Throughput Maximization of Mixed FSO/RF UAV-aided Mobile Relaying with a Buffer

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Abstract

In this paper, we consider an unmanned aerial vehicle (UAV) aided mobile relaying system under a buffer constraint. We propose a new relaying protocol employing mixed free-space optical/radio frequency (FSO/RF) communication, i.e., the source-relay and relay-destination links utilize FSO and RF links, respectively, under the buffer constraint at the UAV relay node. Taking the conditions of an imbalance in transmission rate between RF and FSO links into consideration, we study the trajectory optimization problem of buffer-constrained UAV relay node in order to maximize the end-to-end data throughput. Especially, we classify two relaying transmission schemes according to the delay requirements, i.e., (i) delay-limited transmission and (ii) delay-tolerant transmission. We solve the locally optimal trajectory problem of the UAV to maximize the throughput of ground user terminal. As a result, we propose an iterative algorithm that efficiently finds a local optimum solution for the throughput maximization problems. Through this algorithm, we present the resulting trajectories over the atmospheric condition, the buffer size, and the delay requirement. Also, we show the optimum buffer size and the throughput-delay tradeoff for a given system. Our numerical results validate that the proposed buffer-aided mobile relaying scheme achieves 65.55% throughput gains compared to conventional static relaying scheme.

Index Terms

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Mixed FSO/RF communication, UAV-aided mobile relaying, throughput maximization, buffer constraint, delay-considered design.

I. INTRODUCTION

As it becomes easier to implement unmanned aerial vehicles (UAVs), UAV-aided mobile relaying systems have attracted great research interest [1]. Motivated by the mounting interest in the unmanned flying platforms, a UAV-enabled mobile relaying framework have been proposed to transport the backhaul/fronthaul traffic between the access and core networks [2]–[4]. Compared to a conventional static relaying system, the mobile relaying has several key advantages. Above all, cost-effectiveness and easy deployment make the mobile relaying systems especially suitable for unexpected or temporary events, such as emergency response, disaster recovery, military operation, etc. In addition, its high mobility offers new opportunities for delay-tolerant applications (e.g., periodic sensing, large data uploading/downloading) and performance improvements through the dynamic relay relocations to achieve the better communication environment. In particular, the authors in [5] identified that the mobile relaying offers a new degree of freedom for performance enhancement compared with conventional static relaying, via careful relay trajectory design. Based on the result of [5], a few works including [6]–[8] have focused on utilizing mobile relaying system in various applications.

Especially in fifth-generation (5G) and future wireless networks, wireless backhaul/fronthaul networks are required to meet ultra high rate requirements, particularly in the presence of ultra-dense heterogeneous small cells. Accordingly, several groups of IT industry and academia have focused on this challenge and investigated a free-space optical communication (FSO)-based UAV-enabled relaying as a promising solution [9]–[11]. Extensive works have considered the FSO based communication as an attractive solution to explosive rate requirements in communications and have studied mixed RF/FSO system to take advantage of both RF and FSO links. The authors in [12]–[14] investigated the end-to-end performance analysis of the mixed RF/FSO especially in dual-hop communication system. In [12], [13], the authors provided a generalized framework for performance analysis of mixed RF/FSO systems adopting the most generalized turbulent fading model. Based on the high signal-to-noise-ratio (SNR) analysis, the authors also provided a diversity gain analysis and discussed the bottlenecks in the mixed RF/FSO systems. The result of [14] have demonstrated that pointing error and severe weather turbulence conditions in
mixed RF/FSO link become more tolerable with the existence of the relay’s buffer, furthermore, buffering in the physical layer provides a significant enhancement to the system performance.

The previous works in [14]–[16] focused on the buffer-aided relaying to take advantages of the buffering. The authors in [15] proposed a new protocol exploiting both relay buffering and mobility to enhance the system throughput and the end-to-end packet delay under bursty arrivals. In addition, the works in [16] suggested the design of FSO-based buffer-aided cooperative protocols, and showed that equipping the FSO relays with buffers constitutes an additional degree of freedom (DoF) that significantly enhances the performance at the expense of increased delays. Not only just buffer constraints, but also average delay have been considered in the buffer-aided relaying system [17], [18]. In [17], the two buffer-aided relaying protocols are investigated which focus on the relay node for data link and the relay node for energy harvesting, respectively. Specifically, the relay node is assumed to possess a data buffer to store the received information temporarily, in addition, to be equipped with an energy buffer and can temporarily store the harvested energy. This work showed the performance analysis of average achievable rate, average data buffer size, and average delay, and presented the throughput-delay tradeoff for the buffer-aided relaying system. We note that, in addition to [17], studies on the throughput-delay tradeoff of wireless mobile relay networks have been also discussed in [19], [20].

With the aim of designing a suitable delay-considered system for the delay-constrained application, [18] studied two transmission schemes, e.g., delay-limited and delay-tolerant designs. The data transmission scheme can be classified as either delay-tolerant or delay-limited (e.g., real-time) transmission. Delay-limited traffic supports delay-sensitive services, which include voice over internet protocol, video conferencing, and monitoring of critical processes such as medical packet [21]. On the other hand, delay-tolerant traffic does not carry an urgency and can be served when the reliable reception is important, such as email, instant messages, or sensor data in periodic sensing [22]. In [18], specifically, a hybrid RF/FSO backhaul link transmits and forwards the information for given delay requirements. The authors discussed the optimal fixed and adaptive link allocation policies for both delay-limited and delay-tolerant transmission.

By taking the aforementioned advantages of mobile relaying, buffer-aided relaying, and delay-considered transmission relaying, we consider the scenario of dual-hop mixed FSO/RF backhauling with the help of UAV, which can be a promising solution to the emerging wireless backbone network as discussed in [9], [13]. In such a scenario, we study on the throughput of a new mixed FSO/RF-based mobile relaying system. In order to deal with the packet delay due to the
imbalance in achievable data rate between FSO and RF links according to relay’s position, we
further consider both buffer and average delay constraints on this system. Specifically, the main
contributions of this work are summarized as below:

• We look into the scenario illustrated in Fig. 1 where dual-hop mixed FSO/RF communications
are conducted on UAV-aided relaying with a limited buffer constraint. Especially, considering the
conditions of the mixed FSO/RF systems (e.g., an imbalance in transmission rate between RF and
FSO links, full-duplex decode-and-forward relaying, and atmospheric attenuation), we address the
trajectory optimization problems for the throughput maximization in this system. To the best of our
knowledge, there is no open literature to address the optimization problem of the buffer-aided mobile
relaying system in mixed FSO/RF links.

• Furthermore, we consider buffer constraints to account for practical relay transmission
situations and the data rate imbalance induced from mixed FSO/RF system which uses
different types of link (i.e., FSO link for source-to-relay and RF link for relay-to-destination).
As well as the buffer constraint, we design the system by classifying the relay transmission
schemes (i.e., delay-tolerant transmission and delay-limited transmission) according to the
delay-time requirements of the network. Specifically, we design the system based on the
main service metric of the buffer constraint (e.g., average delay, drop rate or current queue
size).

