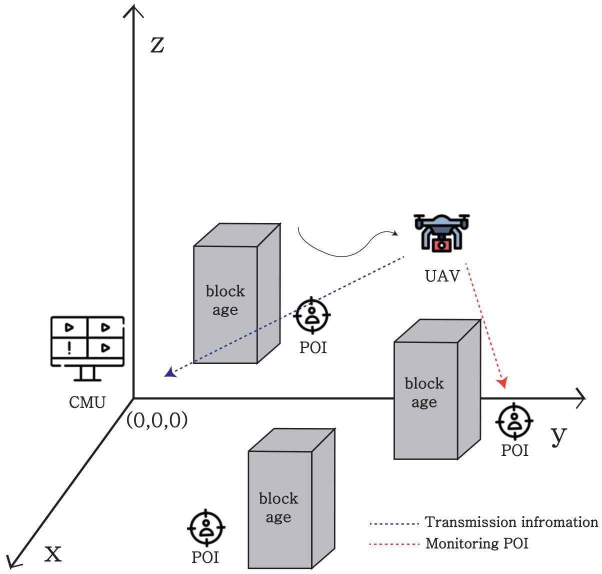


Fig. 1. A UAV monitoring system in an environment with blockages.

ment further optimization. Through simulation, it is confirmed that the proposed algorithm satisfies the avoidance collision and LoS securing constraints with only linear inequality by separating the hyperplane theorem. Additionally, through a comparison of the minimum spectral efficiency between the proposed method and other existing approaches, we confirmed that the proposed method enables more stable and efficient monitoring.

The remainder of this paper is organized as follows. In Section II, we present the system model of the 3D UAV monitoring system along with the problem statement. In Section III, we present the successive convex approximation (SCA) and separating hyperplane theorem to address the non-convexity of the problem. In Section IV, we verify the proposed algorithm and compare the performance gap with baseline schemes, leading to our conclusions in Section VI.

II. System Model

As shown in Fig. 1, there are a UAV and a CMU, the UAV photographs the predetermined point of interest (POI) and transmits the images to the CMU in real time. To make continuous flights mathematically tractable, we set the flight period of UAV to T and divide it into N time slots of sufficiently small and equal-length, $\delta = \frac{T}{N}$.

The 3D coordinates of UAV and CMU are given by $\mathbf{q}[n] = (q_x[n], q_y[n], q_z[n])$ and $\mathbf{w} = (0,0,0)$, respectively. UAV has velocity limitation so it can move $V_{\text{max}}\delta$ in one time slot, where V_{max} denotes the maximum speed of the UAV. UAV also has speed limitations in the z-axis, so it can move $V_{\text{max,z}}\delta$ in the z-axis, where $V_{\text{max,z}}$ denotes the maximum speed of UAV in the z-axis. Generally, $V_{\text{max}} > V_{\text{max,z}}$. Moreover, UAV flights from initial location $\mathbf{q}_{\text{str}}$ to final location $\mathbf{q}_{\text{dst}}$ at limited altitudes from minimum altitude H_{min} to maximum altitude H_{max}. Therefore, the following constraints must be satisfied.

$$\|\mathbf{q}[n] - \mathbf{q}[n-1]\| \le V_{\text{max}}\delta, \quad \forall n \in \mathcal{N}/\{1\}, \tag{1}$$

$$|q_z[n] - q_z[n-1]| \le V_{\text{max,z}}\delta, \quad \forall n \in \mathcal{N}/\{1\}, \tag{2}$$

$$\mathbf{q}[1] = \mathbf{q}_{\text{str}}, \tag{3}$$

$$\mathbf{q}[N] = \mathbf{q}_{\text{dst}}, \tag{4}$$

$$H_{\text{min}} \le q_z[n] \le H_{\text{max}}, \quad \forall n. \tag{5}$$

There are L rectangular blockages, the UAV must avoid them to successfully carry out its missions. The coordinates of UAV must not be in any blockage l at any time slot n. Let A_l denote l-th blockage space in 3D. Therefore, the collision avoidance constraint can be expressed as follows.