• To tackle these non-convex trajectory optimization problems, we propose an iterative algo-

rithm by adopting the successive optimization method to obtain the locally optimal solution.
Then, the trajectories can be determined by applying quadratically constrained programming
(QCP).

• Under the different conditions, e.g., visibility, buffer size, and delay limit, the simulation
results for throughput maximized trajectories are presented. Also, based on the buffer and
delay-constrained system, the throughput-delay and the throughput-buffer tradeoff. Conse-
quently, we validate the superiority of the proposed scheme compared to the conventional
schemes (e.g., static relaying and data-ferrying relaying) according to the simulation and
numerical results.

The remainder of the paper is organized as follows: In Section II, the system model for the
FSO and RF link and the metrics for the buffer constraint of dual-hop mixed FSO/RF network are
presented. The throughput maximization problem for buffer-aided mobile relaying is formulated
Fig. 1. Illustration of dual-hop mixed FSO/RF communication with the help of a UAV-assisted relay.

and optimized by two delay-considered transmission schemes (e.g., delay-limited transmission
and delay-tolerant transmission) in Section III. In Section IV numerical results are presented,
and concluding remarks are drawn in Section V.

Notation: Throughout this paper, we use the normal-face font to denote scalars, and boldface
font to denote vectors. We use \( \mathbb{R}^{D \times 1} \) to represent the \( D \)-dimensional space of real-valued vectors.
We also use \( \| \cdot \| \) to denote the \( L^2 \)-norm (i.e., an Euclidean norm) and \( \log(\cdot) \) to represent a natural
logarithm. The expression \( O(\cdot) \) stands for describing the Big O notation.

II. SYSTEM MODEL

We consider a dual-hop mixed FSO/RF communication via a UAV-assisted relay as illustrated
in Fig. 1. Specifically, the UAV-aided relay node employs FSO link for receiving information
from a backhaul terminal and RF link for forwarding information to a user terminal. Based on
three dimensional Cartesian coordinates for the location of the terminals, we assume that the
backhaul terminal and the user terminal are located at position \( \mathbf{q}_S = [0, 0, 0]^T \) and \( \mathbf{q}_D = [L, 0, 0]^T \),
respectively, while the UAV flies at a constant altitude of \( H \) within a predetermined maximum
speed \( V_{\text{max}} \) and acceleration \( A_{\text{max}} \) for a period \( T \). The time-varying coordinate of the UAV node
can be denoted as \( \mathbf{q}_R(t) = [x_R(t), y_R(t), H]^T \in \mathbb{R}^{3 \times 1} \), \( 0 \leq t \leq T \).

For ease of analysis, we consider a discrete-time model as in [1]. The time horizon \( T \) is
divided into \( N \) time intervals each with duration \( \delta_t \), i.e., \( T = N \cdot \delta_t \). The duration \( \delta_t \) is chosen to
be sufficiently small so that the UAV’s location can be adequately approximated within each slot,

\(^1\) We can also consider the opposite uplink situation, e.g., FSO for forwarding information to the backhaul terminal and
RF link for receiving information from the user terminal(s), such as the application of information collection. Note that the
extension of the mixed FSO/RF UAV-enabled mobile relaying design to the more general cooperative system remains to be our
future work.
i.e., \( q_R[n] \triangleq q_R(n \delta_t) = [x_R(n \delta_t), y_R(n \delta_t), H]^T = [x_R[n], y_R[n], H]^T \in \mathbb{R}^{3 \times 1}, 0 \leq n \leq N + 1. \)

Note that \( n = 0 \) and \( n = N + 1 \) denote the initial time slot and final time slot, respectively.

In the following, we present channel and transmission rate models for FSO and RF communication, respectively, and introduce a buffer constraint that describes the queuing system of a practical relay with a finite size of the buffer.

A. System Model for the FSO Link

In FSO, the channel gain at a link distance \( l_{FSO} \), based on the Beer-Lambert Law \( ^2 \), can be expressed as

\[
h_{FSO}[n] = e^{-\beta_{FSO}[n]} = e^{-\beta ||q_R[n] - q_s||}, \forall n,
\]

where \( \beta_{dB} = \frac{2.91}{V} \left( \frac{\lambda}{550 [\text{nm}]} \right)^p \) [dB/km] value depends on the wavelength \( \lambda \) assumed to be 1550 [nm] in this paper, \( V \) is the visibility in [km], and the size distribution coefficient \( p \) determined by Kim model [23]. Note that \( \beta = \log_{10} \frac{\beta_{dB}}{10^{4}} \) [m\(^{-1}\)].

While the capacity of FSO channel has not been known in a closed-form, capacity bounds of FSO have been proposed in several papers. In this paper, we use the lower bound of FSO capacity introduced in [24] to describe data rate of FSO link between source and relay. The average optical SNR (ASNR) is denoted as \( \gamma_{FSO}^2 = \frac{\varepsilon^2}{\sigma_{FSO}^2} \) where \( \varepsilon \) and \( \sigma_{FSO}^2 \) are the average optical power and noise variance for FSO, respectively. The parameter, \( k_1 \), related to ASNR and parameter, \( k_2 \), related to attenuation condition are formulated, respectively, as

\[
k_1 = \begin{cases} 
\frac{\varepsilon^2 \mu^*}{2\pi e} \left( 1 - e^{-\mu^*} \right) & \text{if } 0 < \alpha < \frac{1}{2}, \\
\frac{\gamma_{FSO}^2}{2\pi e \alpha^2} & \text{if } \frac{1}{2} < \alpha < 1 
\end{cases}
\]

\( k_2 = 2\beta. \)

Note that \( \mu \) is the free parameter which indicates the solution to the equation \( \alpha = \frac{1}{\mu^*} - \left( \frac{e^{-\mu^*}}{1-e^{-\mu^*}} \right) \) when the average-to-peak ratio (APR) is set to \( \alpha = \frac{\varepsilon}{\Lambda} \) where \( \Lambda \) is peak optical power.

The transmission rate of FSO in bits/second (bps) for the time slot \( n \) can be expressed with the channel gain for FSO link in (1), the parameters in (2) and (3), the bandwidth in hertz (Hz) of FSO link \( B_{FSO} \), and the received ASNR \( \tilde{\gamma}_{FSO}^2 = h_{FSO}^2 \cdot \gamma_{FSO}^2 \) as follows:

\footnote{Note that if other attenuation factors, e.g., rain, snow and haze, need to be considered, the optimization framework can be solved by adjusting only some parameters, e.g., \( \beta \) or \( k_2 \).}
\[ R_{\text{FSO}}[n] = \frac{B_{\text{FSO}}}{2\log2} \cdot \log \left( 1 + k_1 e^{-k_2 \|qR[n]-qS\|} \right) \text{ [bps]}, \]
\[ \forall n. \] (4)