$$\mathbf{q}[n] \notin A_l \quad \forall l, n. \tag{6}$$

The channel between the UAV and CMU must be LoS because of the high-capacity image. In mathematical terms, the line segment connecting the coordinates of the UAV and the CMU must not meet any blockages in each time slot. The LoS channel ensuring constraint with the CMU can be expressed as follows.

$$\overline{\mathbf{q}[n]\mathbf{w}} \cap A_l = \emptyset, \quad \forall l, n, \tag{7}$$

where $\overline{\mathbf{q}[n]\mathbf{w}}$ denote the line segment connecting $\mathbf{q}[n]$ and $\mathbf{w}$.

In each time slot, the UAV must have all POI in its field of view. Similar to (7), the line segment connecting the UAV and POI must not intersect blockages in each time slot. Let the $\mathbf{I}[n]$ and $\mathbf{w}_{i[n]}$ denote a set of POIs at time slot n and coordinates of a POI, respectively. Therefore, at time slot n, the line segment connecting $\mathbf{w}_{i[n]}$, which is an element of $\mathbf{I}[n]$, and $\mathbf{q}[n]$ must not intersect blockages. The LoS constraint with the POIs can be expressed as follows.

$$\overline{\mathbf{q}[n]\mathbf{w}_{i[n]}} \cap A_l = \emptyset, \quad \forall l, n, \mathbf{w}_{i[n]} \in \mathbf{I}[n], \tag{8}$$

where $\overline{\mathbf{q}[n]\mathbf{w}_{i[n]}}$ denotes the line segment connecting $\mathbf{q}[n]$ and $\mathbf{w}_{i[n]}$.

The UAV is limited in the maximum power they can use at one time and the average power they consume. The power constraints of the UAV are as follows.

$$0 \le p[n] \le P_{\text{peak}}, \quad \forall n, \tag{9}$$

$$\sum_{n=1}^{N} p[n] \le P_{\text{avg}}, \tag{10}$$

where P_{avg} and P_{peak} are the average and peak power available to UAV, respectively.

Under the constraint that the UAV and CMU are always in LoS, the channel between UAV and CMU can be expressed as follows.

$$h[n] = \beta_0 \|\mathbf{q}[n] - \mathbf{w}\|^{-\alpha_L}, \tag{11}$$

where β_0 is channel gain at reference distance and α_L is LoS pathloss exponent.

The spectral efficiency of CMU at time slot n is the following.

$$R[n] = \delta \log_2 \left(1 + \frac{p[n]h[n]}{\sigma^2}\right), \tag{12}$$

where σ^2 denotes noise power.

In this study, our goal is to maximize minimum spectral efficiency among the time slots while maintaining the transmitting channel and interesting areas at LoS. To achieve this, we aim to optimize the UAV's transmit power $\mathbf{P} = \{p[n], \forall n\}$ and trajectory $\mathbf{Q} = \{\mathbf{q}[n], \forall n\}$. We can formulate the optimization problem as follows:

$$\textbf{(P0):} \quad \max_{R_{\min},\, \mathbf{P},\, \mathbf{Q}} \quad R_{\min}$$
$$\text{s. t.} \quad R[n] \geq R_{\min}, \quad \forall n, \tag{13}$$
$$(1) - (10).$$

III. Proposed Algorithm

Note that the constraint (6), (7), (8) and (13) are not jointly convex sets with respect to (w.r.t) $\mathbf{Q}$ and $\mathbf{P}$. Thus, **(P0)** is non-convex problem w.r.t $\mathbf{Q}$ and $\mathbf{P}$. In general, non-convex problems are difficult to solve. To solve this, we transform the non-convex sets into convex sets using quadratic transform and separating hyperplane theorem.