**B. System Model for the RF Link**

The channel gain of RF link \( h_{\text{RF}} \) between UAV and the user terminal can be expressed as

\[ h_{\text{RF}}[n] = \sqrt{\tau_{\text{RF}}[n]} \cdot \tilde{h}_{\text{RF}}[n], \quad \forall n, \] (5)

where \( \tau_{\text{RF}}[n] \) and \( \tilde{h}_{\text{RF}}[n] \) account for the effect of large-scale fading (e.g., path loss and shadowing), and the effect of small-scale fading with \( \mathbb{E}\{ |\tilde{h}_{\text{RF}}[n]|^2 \} = 1 \), respectively. Furthermore, for UAV-ground RF link, the large-scale attenuation is usually modeled with the probabilities of LoS and non-LoS (NLoS) links. As in [25], \( \tau_{\text{RF}}[n] \) can be expressed by

\[
\tau_{\text{RF}}[n] = \begin{cases} 
\beta_0 l_{\text{RF}}^{-\tilde{\alpha}}[n], & \text{LoS link,} \\
\kappa \beta_0 l_{\text{RF}}^{-\tilde{\alpha}}[n], & \text{NLoS link,}
\end{cases} \tag{6}
\]

where \( \beta_0 \) represents the received power at the reference distance \( d_0 = 1 \text{ [m]} \), \( l_{\text{RF}} \) denotes a link distance between \( R \) and \( D \), \( \tilde{\alpha} \) is the path loss exponent, \( \tilde{\alpha} \geq 2 \), and \( \kappa \) is an additional attenuation factor due to the NLoS link. As a result, \( h_{\text{RF}}[n] \) is a random variable with random occurrence of LoS and NLoS, as well as the random small-scale fading. Accordingly, the expected channel gain by averaging over both randomness is, as expressed in [26],

\[
\mathbb{E}\{ |h_{\text{RF}}[n]|^2 \} = \hat{P}_{\text{LoS}}[n] \beta_0 l_{\text{RF}}^{-\tilde{\alpha}}[n], \quad \forall n. \tag{7}
\]

where \( \hat{P}_{\text{LoS}}[n] = P_{\text{LoS}}[n]+(1-P_{\text{LoS}}[n])\kappa \), and \( P_{\text{LoS}}[n] = \frac{1}{1+C_1 \exp(-D_1|\theta[n] - \theta_0|)} \) is the LoS probability between UAV and the user terminal in which \( C \) and \( D \) are the parameters depending on the propagation condition, and \( \theta[n] = \frac{180}{\pi} \sin^{-1}(H/l_{\text{RF}}[n]) \) is the elevation angle in degree.

The achievable rate in bps between UAV and the user terminal with the constant transmission power \( P \) at time slot \( n \) is expressed as

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3 Note that, due to the shadowing effect and the reflection of signals from obstacles, different large-scale attenuation models need to be considered for LoS and NLoS links.

4 \( \tilde{\alpha} \) represents the more general path loss exponent \( \tilde{\alpha} \geq 2 \), rather than the special case of \( \tilde{\alpha} = 2 \) which only consider free-space condition considered.
\[ \hat{R}_{RF}[n] = \frac{B_{RF}}{\log 2} \cdot \log \left( 1 + \frac{P|h_{RF}[n]|^2}{\sigma_{RF}^2} \right) \text{ [bps]}, \quad \forall n, \quad (8) \]

where \( B_{RF} \) represents the RF bandwidth in Hz, and \( \sigma_{RF}^2 \) is the noise variance for RF. Note that as the channel gain \( h_{RF}[n] \) is the random variable, \( R_{RF}[n] \) is also a random variable. Using the concavity of (8) and the Jensen’s inequality, we have

\[ \mathbb{E}\{\hat{R}_{RF}[n]\} \leq \sum_{n=1}^{N} \frac{B_{RF}}{N \log 2} \cdot \log \left( 1 + \frac{P\mathbb{E}\{|h_{RF}[n]|^2\}}{\sigma_{RF}^2} \right) \]

\[ = \sum_{n=1}^{N} \frac{B_{RF}}{N \log 2} \cdot \log \left( 1 + \frac{\tilde{\gamma}_0 \hat{P}_{LoS}[n]}{\|q_D - q_R[n]\|^\alpha} \right), \quad (9) \]

where \( \tilde{\gamma}_0 \triangleq \beta_0 \cdot \frac{P}{\sigma_{RF}^2} \). It can be found that (10) depends on the UAV location \( q_R[n] \) not only over \( l_{RF}[n] \), but also over \( \hat{P}_{LoS}[n] \). For this reason, it is challenging to handle (10) directly. To resolve this issue, we use the homogeneous approximation of the LoS probability, i.e., \( \hat{P}_{LoS}[n] \simeq \bar{P}_{LoS}, \forall n \), as in [26]. Note that \( \bar{P}_{LoS} \) could be the value corresponding to the most likely elevation angle or the average value based on certain heuristic UAV trajectory. Accordingly, (10) can be rewritten as

\[ \tilde{R}_{RF} = \sum_{n=1}^{N} \frac{B_{RF}}{N \log 2} \cdot \log \left( 1 + \frac{\tilde{\gamma}_0}{\|q_D - q_R[n]\|^\alpha} \right) \text{ where } \tilde{\gamma}_0 \triangleq \gamma_0 \bar{P}_{LoS}. \]

Thus, the transmission rate of RF link for the time slot \( n \) can be expressed as [26], [27]

\[ R_{RF}[n] = \frac{B_{RF}}{\log 2} \cdot \log \left( 1 + \frac{\tilde{\gamma}_0}{\|q_D - q_R[n]\|^\alpha} \right), \quad \forall n, \quad (11) \]

It is worth noting that \( \tilde{R}_{RF} \) can be understood as an approximation of \( \mathbb{E}\{\hat{R}_{RF}[n]\} \), and \( R_{RF}[n] \) is the corresponding average rate expression between \( R \) and \( D \) at any time slot \( n \).

\textbf{C. Quality of Service (QoS) Metrics for Buffer Constraint at UAV-assisted Relay}

Consider a dual-hop mixed FSO/RF network communicating between a source \( S \) and a destination \( D \) via a single UAV-enabled mobile relay node \( R \), as shown in Fig. [2]. Throughout the system, we assume that the source transmits the message via an FSO link at the rate of \( R_{FSO}[n] \) and the data is sent in packets. For ease of analysis, we consider the amount of data rate instead of the packet rate. Note that this analysis can be performed based on packet rate by dividing bit rate by number of bits per packet, if necessary. We consider first-in-first-out (FIFO) for the scheduling policy at queuing node, which states that packets are enqueued in turn and
the packets that wait longest in a buffer is de-queued first. Moreover, we leverage a full-duplex relaying (FDR) which works in decode-and-forward (DF) protocol thanks to the mixed FSO/RF characteristic that it has no self-interference \[16\]. In the following, we discuss on the queuing dynamics when source and relay transmit data as in \[28\], \[29\].

1) Source transmits: As FSO is chosen for \(S \rightarrow R\) link, the instantaneous achievable rate of \(S \rightarrow R\) link in time slot \(n\) in bps\(^5\) is given by

\[ C_{SR}[n] \leq R_{FSO}[n], \quad n = 1, 2, \cdots, N. \]  

Let \(C_{SR}[n]\) represent the amount of data transmitted to queue at slot \(n\). In the case of limited buffer size, this can happen that the data arriving into the buffer has to be dropped when the buffer is full.

2) Relay enqueues: Hence, the relay receives \(C_{SR}[n]\) data bits from \(S\) and appends them to the queue in its buffer. The controller of \(R\) first decides on whether the data can be admitted to the system or not over slots. If not, it directly drops the data. It takes actions to drop some of the data, only when the limited size of buffer cannot store so much data at slot \(n\), i.e., \(Q[n-1] + C_{SR}[n]\delta_t - C_{RD}[n]\delta_t > L_Q\), in which \(Q[n]\) and \(L_Q\) indicate the queuing length and size of buffer, respectively. The relationship among the queue length of the buffer, transmission rate, and the drop rate above is illustrated in Fig. 2. Note that we follow the first-out scheme for admission control as described in \[30\]. The FSO link can provide a higher data rate (in excess of tens of Gbps) than the RF link since it can use a wider bandwidth in general \[31\]. Accordingly, by reason of the imbalance of transmission rate between FSO and RF links can easily occur, we therefore deal with the overflow situation more concretely in this work. Specifically, we

\[^5\]Since we consider the discrete-time model (e.g., \(t = n \cdot \delta_t\)), we assume \(\delta_t = 1\) s, thus normalize variables which depend on the time slot \(n\).
consider the buffer constraint of $Q[n-1] + C_{SR}[n] \delta_t - C_{RD}[n] \delta_t \leq L_Q$, $\forall n$ in the main problem of following section. The normalized remaining bits in the buffer of relay evolves according to

$$Q[n] = Q[n-1] + C_{SR}[n] \delta_t - C_{RD}[n] \delta_t, \quad n = 1, 2, \cdots, N. \quad (13)$$

where $Q[0]$ and $C_{RD}[1]$ are equal to zero. Note that $C_{RD}[n]$ denotes the bits received by the destination (i.e., the user terminal) in time slot $n$.

3) Destination receives:

$$C_{RD}[n] = \min\{R_{RF}[n], \frac{Q[n-1]}{\delta_t} + C_{SR}[n]\},$$

$$n = 2, \cdots, N, \quad (14)$$

where we consider that the maximum number of transmit bits at the relay is limited by the remaining bits in the buffer or the instantaneous capacity for $R - D$ link. The conventional relaying introduces a delay of one time slot, since the relay has to wait until the entire data is received and decoded before sending the data to the destination, especially in DF protocol. The relay in this system receives data from the source in the first time slots and sends this cumulative information to the destination in the next time slots. We thus consider $C_{RD}[n]$ over time slots $n = 2, \cdots, N$ (i.e., $C_{RD}[1] = 0$).

Subsequently, the average throughput in the mixed FSO/RF communication with the limited buffer is given by

$$\Phi = \frac{1}{N-1} \sum_{n=2}^{N} C_{RD}[n]. \quad (15)$$

The delay in the system is defined by the duration between the time when the bits leaves the source node and the time when it arrives the destination. We note that the average delay is proportional to the average queue length for a given arrival rate from Littles Theorem [28], [32]. As a result, the average queue length can bridge the average delay. Thus, we can address the average delay at relay $R$ by the average delay as following

$$L = \frac{\mathbb{E}\{Q[n]\}}{\lambda}. \quad (16)$$

Note that the average arrival rate of bits per slot into the queue of the buffer denoted by $\lambda$ is defined as $\mathbb{E}\{C_{SR}[n]\}$. Since it takes one time slot to transmit a packet from the source to a relay node, the average packet delay in the system is given by $\bar{L} = L - \delta_t$. 
In practice, there is usually some constraint on the delay and on the buffer size. In the following section, these constraints are investigated in the proposed mixed FSO/RF mobile relaying system. For the three-node network considered, we assume that the source always has the information to transmit, then the transmission delay is only caused by a buffer in the relay. In the following section, we will adjust the delay with two approaches. The first approach is to restrain the buffer size by forcing the relay to transmit if the buffer gets full. The second approach is to manage the average delay the arrival rate and the average queue length. Based on the given system model, including the QoS metrics related for buffer constraints above, the goal of the following section is the maximization of throughput $\Phi$ by optimizing UAV’s trajectory.

III. THROUGHPUT MAXIMIZATION WITH A LIMITED BUFFER UNDER A DELAY CONSTRAINT

In order to tackle the trajectory optimization of UAV-aided relay to maximize the throughput of mixed FSO/RF under UAV mobility and buffer constraints, the following two problems are formulated. Motivated by employing mobile relay to provide both delay-tolerant and delay-limited services in future wireless networks as in [18], we find the optimal delay-considered policies which study not only buffer requirement but also delay requirements. Without loss of generality, we consider two types of transmission for the mobile relay: On the one hand, we investigate the delay-limited transmission case. On the other hand, as a case study of the delay-limited transmission, the delay-tolerant transmission case [33] is also studied.

A. Problem Formulation

Delay-limited transmission scheme follows that the $R$ stores the received data from $S$ link in its buffer and forwards them to $D$ taking account for a given delay-requirement. The throughput maximization problem for this transmission scheme should consider a delay in a queue, hence, we use the average delay $L$ in (16) for the delay-requirement.

Since the average throughput $\Phi$ can be dealt equivalently with a total amount of throughput received by the destination, we set the object function with $\sum_{n=2}^{N} C_{RD}[n]$. Note that we adopt the following notations to better understand the continuous variables in the optimization problems: the position of UAV $Q = \{q_{R}[n], \forall n\}$, the velocity of UAV $V = \{v_{R}[n], \forall n\}$, and the acceleration of UAV $A = \{a_{R}[n], \forall n\}$. Thus, we can formulate the throughput maximization for delay-limited transmission as the following (P1):
\[
(P1) \quad \max_{Q, V, A} \sum_{n=2}^{N} C_{RD}[n] \\
\text{s.t} \quad v_{R}[n+1] = v_{R}[n] + a_{R}[n] \delta t, \\
q_{R}[n+1] = q_{R}[n] + v_{R}[n] \delta t + \frac{1}{2} a_{R}[n] \delta t^2, \\
n = 0, 1, \cdots, N, \\
\|a_{R}[n]\| \leq A_{max}, \ n = 0, 1, \cdots, N, \\
\|v_{R}[n]\| \leq V_{max}, \ n = 1, 2, \cdots, N, \\
0 \leq Q[n] \leq L_{Q}, \ n = 1, 2, \cdots, N, \\
L \leq L_{req}.
\]