First, $R[n]$ is rewritten as an expression for $p[n]$ and $\mathbf{q}[n]$.

$$R[n] = \delta \log_2 \left(1 + \frac{p[n]\beta_0}{\sigma^2(\|\mathbf{q}[n] - \mathbf{w}\|^{\alpha_L})}\right). \tag{14}$$

Since the numerator of $R[n]$ is a non-negative concave and the denominator is a positive convex, we transform (13) into a convex set using quadratic transform [12].

$$\hat{R}[n] = \delta \log_2 \left(1 + 2y[n]\sqrt{p[n]\beta_0} - y^2[n]\sigma^2(\|\mathbf{q}[n] - \mathbf{w}\|^{\alpha_L})\right), \tag{15}$$

where $y[n]$ denote an auxiliary variable used in quadratic transform. For fixed $y[n]$, $\hat{R}[n]$ is concave function w.r.t $p[n]$ and $\mathbf{q}[n]$. The optimal solution can be obtained by alternately updating the main and auxiliary variables. The optimum of auxiliary variable $y[n]$ is obtained through closed form from $\frac{\partial \hat{R}[n]}{\partial y[n]} = 0$.

$$y^*[n] = \frac{\sqrt{p[n]\beta_0}}{\sigma^2(\|\mathbf{q}[n] - \mathbf{w}\|^{\alpha_L})}. \tag{16}$$

Next, we use the separating hyperplane theorem to solve the non-convexity of (6), (7), and (8). According to separating hyperplane theorem, there exists a hyperplane separating two disjoint convex sets. Specifically, the following proposition holds true.

Proposition 1: For two disjoint convex sets $\mathbf{A}$ and $\mathbf{B}$, hyperplane $(a^* - b^*)^T x - \frac{\|a^*\|^2 - \|b^*\|^2}{2}$ separates $\mathbf{A}$ and $\mathbf{B}$, where a^* and b^* are optimum of $\min_{a,b} \|a - b\|$ for $a \in \mathbf{A}, b \in \mathbf{B}$. Specifically, for any $a \in \mathbf{A}$, $(a^* - b^*)^T a - \frac{\|a^*\|^2 - \|b^*\|^2}{2} \geq 0$ holds, and for any $b \in \mathbf{B}$, $(a^* - b^*)^T b - \frac{\|a^*\|^2 - \|b^*\|^2}{2} \leq 0$ holds.

Proof: Please refer to the [13]. ■

This proposition suggests that if the two closest points between two disjoint convex sets are known, a hyperplane separating the two sets can be obtained. Specifically, a hyperplane that is perpendicular to the line connecting the closest points of the two disjoint convex sets and includes their midpoint separates the two sets. Also, the closest points between two convex sets can be obtained using optimization tools such as CVX because they are convex problems.

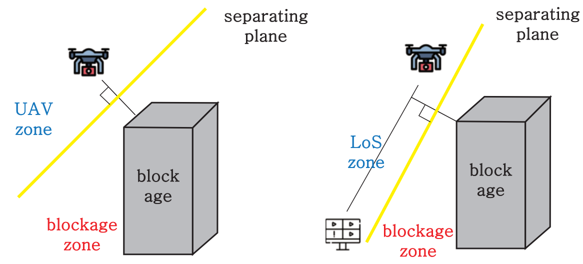


Fig. 2. Separating hyperplane theorem.

Since we previously assumed that the blockage is a cuboid, location of UAV $\mathbf{q}[n]$, location of CMU $\mathbf{w}$, and blockages space $\mathbf{A}_l$ are all convex sets. Thus, the planes that separate them can be obtained according to proposition 1. In the left part of Fig. 2, it can be seen that a plane divides the region containing the UAV and the blockage. Any point within the region containing the UAV, referred to as the UAV zone, does not collide with the blockage. In the right part, a plane is shown separating the line segment connecting the UAV and the CMU from the blockage. Any line segment within the region, referred to as the LoS zone, does not intersect with the blockage.

For avoiding collision constraint (6), it can be satisfied to avoid blockages by ensuring that $\mathbf{q}[n]$ belongs to the region where blockages do not belongs. According to proposition 1, we can find the area where blockages do not belong to solve the minimum distance problem between A_l and any convex set disjoint with A_l. The r-th $\mathbf{q}[n]$ value of the algorithm, $\mathbf{q}^r[n]$, is disjoint from A_l by utilizing the characteristics of SCA.

$$\textbf{(P-A):} \quad \min_{b} \quad \|\mathbf{q}^r[n] - b\|$$
$$\text{s. t.} \quad b \in A_l,$$

where b denote element of A_l. Let $b_l^*[n]$ be the optimum of **(P-A)**. According to proposition 1, The feasible region of inequality $(\mathbf{q}^r[n] - b_l^*[n])^T x - \frac{\|\mathbf{q}^r[n]\|^2 - \|b_l^*[n]\|^2}{2} \geq 0$ does not contain elements of blockages. Therefore, the collision avoidance constraint can be replaced by the following inequality.

$$(\mathbf{q}^r[n] - b_l^*[n])^T \mathbf{q}[n] - \frac{\|\mathbf{q}^r[n]\|^2 - \|b_l^*[n]\|^2}{2} > 0, \ \forall n, l. \tag{17}$$

For LoS channel between UAV and CMU constraint (7), it can be satisfied to maintain LoS by ensuring that the solution of the $\mathbf{q}[n]$ belongs LoS area of CMU. To find the area, we need to solve the following minimum distance problem between $\overline{\mathbf{q}[n]\mathbf{w}}$ and A_l.

$$\textbf{(P-B):} \min_{\hat{a},\hat{b}} \ \|\hat{a}-\hat{b}\| \quad \text{s. t.} \ \ \hat{a} \in \overline{\mathbf{q}[n]\mathbf{w}}, \quad \hat{b} \in A_l.$$

Let $\hat{a}_l^*[n]$ and $\hat{b}_l^*[n]$ be the optimum of **(P-B)**. The feasible region of inequality $(\hat{a}_l^*[n]-\hat{b}_l^*[n])^T\mathbf{q}[n]-\frac{\|\hat{a}_l^*[n]\|^2-\|\hat{b}_l^*[n]\|^2}{2} \geq 0$ is convex set and does not contain elements of blockages. In addition $\mathbf{w}$ belongs to this region. Thus for any feasible x, $\overline{x\mathbf{w}}$ does not meet blockage l. As a result, LoS channel between UAV and CMU constraint can be replaced by the following inequality.

$$(\hat{a}_l^*[n]-\hat{b}_l^*[n])^T\mathbf{q}[n]-\frac{\|\hat{a}_l^*[n]\|^2-\|\hat{b}_l^*[n]\|^2}{2}>0, \ \forall n,l. \quad (18)$$

Similar to the principle applied in constraint (7), for LoS between UAV and POI constraint (8), we need to solve the following minimum distance problem between $\overline{\mathbf{q}[n]\mathbf{w}_{i[n]}}$ and A_l.

$$\textbf{(P-C):} \min_{\tilde{a},\tilde{b}} \ \|\tilde{a}-\tilde{b}\| \quad \text{s. t.} \ \ \tilde{a} \in \overline{\mathbf{q}[n]\mathbf{w}_{i[n]}}, \quad \tilde{b} \in A_l.$$

Let $\tilde{a}_{l,\mathbf{w}_{i[n]}}^*[n]$ and $\tilde{b}_{l,\mathbf{w}_{i[n]}}^*[n]$ be the optimum of **(P-C)**. Likewise, LoS between UAV and POI constraint can be replaced by the following inequallity.

$$(\tilde{a}_{l,\mathbf{w}_{i[n]}}^*[n]-\tilde{b}_{l,\mathbf{w}_{i[n]}}^*[n])^T\mathbf{q}[n] -\frac{\|\tilde{a}_{l,\mathbf{w}_{i[n]}}^*[n]\|^2-\|\tilde{b}_{l,\mathbf{w}_{i[n]}}^*[n]\|^2}{2}>0, \quad \forall n,l,\mathbf{w}_{i[n]} \in \mathbf{I}[n]. \quad (19)$$

Now, problem **(P0)** can be reformulated as the following convex problem.

$$\textbf{(P1):} \max_{R_{\min},\ \mathbf{Y},\ \mathbf{P},\ \mathbf{Q}} \ R_{\min} \quad \text{s. t.} \ \ \hat{R}[n] \geq R_{\min}, \ \forall n, \ (1)-(5), \ (9)-(10). \ (17)-(19),$$

where $\mathbf{Y}$ denote set of auxiliary variables $y[n]$, i.e. $\{y[n], \forall n\}$. When $y[n]$ is fixed, the problem **(P1)**, in which non-convex constraints are replaced with convex constraints by quadratic transform and separating hyperplane theorem, is a convex problem. Thus, it can be solved iteratively using convex problem solver such as CVX [14] until convergence.