We note that the equality constraint in (17) characterizes the discrete state-space model of UAV’s location and velocity related to the position \(q_{R}[n]\), the velocity \(v_{R}[n]\), as well as the acceleration \(a_{R}[n]\). To take UAV’s flight practical constraints into account, UAV is constrained with the maximum acceleration in (18), and the maximum velocity in (19). Along with the above UAV-enabled mobile relay’s flight constraints (17)-(19), we can express the mobile relay’s trajectory characterized by a sequence of locations, velocities, and accelerations. Note that, in some applications (e.g., sensing and border surveillance), UAV can be constrained with the initial and final positions/velocities. Obviously, the initial and final position/velocity constraints can be further considered in this framework (P1) as follows

\[
q_{R}[0] = q_{I}, \quad q_{R}[N+1] = q_{F}, \\
v_{R}[0] = v_{I}, \quad v_{R}[N+1] = v_{F},
\]

in which \(q_{I}, q_{F}, v_{I}, \) and \(v_{F}\) denote a desired initial/final position and velocity, respectively. In this system, we do not consider these constraints to focus on the mobile relaying system especially for mixed FSO/RF-enabled backhaul networks. In addition, we establish (20) to hold the buffer constraint which limits the queue length to \(L_{Q}\). Furthermore, delay-considered transmission yields the average delay constraint of (21), which includes the value of the average delay \(L_{req}\). Depending on a certain delay-requirement, the delay-time limit can be flexibly managed by adjusting \(L_{req}\).
B. Proposed Algorithm

Despite of the convex constraints (17)-(19), the non-concave objective function $C_{RD}[n]$ and non-convex constraints (20)-(21) cause (P1) to be non-convex optimization problem, which therefore can not be addressed with standard convex optimization method. To tackle such the non-convex problem, firstly, we use the first-order Taylor approximation to $R_{RF}[n]$. Accordingly, with any given local value $q_k[n]$ at the iteration $k$, we approximate the throughput of RF as

$$R_{RF}[n] = B_{RF} \cdot (A^k - B^k(\|q_D - q_R[n]\|^2 - \|q_D - q_R^k[n]\|^2)), \quad n = 2, 3, \cdots, N.$$ (24)

Note that, as approximated in [34], $A^k$ and $B^k$ can be expressed as

$$A^k = \frac{1}{\log 2} \cdot \log \left(1 + \frac{\gamma_0}{\|q_D - q_R^k[n]\|^{\tilde{\alpha}}}\right),$$ (25)

$$B^k = \frac{\gamma_0}{\log 2 \cdot (\gamma_0 + \|q_D - q_R^k[n]\|^2) (\|q_D - q_R[n]\|^{\tilde{\alpha}})}, \quad n = 2, 3, \cdots, N.$$ (26)

Secondly, using high-SNR approximation\(^6\), we can express the lower bounded throughput of FSO as

$$R_{FSO}[n] = \frac{B_{FSO}}{2\log 2} (\log(k_1) - k_2 \cdot \|q_R[n] - q_S\|), \quad n = 1, 2, \cdots, N.$$ (27)

Note that $R_{RF}[n]$ and $R_{FSO}[n]$ are concave functions with respect to $q_R[n]$.

Now, let us introduce the slack variables $t_S = \{t_S[n] = C_{SR}[n], \quad n = 1, \cdots, N\}$, $t_D = \{t_D[n] = C_{RD}[n], \quad n = 2, \cdots, N\}$ for the non-concave objective function, and replace the non-convex constraints (20)-(21) to convex constraints with $\{t_S[n]\}_{n=1}^N$ and $\{t_D[n]\}_{n=2}^N$.

Thus, we can reformulate (P1) into the following optimization problem for any given local value $\{q_R^k[n]\}_{n=1}^N$ at the $k$-th iteration.

\(^6\)Since $k_1 \cdot e^{-k_2 \cdot \|q_R[n] - q_S\|} \gg 1$ even under the worst atmospheric conditions (e.g., heavy-fog condition), the high-SNR approximation can be applied to the achievable rate of FSO link.
(P1*) \[
\begin{align*}
\max_{t_S, t_D, Q, V, A} & \quad \sum_{n=2}^{N} t_D[n] \\
\text{s.t} & \quad (17) - (19), \\
& \quad t_S[n] \leq R_{FSO}^k[n], n = 1, 2, \cdots, N, \quad (28) \\
& \quad t_D[n] \leq R_{RF}^k[n], n = 2, 3, \cdots, N, \quad (29) \\
& \quad t_D[n] \leq Q'[n-1] + t_S[n], \\
& \quad n = 2, 3, \cdots, N, \quad (30) \\
& \quad Q'[n] \geq 0, n = 1, 2, \cdots, N, \quad (31) \\
& \quad Q'[n] \leq L_Q, n = 1, 2, \cdots, N, \quad (32) \\
& \quad L' \leq L_{\text{req}}. \quad (33)
\end{align*}
\]

Note that, deriving from the expression in (13) and the constraint in (20), we have
\[
Q'[n] = \sum_{i=1}^{n} t_S[i] - \sum_{i=2}^{n} t_D[i], \quad n = 2, 3, \cdots, N, \quad (34)
\]
in which \(Q'[1] = t_S[1]\). Accordingly, we also have the rewritten average delay as following
\[
L' = \frac{\sum_{n=1}^{N} Q'[n]}{\sum_{n=1}^{N} t_S[n]}. \quad (35)
\]

We set (28) to address the non-convex constraints in (20)-(21) and non-convex term \(C_{SR}[n]\) in (12). In addition, (29) and (30) tackle the non-concave objective function \(C_{RD}[n]\).

The type of optimization problem (P1*) is the convex quadratically constrained program (QCP). The convex QCP can be solved within a polynomial complexity, by interior-point methods with a standard convex optimization solvers such as CVX. Then, we can suboptimally solve (P1) via the successive convex optimization to (P1*) by iteratively updating the local points \(\{q_k[n]\}_{n=1}^{N} \) \(35\). Note that it has been proved that the successive convex optimization method converges to at least a local optimal point \(5\). We further show the convergence through the numerical results in the numerical results in Section IV.

It is worth noting that the extension of the delay-limited transmission design to the more specific delay-sensitive applications, e.g., medical packets \(21\), virtual reality applications \(36\),
multimedia streaming and video telephony will be left as our future work. In this paper, we focus on the UAV-enabled mobile relaying with general buffer constraint and average delay constraint, to describe general UAV-enabled mobile relaying system especially for mixed FSO/RF-based backhaul network.

In closing this subsection, we summarize the proposed successive optimization steps for the delay-limited transmission (P1) in Algorithm 1. Note that we can also apply Algorithm 1 to the throughput maximization of delay-tolerant transmission by replacing (P1*) to (P2*) and (33) to (36).

C. Case Study: Delay-Tolerant Transmission

Formerly, we have dealt the delay-limited transmission scheme, and have studied on optimizing throughput on UAV-assisted mobile relaying under a limited buffer constraint. Surely most applications concerns the throughput and delay, which has been known to be in tradeoff relationship (see e.g., [28], [30]). In contrast, some applications, such as periodic sensing, does not concern the delay as sensitively as delay-limited application does. Hence, we address the delay-tolerant transmission scheme based on the previous problem (P1).