Remark 1: Let $R_{\min}^*$ be the optimum obtained by repeatedly solving **(P1)**. It is the result of maximizing the minimum SE among time slots, but it cannot be guaranteed that it is optimal from an overall performance perspective. Therefore, we performed additional optimization in the proposed method by changing the objective expression to $\sum_{n=1}^{N}\hat{R}[n]$, while ensuring that the minimum value among the time slots is greater than $R_{\min}^*$. Fig. 3 illustrates the spectral efficiency and transmit power over flight time for two approaches: solving the **(P1)** problem iteratively (Only P1), and solving the **(P1)** problem to obtain $R_{\min}^*$, followed by solving the **(P2)** problem (P1 and P2). Both approaches have the same total power consumption and minimum spectral efficiency, but the P1 and P2 approach shows a higher sum rate and overall better performance.

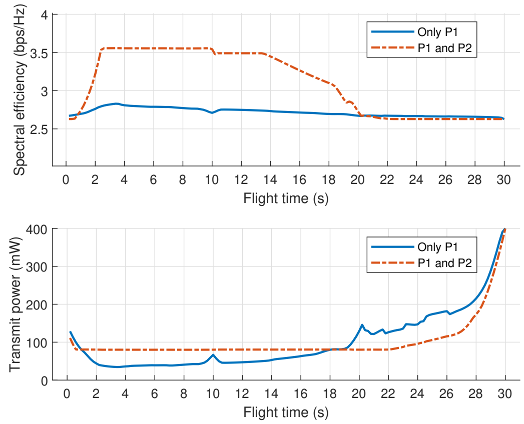


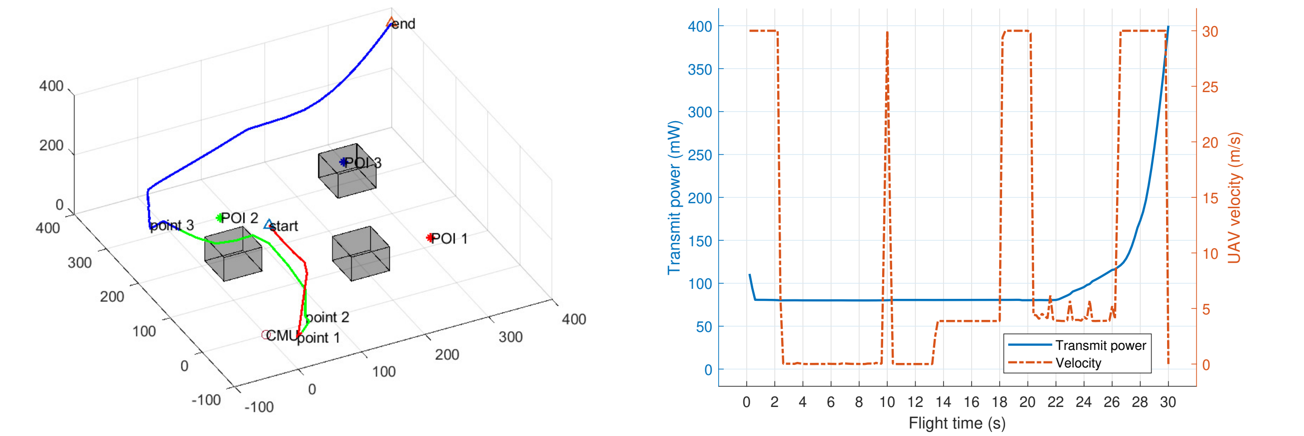
Fig. 3. Spectral efficiency and resource allocation comparison over flight time between the two approaches.

$$\textbf{(P2):} \max_{\mathbf{Y},\ \mathbf{P},\ \mathbf{Q}} \ \sum_{n=1}^{N}\hat{R}[n] \quad \text{s. t.} \ \ \hat{R}[n] \geq R_{\min}^*, \ \forall n, \ (1)-(5), \ (9)-(10), \ (17)-(19).$$

Algorithm 1 Proposed Optimization Algorithm

Set $r = 1$
Initialize $\mathbf{Q}^r$, $\mathbf{P}^r$
Calculate $f^r = \min_n R[n]$
repeat
  Update $r \leftarrow r+1$
  Update $f^{\text{old}} \leftarrow f^{r-1}$
  Find hyperplanes by solving **(P-A)**, **(P-B)** and **(P-C)**
  Calculate optimal value of $\mathbf{Y}$ according to (16)
  Find $\mathbf{Q}^r$ and $\mathbf{P}^r$ by solving **(P1)** for given $\{\mathbf{Q}^{r-1}, \mathbf{P}^{r-1}\}$
  Calculate $f^r = \min_{k\in\{1,2,\dots,N\}} R[n]$
until $|f^r - f^{\text{old}}| < \epsilon$
Initialize $\mathbf{Q}^r$, $\mathbf{P}^r$
Calculate $f^r = \sum_{n=1}^{N} R[n]$
repeat
  Update $r \leftarrow r+1$
  Update $f^{\text{old}} \leftarrow f^{r-1}$
  Find hyperplanes by solving **(P-A)**, **(P-B)** and **(P-C)**
  Calculate optimal value of $\mathbf{Y}$ according to (16)
  Find $\mathbf{Q}^r$ and $\mathbf{P}^r$ by solving **(P2)** for given $\{\mathbf{Q}^{r-1}, \mathbf{P}^{r-1}\}$
  Calculate $f^r = \sum_{n=1}^{N} R[n]$
until $|f^r - f^{\text{old}}| < \epsilon$

Algorithm 1 summarizes the detailed procedure of the proposed method. The optimal value sequences in **(P1)** and **(P2)** have a non-decreasing nature because they are convex problem. It is also bounded due to power constraints and system characteristics. Therefore, convergence of Algorithm 1 is guaranteed.



(a) 3D UAV trajectory

(b) UAV transmit power and velocity

Fig. 4. UAV Resource allocation of the proposed scheme.

IV. Simulation Results

For performance evaluations, we consider the following parameters as default values: $T = 30$ s, $\delta = 0.2$ s, $N = 150$, $L = 3$, $H_{\text{min}} = 20$ m, $\sigma^2 = -100$ dBm , $V_{\text{max}} = 30$ m/s, $V_z = 15$ m/s, $P_{\text{avg}} = 20$ dBm, $P_{\text{peak}} = 4P_{\text{avg}}$, $\beta_0 = 10^{-3}$, $\epsilon = 0.001$, $\mathbf{q}_{\text{str}} = (10, 10, 350)$, $\mathbf{q}_{\text{dst}} = (400, 400, 350)$, the coordinates of the POI, $\mathbf{w}_1 = (320, 120, 0)$, $\mathbf{w}_2 = (80, 300, 0)$ and $\mathbf{w}_3 = (300, 350, 0)$. Also, $\mathbf{w}_1 \in \mathbf{I}[n]$, $\forall 1 \leq n \leq 50$, $\mathbf{w}_2 \in \mathbf{I}[n]$, $\forall 50 \leq n \leq 100$, $\mathbf{w}_3 \in \mathbf{I}[n]$ and $\forall 100 \leq n \leq 150$.