Delay-tolerant transmission scheme is that the relay is allowed to store the received data in its buffer and forward them to the destination without any limit of delay. As in (P1), we consider a buffer constraint in addition to the mobile relay’s flight constraints in the delay-
tolerant transmission. In particular, we can deal with the delay-tolerant transmission scheme by simply changing the constraint in (P1\*) as follows:

\[
(P2^*) \max_{t_S, t_D, Q, V, A} \sum_{n=2}^{N} t_D[n] \\
\text{s.t} \quad (17) - (19), (28) - (32), \quad L' \leq \infty. \tag{36}
\]

Such as in the problem (P1\*), the problem (P2\*) is also QCP. Then corresponding to (P1), we can suboptimally solve (P2\*) via the successive convex optimization by iteratively updating the local points \(\{q^k_{R}[n]\}_{n=1}^{N}\), which ensure to converge.

D. Complexity Analysis

To better understand the proposed algorithm, we present the proof of complexity of our algorithm. In order to determine the complexity of Algorithm\(1\), we need to decide the complexity of subproblem (P1\*) described in Section [III-A] for delay-limited transmission, and the complexity of (P2\*) described in Section [III-C] especially for delay-tolerant transmission. Note that the complexity of both (P1\*) and (P2\*) are equivalent.

Looking at the complexity analysis in [37], [38], to solve the convex optimization problem especially with the interior-point methods, (ignoring any structure in the problem, such as sparsity) each step requires on the order of

\[
\max\{\zeta^3, \zeta^2 \xi, F\} \tag{37}
\]

operations. Note that \(\zeta\) and \(\xi\) denote the number of variables and constraints, respectively, and \(F\) denotes the cost of evaluating the first and second derivatives of the objective and constraint functions.

For (P1\*) and (P2\*), it can be easily found that \(\zeta = 8N + 1\). Also, we can compute the number of constraints \(\xi\), according to Table\(II\) at the top of next page, as \(\xi = 11N + 4\). Therefore, comparing the order of \(\zeta^3, \zeta^2 \xi, \text{ and } F\), it can be found that \(\zeta^2 \xi\) is greater than \(\zeta^3\) and \(F\). Note that \(F\) follows \(O(N)\) in the problems, whereas, \(\zeta^3\) and \(\zeta^2 \xi\) follow \(O(N^3)\).

As a result, considering the interior point method, the computational complexity for Algorithm\(1\) can be derived by
Table I: Number of constraints in each Equation.

| Eq. | (17) | (18) | (19) | (28) | (29) | (30) | (31) | (32) | (33) |
|-----|------|------|------|------|------|------|------|------|------|
| The number of constraints in Eq. | $4(N + 1)$ | $N + 1$ | $N$ | $N$ | $N - 1$ | $N - 1$ | $N$ | $N$ | $1$ |

\[ \sum_{m=1}^{\vartheta} 704N^3 + 432N^2 + 75N + 4. \]  

(38)

Note that $\vartheta$ denotes the number of iterations for Step 3 - 5 in Algorithm 1. Then, in typical usage, the $O$ notation is asymptotical, the complexity of Algorithm 1 can be reduced to the order of $O(\vartheta N^3)$.

**IV. Numerical Results**

In this section, we provide some selected numerical results to validate our proposed mixed FSO/RF UAV-enabled mobile relaying system with a buffer. In particular, initially, the simulation results for delay-tolerant transmission, as a general case of throughput maximization with a buffer constraint, is presented. Then, the simulation results for delay-limited transmission is presented. Lastly, we compare and analyze the proposed scheme with conventional scheme.

We consider a system with the altitude of UAV $H = 100$ [m], the location of backhaul terminal $\mathbf{q}_S = [0, 0, 0]^T$, the location of user terminal $\mathbf{q}_D = [L, 0, 0]^T$ where $L = 2000$ [m]. For the UAV-enabled mobile relaying system, we assume that the maximum velocity $V_{\text{max}} = 50$ [m/s], and the maximum acceleration $A_{\text{max}} = 5$ [m/s$^2$]. Unless stated otherwise, we set the period $T = 200$ [s] with the time-step size $\delta_t = 1$ [s], the visibility $V = 1.0$ [km] which describes the light-fog condition, the bandwidth for FSO $B_{\text{FSO}} = 10^9$ [Hz] and the bandwidth for RF $B_{\text{RF}} = 10^8$ [Hz], the ASNR $\gamma_{\text{FSO}} = 5$ [dB] ($\alpha = \frac{1}{10}$), the reference SNR $\gamma_0 = 40$ [dB]. The parameters for the probabilistic LoS channel model in $\bar{P}_{\text{LoS}}$ are set as $C = 10$, $D = 0.6$, $\kappa = 0.2$, and $\bar{\alpha} = 2.2$. Moreover, the regularized homogeneous LoS probability $\bar{P}_{\text{LoS}}$ in (11) is set as the value corresponding to the elevation angle of $90^\circ$. The simulation results of this paper are obtained through CVX.
Fig. 3. Throughput maximized UAV’s x-coordinate position over time $T$ with respect to different weather condition.

Fig. 4. PMF based on 300 [m] interval for Fig. 3’s throughput maximized trajectories over different weather condition.

A. Simulation Results for Delay-Tolerant Transmission

Figs. 3 and 4 are the result of the optimization problem for delay-tolerant transmission with infinite buffer size (i.e., $L_Q = \infty$). Fig. 3 represents the throughput maximized path, specifically, shows that the optimized trajectories in x-axis over different atmospheric conditions. Note that since position $q_{\mathcal{R}}[n]$ of the UAV and velocity $v_{\mathcal{R}}[n]$ and acceleration $a_{\mathcal{R}}[n]$ are correlated by (17), the optimal $v_{\mathcal{R}}[n]$ and $a_{\mathcal{R}}[n]$ result are not shown due to space limitations. As shown in Fig. 3 for thin fog condition which is best atmospheric condition in Fig. 3, UAV hovers near on the user terminal during every time slots. Whereas, for heavy fog condition which is worst

\footnote{Note that we consider the discrete-time model (i.e., $t = n \cdot \delta_t$) and assume $\delta_t = 1$ [s], thus $t = n$ in this numerical results.}
atmospheric condition in Fig. 3, UAV hovers on the backhaul terminal for up to $T = 170$ [s] and then flies to the user terminal to forward accumulated data. Namely, in worse atmospheric condition, UAV tends to stay above the ground terminal for longer periods to store enough data in the buffer. Note that we consider the infinite buffer size so that UAV can accumulate enough data in queue, and UAV transmits data to user terminal via RF link even near backhaul terminal. Fig. 4 shows probability mass function (PMF) of each optimized trajectory in Fig. 3 based on 300 [m] interval (e.g., 250 [m] $\sim$ 550 [m]). From the result of Fig. 4, it can be found that how long UAV stays in a certain interval between the ground terminal and the user terminal. For instance, in moderate fog condition, UAV hovers at a time of 65% of the total flight time from $-50$ [m] to $250$ [m] near the backhaul terminal, whereas UAV hovers at a time of 20% of the total flight time from $1750$ [m] to $2050$ [m] near the user terminal. Also, for thin fog condition, UAV flies at a time of 21% of the total flight time near the backhaul terminal, whereas UAV flies at a time of 70% of the total flight near the user terminal. From Figs. 3 and 4 which show the results for different weather condition (e.g., different atmospheric condition or visibility), it can be observed that the better weather condition, the shorter the mobile relay hovers near the backhaul terminal and the longer it flies near the user terminal to forward data accumulated in the buffer. It is worth noting that, even in heavy fog conditions, FSO can be considered as a valid option as a backhaul link. In addition, better weather conditions, such as clear condition, can yield same result of trajectory and PMF of ‘thin fog condition’, while higher transmission rate of FSO link can be supported.