For performance comparisons, the following five schemes are considered:

1) *Proposed scheme (Proposed)*: The UAV trajectory $\mathbf{Q}$ and transmit power $\mathbf{P}$ are found by Algorithm 1.
2) *Baseline scheme I (Fixed Q)*: The transmit power $\mathbf{P}$ is found by Algorithm 1, while the UAV flies in a straight line at a constant speed from the starting point $\mathbf{q}_{\text{str}}$ to the ending point $\mathbf{q}_{\text{dst}}$.
3) *Baseline scheme III (Fixed P)* : The UAV trajectory $\mathbf{Q}$ is found by Algorithm 1, while transmit power for every time slot is fixed at P_{avg}.
4) *Baseline scheme IV (Fixed All)* : The transmit power for every time slot is fixed at P_{avg} and UAV flies in a straight line at a constant speed from the starting point $\mathbf{q}_{\text{str}}$ to the ending point $\mathbf{q}_{\text{dst}}$.

Fig. 4 shows the resource allocation of the proposed scheme : (a) 3D UAV trajectory and (b) UAV transmit power and velocity. UAV must monitor POI 1 from 1 to 10 seconds, POI 2 from 10 to 20 seconds, and POI 3 from 20 to 30 seconds. Additionally, the red, green, and blue UAV trajectories represent from 1 to 10 seconds, 10 to 20 seconds, and 20 to 30 seconds, respectively. The UAV flies at maximum velocity from the starting point to point 1. Here, the UAV does not fly directly to point 1, as it maintains a LoS with both the CMU and POI 1 simultaneously during the flight. Then, during the 8 seconds, it hovers at that location, point 1, which maintains LoS with both the CMU and POI 1 simultaneously while being the closest point to the CMU. This movement of the UAV occurs to maximize the transmission rate while satisfying the LoS guarantee constraints. Next, when monitoring POI 2, it hovers at point 2, which also maintains LoS with both the CMU and POI 2 simultaneously while being the closest point to the CMU. However, this time, it hovers for only 2 seconds before moving, in order to prepare for monitoring POI 3 during the 20 to 30 second interval. After 20 seconds, the UAV flies continuously without stopping to reach the end point. the flight altitude is increased not only to ensure LoS but also as the UAV moves farther from the CMU to reach the end point, further deteriorating the channel. To compensate for this, the UAV increases its transmit power as the flight time approaches the end. Here, we can see that the UAV provides efficient communication with LoS guarantee and collision avoidance.

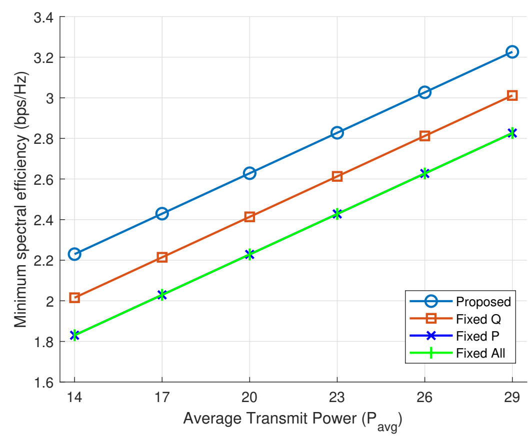


Fig. 5. Performance comparison between the proposed and base schemes for UAV transmit power.

Fig. 5 shows the minimum achievable spectral efficiency of proposed and base schemes for average transmit power P_{avg}. Regardless of all schemes, as P_{avg} increases, the minimum achievable spectral efficiency also increases. This is because, as the average available power for the UAV increases, the power allocated to the time slots with low spectral efficiency increases. The Fixed all scheme and the Fixed P scheme show the worst performance. This confirms that power allocation optimization is crucial for enhancing the minimum spectral efficiency in environments with blockages. Fixed Q shows the best performance among the base schemes, but the proposed scheme outperforms all. This demonstrates that not only power optimization but also UAV trajectory optimization is crucial for maximizing the minimum spectral efficiency. From Fig. 5, we can see that the proposed scheme provides efficient resource allocation for communication while satisfying the constraints.

V. Conclusions

In this paper, we investigated the joint optimization of the UAV trajectory and transmit power in UAV monitoring system while avoiding collision, ensuring LoS channel with CMU and LoS with PoI are satisfied for stable and efficient task. It is difficult to solve this problem because it contains non-convex constraints, specifically, collision avoidance and LoS coverage constraints. Unlike previous studies that used the introduction of binary variables or regression function approximation to address non-convexity of them, we propose linear inequalities using the separating hyperplane theorem and explain they ensure collision avoidance and LoS guarantee constraints are satisfied. Moreover, we made the problem a convex function by applying quadratic transform to the objective equation. To obtain optimal solution, transformed problem is optimized iteratively based on SCA. The simulation results show that proposed algorithm satisfies the constraints and performs better than existing schemes.

References

[1] S. Hayat, E. Yanmaz, and R. Muzaffar, “Survey on unmanned aerial vehicle networks for civil applications: A communications viewpoint,” *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2624-2661, 4th Quart., 2016.

[2] Y. Zeng, R. Zhang, and T. J. Lim, “Wireless communications with unmanned aerial vehicles: Opportunities and challenges,” *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 36-42, May 2016.

[3] S. Zhang, H. Zhang, Q. He, K. Bian, and L. Song, ”Joint trajectory and power optimization for UAV relay networks,” *IEEE Commun. Lett.*, vol. 22, no. 1, pp. 161-164, Jan. 2018.

[4] Q. Wu, Y. Zeng, and R. Zhang, ”Joint trajectory and communication design for multi-UAV enabled wireless networks,” *IEEE Trans. Wireless Commun.*, vol. 17, no. 3, pp. 2109-2121, Mar. 2018.

[5] Z. Yang, W. Xu, and M. Shikh-Bahaei, ”Energy efficient UAV communication with energy harvesting,” *IEEE Trans. Veh. Technol.*, vol. 69, no. 2, pp. 1913-1927, Feb. 2020.

[6] Y. Cai, W. Yuan, Z. Wei, C. Liu, S. Hu, and D. W. K. Ng, ”Trajectory design and resource allocation for UAV-enabled data collection in wireless sensor networks with 3D blockages,” in *Proc. 1st Int. Conf. 6G Netw. (6GNet)*, Paris, France, 2022, pp. 1-8.

[7] P. Yi, L. Zhu, Z. Xiao, R. Zhang, Z. Han, and X.-G. Xia, ”Trajectory design and resource allocation for multi-UAV communications under blockage-aware channel model,” *IEEE Trans. Commun.*, vol. 72, no. 4, pp. 2324-2338, Apr. 2024.

[8] E. Semsch, M. Jakob, D. Pavlicek, and M. Pechoucek, ”Autonomous UAV surveillance in complex urban environments,” in *Proc. IEEE/WIC/ACM Int. Jt. Conf. Web Intell. Intell. Agent Technol.*, Milan, Italy, 2009, pp. 82-85.

[9] N. V. Cuong, Y. W. P. Hong, and J. P. Sheu, ”UAV trajectory optimization for joint relay communication and image surveillance,” *IEEE Trans. Wireless Commun.*, vol. 21, no. 12, pp. 10177-10192, Dec. 2022.

[10] R. Li, Z. Wei, L. Yang, D. W. K. Ng, J. Yuan, and J. An, ”Resource allocation for secure multi-UAV communication systems with multi-eavesdropper,” *IEEE Trans. Commun.*, vol. 68, no. 7, pp. 4490-4506, Jul. 2020.

[11] D. Xu, Y. Sun, D. W. K. Ng, and R. Schober, ”Multiuser MISO UAV communications in uncertain environments with no-fly zones: Robust trajectory and resource allocation design,” *IEEE Trans. Commun.*, vol. 68, no. 5, pp. 3153-3172, May 2020.

[12] K. Shen and W. Yu, ”Fractional programming for communication systems–Part I: Power control and beamforming,” *IEEE Trans. Signal Process.*, vol. 66, no. 10, pp. 2616-2630, May 2018.

[13] T. Lipp and S. Boyd, ”Variations and extension of the convex-concave procedure,” *Optim. Eng.*, vol. 17, no. 2, pp. 263-287, 2016.

[14] M. Grant and S. Boyd. (2017). *CVX: MATLAB software for disciplined convex programming, version 2.1.* [Online]. Available: http://cvxr.com/cvx.