Figs. 5 and 6 show the results according to the throughput maximization problem for buffer constrained delay-tolerant transmission (i.e., (P2)). In Fig. 5, the optimized trajectories in $x$-coordinate for the mobile relay are plotted over the different buffer sizes. In the throughput maximized trajectories, on the one hand, the UAV circulates around $y = 1300$ [m] about 7 times and about 3 times with $L_Q = 5 \cdot 10^9$ [bits] and $L_Q = 5 \cdot 10^{10}$ [bits], respectively. On the other hand, without any circulation, the UAV hovers only around $y = 1300$ [m] with $L_Q = 5 \cdot 10^8$ [bits], and the UAV hovers a while around backhaul terminal and then flies to user terminal with $L_Q = 7 \cdot 10^{10}$ [bits]. Namely, if not enough buffer size provided, UAV circulates (or stays)

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8 The backhaul terminal and user terminal are positioned horizontally with respect to x-axis. It can be intuitively seen that to fly between backhaul terminal and user terminal in parallel is optimal. Thus we provide only the result of the x-axis, not the trajectory of xy-axis or xyz-axis.
between $S$ and $D$. If enough buffer size provided, UAV hovers on the backhaul terminal for up to a certain period (e.g., $T = 50$ [s]) and then flies to the user terminal.

Fig. 6 shows PMF in each optimized trajectory of Fig. 5 based on 300 [m] interval. For the
buffer size $L_Q = 5 \cdot 10^8$ [bits], UAV stays about 98% of the total flight time between 1150 [m] and 1450 [m]. Differently, for the larger buffer size $L_Q = 7 \cdot 10^{10}$ [bits], UAV stays about only 3% of the total flight time at between 1150 [m] and 1450 [m], while stays about 56% flight time at between 1750 [m] and 2050 [m] near the user terminal. It is clear that, with enough buffer size, UAV stays enough duration near the backhaul terminal to store data in the buffer, and then flies towards the user terminal.

Given these points, Figs. 5 and 6 provide the insight that a limited buffer size (which accounts for the practical condition of mobile relaying system) forces the UAV to circulate between the backhaul terminal and the user terminal, for efficient delivering data in the buffer by storing and forwarding. We also note that the transmission rates of the RF link and FSO link are equal around $x = 1830$ [m] in the fixed relaying and the mobile relaying without the buffer, this equal position can be the optimal location for the mixed FSO/RF relaying systems. Whereas in practical mobile relaying, to consider a limited size buffer constraint, the UAV-assisted mobile relay stays closer to the source link rather than destination link, since a certain amount of data can be stored in the buffer. It is worth nothing that mobile relaying is superior rather than fixed relaying (e.g., static relaying) in terms of throughput performance, as shown in Table II.

Fig. 7 shows the optimal average throughput of delay-tolerant transmission (P2) over buffer size. We can see that the buffer size $L_Q$ is proportional to the optimal average throughput. This

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9 The result of Fig. 5a (i.e., mobile relay stays around $y = 1300$ [m]) can be understood as the imbalance of mixed FSO/RF can be admitted in the given buffer size $L_Q = 5 \cdot 10^8$ and time slot $T = 200$ [s].
is because, as the buffer size increases, the trajectory design of the UAV can be more freely optimized to maximize the average throughput of the mobile relay, while being less constrained by the buffer constraint. Note that the result of “Delay-Tolerant Transmission with \( L_Q = \infty \)” in Fig. 7, which considers the infinite buffer size, can be used as the upper bound of (P1). With the buffer size bigger than \( L_Q = 7 \cdot 10^{10} \) [bits], the average throughput results are close to the upper bound result as shown in Fig. 7. Thereby, we can verify that \( L_Q = 7 \cdot 10^{10} \) [bits] is the optimal buffer size in this system. This result demonstrates that throughput and buffer are two conflict metrics and thus, it is necessary to effectively balance them.

B. Simulation Results for Delay-Limited Transmission

With the average delay requirement \( L_{\text{req}} \), we present the simulation results of the throughput maximization problem for delay-limited transmission (P1) as following Figs. 8, 9, and 10.

In Fig. 8, the optimized trajectories in x-coordinate for the mobile relay are drawn over the different average delay limit \( L_{\text{req}} \). With the given buffer size \( L_Q = 7 \cdot 10^{10} \) [bits] (which is the optimal buffer size [bits] verified from Fig. 7), UAV flies from backhaul terminal and user terminal directly if not considering the delay requirement (e.g., \( L_{\text{req}} = \infty \)) as shown in Figs. 5d. On the other hand, by taking account of the delay requirements, optimal trajectory is drawn in the different pattern as seen from the result of Fig. 8a - 8c. Namely, the tighter delay requirement given, UAV tends not to circulate and to stay at a certain position, since data in the buffer needs to be de-queued faster. Fig. 9 presents the PMF based on 300 [m] interval for the different average delay limit \( L_{\text{req}} \) and the buffer size \( L_Q \). With \( L_Q = 7 \cdot 10^{10} \) [bits] and \( L_{\text{req}} = 100 \) [slot],
the UAV stays at about 29% of the total flight time near the backhaul terminal (−50 [m] ∼ 250 [m]) or user terminal (1700 [m] ∼ 2100 [m]), and stays at about 40% of the total flight time around 1150 [m] ∼ 1450 [m]. On the other hand, when \( L_Q = 7 \cdot 10^{10} \) [bits] and \( L_{\text{req}} = 10 \) [slot], the UAV stays mainly hovers between the backhaul terminal and user terminal (around 1150 [m] ∼ 1450 [m]). From the results of Figs. 8 and 9, it can be seen that the smaller \( L_{\text{req}} \) (i.e., more strongly constrained by (33)), the shorter the time UAV to stay near the backhaul terminal and user terminal.

Fig. 10 shows the optimal average throughput of delay-limited transmission (P1), depending on the average delay limit. This figure shows that as \( L_{\text{req}} \) increases, the average throughput increases. It can be understood as \( L_{\text{req}} \) increases, the path for UAV can be designed more freely to maximize the average throughput of mobile relays (i.e., less constrained by (33)). Note that the result of “Delay-Tolerant Transmission with \( L_Q = 7 \cdot 10^{10} \) [bits] \( (L_{\text{req}} = \infty)\) ” in Fig. 10, which considers no delay limit, can be used as the upper bound of (P1). For the average delay requirement bigger than \( L_{\text{req}} = 600 \) [slot], the average throughput results are close enough to the upper bound as shown in Fig. 10. Thus, we can confirm that \( L_{\text{req}} = 7 \cdot 10^{10} \) [bits] is the optimal average delay limit size in terms of throughput. It is worth noting that Fig. 10 shows the throughput-delay tradeoff in the buffer-aided mobile relaying system especially via mixed FSO/RF. This tradeoff indicates that throughput and delay are two conflict metrics and thus, it is necessary to effectively balance them. As a result, we obtain the optimal buffer size \( L_Q = 7 \cdot 10^{10} \) [bits] and then the optimal delay requirement \( L_{\text{req}} = 600 \) [bits] for the throughput maximization, according to the given mixed FSO/RF UAV-aided mobile relay conditions (e.g., weather condition, conditions of FSO link \( \gamma_{\text{FSO}} \) and \( B_{\text{FSO}} \), and conditions of RF link \( \gamma_0 \) and \( B_{\text{RF}} \)).

Fig. 11 shows the convergence of Algorithm 1. In particular, this figure shows how much the slack variable \( t_D \), which is introduced for non-convexity of (P1) (or (P2)), approaches to the actual throughput value \( C_{RD} \) according to the number of iterations, in Algorithm 1. Note that the result of Fig. 11 yields from (P2) with \( L_Q = 7 \cdot 10^{10} \) [bits] and \( L_{\text{req}} = 600 \) [bits]. As shown in this figure, the average throughput value obtained by \( C_{RD} \) and the average throughput value obtained by \( t_C \), which is the lower bound of \( \Phi \), are close enough after 4 iterations.
Fig. 8. Throughput maximized UAV’s x-coordinate position over time $T$ with respect to the given average delay limit $L^{req}$ and the given buffer size $L_Q$.

Fig. 9. PMF based on 200 [m] interval for Fig. 8’s throughput maximized trajectories over different average delay limit $L^{req}$.

C. Comparison with Conventional Scheme

As a final remark, Table. II shows the performance comparison of the conventional and proposed schemes. This table compares the proposed schemes with the baseline schemes (e.g., static relaying scheme, data-ferrying scheme, and circulation scheme [3], [5], [39], [40]). Static relaying is a scheme (which refers the fixed relaying system as in [3]) where the relay system stays in one position and transfers data. Particularly, we consider the UAV (as a fixed relay) stays at $x_s = 1830$ [m] which is the equivalent position for FSO and RF links (i.e., $R_{FSO} = R_{RF}$) with
Fig. 10. Average throughput over average delay limit $L^{\text{seq}}$.

Fig. 11. Convergence plot of Algorithm 1.

A infinite buffer size $L_Q = \infty$. We also consider another benchmark scheme called data-ferrying \cite{5, 39}. In this scheme, UAV first loads the data from $S$ within some predetermined range $d_1$ from $S$, flies towards $D$ without any data reception or transmission, and then de-queued the data to $D$ when it is within range $d_2$ from $D$. Specifically, the numerical results of the data-ferrying scheme yields from $d_1 = d_2 = 200$ [m] and $L_Q = \infty$. In addition to the conventional benchmarks (static relaying and data-ferrying schemes), we further introduce the circulation scheme that can be considered as another baseline scheme for the mobile relaying, especially when the relay system uses mixed RF/FSO links (where transmission rate difference can occur depending on communication conditions of each link). In the circulation scheme, the mobile relay circulates around the position $x_c$ at a constant speed with a radius of $d_3$. In the circulation scheme of this
Table II: Comparison of proposed scheme and conventional scheme.

| Scheme                              | Parameters                      | Throughput [bps] |
|-------------------------------------|---------------------------------|------------------|
| Static Relaying [3]                 | \((x_s = 1830 \text{ m}, L_Q = \infty)\) | 3.3006\times10^7 |
| Data-Ferrying [5, 39]               | \((d_1, d_2 = 200 \text{ m}, L_Q = \infty)\) | 3.3938\times10^7 |
| Circulation Scheme (\(x_c = 1830 \text{ m}, d_3 = 200 \text{ m} \), \(L_Q = \infty)\) | | 3.7188\times10^7 |
| Delay-Limited Transmission Scheme, (P1) | \((L_Q = 7.0 \cdot 10^{10} \text{ bits}, L_{\text{req}} = 600 \text{ slot})\) | 5.4643\times10^7 |
| Delay-Tolerant Transmission Scheme, (P2) | \((L_Q = 7.0 \cdot 10^{10} \text{ bits})\) | 5.5157\times10^7 |
| Delay-Tolerant Transmission Scheme, (P2) | \((L_Q = \infty)\) | 5.5158\times10^7 |

In Table II, we consider that the mobile relay circulates four times between the backhaul terminal and user terminal with \(d_3 = 200 \text{ m}\) around the equal point \(x_c = 1830 \text{ m}\) (i.e., 1730 [m] \sim 1930 [m]), while stores and transfers data with \(L_Q = \infty\).

In Table II, it can be found that the result of (P1) with the optimal buffer size \(L_Q = 7 \cdot 10^{10}\) [bits] and optimal delay limit \(L_{\text{req}} = 600 \text{ slot}\) is tight enough to the result of (P2) with \(L_Q = \infty\), which is the upper bound of the proposed buffer constrained mobile relaying schemes. In other words, even in limited delay requirement and buffer size, if appropriate \(L_Q\) and \(L_{\text{req}}\) are found, the optimal throughput for the system can be achieved. Note that, in the case of delay-sensitive (low \(L_{\text{req}}\)-considered) applications, the lower average throughput can be achieved since the throughput and the delay requirement follow tradeoff relationship. Although there are additional buffer constraints and delay limit constraints, proposed schemes achieve better throughput performance compared to the three baseline schemes as found in Table II. Specifically, the results of (P1) with \(L_Q = 7 \cdot 10^{10}\) [bits] \(L_{\text{req}} = 600 \text{ slot}\) obtains 46.93%, 61.01%, and 65.55% gain compared to the circulation scheme, the data-ferrying scheme, and the static relaying scheme, respectively. Thus, it is verified that the superiority of our proposed schemes compared to the baseline schemes.

V. CONCLUSION

This paper has investigated the problem of the throughput maximization in mixed FSO/RF UAV-assisted mobile relaying system with a buffer. For the throughput maximization, we have optimized the trajectory of a UAV-enabled relay under the different weather condition (e.g., attenuation conditions). To consider the mixed FSO/RF system with the achievable rate difference, we have practically considered the finite sized buffer and ascertained the effect of buffer size to the mobile relaying system. Furthermore, we have classified buffer constrained throughput maximization problem into two different transmission polices, i.e., delay-limited...
transmission and delay-tolerant schemes, to deal with the delay requirement. To tackle these non-convex problems, we adopted the successive optimization algorithm. Thus, the trajectory can be determined by applying convex QCP. Through the simulation results, we validated the superiority of the proposed algorithm over the conventional schemes and obtained the optimal buffer size and the optimal delay-time requirement, and further showed the throughput-delay tradeoff (and throughput-buffer size tradeoff) for the system.

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