Performance Analysis and Optimization of a UAV-Enabled Two-Way Relaying Network under FSMH, NC, and PNC Schemes

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Abstract—Unmanned aerial vehicles (UAVs) have played an important role in wireless communications due to the advantages such as highly controllable mobility in three-dimensional (3D) space, swift deployment, line-of-sight (LoS) aerial-ground links, and so on. In this paper, we consider a UAV-enabled two-way relaying system where the UAV relay assists the information exchange between two ground users (GUs) under three different schemes, i.e., four-slot multi-hopping (FSMH) without network coding (NC), three-slot NC and two-slot physical NC (PNC). Firstly, the capacity region of each scheme in this relaying system is analyzed. Then, we maximize the system average sum rate by jointly optimizing the time resources allocation, transmission powers of the transceivers, and the UAV trajectory subject to the constraints on UAV mobility and information causality under each scheme. To solve those problems, we propose an iterative algorithm by applying the successive convex approximation and block coordinate descent techniques. Specifically, the time resources allocation, transmission powers and the UAV trajectory are alternatively optimized in each iteration. In addition, the non-convex trajectory optimization problem is solved by successively solving an approximate convex optimization problem. To gain more insights, we also investigate the performance of those three schemes with symmetric and asymmetric traffic respectively by introducing a new traffic pattern constraint. Numerical results show that the proposed relaying schemes with moving relay can achieve great throughput gains as compared to the conventional scheme with static relay. The three relaying schemes also show great performance heterogeneity under different traffic patterns.

Index Terms—UAV, two-way relaying, FSMH, NC, PNC

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) enabled wireless communications have drawn significant attention in the past few years [1]. Compared to conventional communications with static ground infrastructures, UAV-enabled communications have the following advantages. Firstly, the highly controllable mobility of UAV in a three-dimensional (3D) space provides a new design degree of freedom (DoF) to enhance the system performance by adjusting the UAV’s trajectory [2]. Secondly, the UAV-enabled base stations are more likely to provide line-of-sight (LoS) connections to the ground users (GUs) [3]. In addition, the UAV can be deployed on demand swiftly, which is appealing in emergency communications [4]. Numerous UAV-enabled wireless communication systems have been proposed. For example, the UAV has been used for being aerial BS in ubiquitous coverage [5]–[10], for data collection or information dissemination in the internet of things (IoT) networks [11]–[16], and for being aerial relay in wireless relaying system [17]–[19].

Among all the UAV-enabled communication techniques, the UAV-enabled relaying is an effective technique to improve the network throughput or extend the communication range under complex terrain. According to the direction of information flow, it can be divided into two categories, i.e., UAV-enabled one-way relaying [17] and UAV-enabled two-way relaying [20]. In the one-way relaying network, where the information flow is unidirectional from the source station to the destination station [21], the relay only needs to forward the information received from the source to the destination. However, the UAV relay in the two-way relaying system is deployed to assist the information exchange between two GUs which cannot communicate directly [22]. According to spectrum utilization, there are three typical kinds of information exchange schemes, i.e., four-slot multi-hopping scheme (FSMH) which is the common TDMA scheme without any coding operation on the received packets [23], three-slot network coding scheme (NC) [24]–[26], and the two-slot physical network coding scheme (PNC) [27]–[29]. In NC and PNC schemes, the received packets in the relay will be coded before forwarded to achieve better spectrum utilization. The detailed process of those three schemes is introduced in Section III-B.

In spite of the wide investigation of UAV-enabled relaying, there are still some open problems to be discussed. Firstly, most of the existing works focus on the one-way relaying system [18] while the UAV-enabled two-way relaying system has not been well investigated. Secondly, although the performance of the three schemes, i.e., FSMH, NC, PNC has been widely investigated in conventional relaying system with fixed ground relay [23], [24], [27], their corresponding performance in a UAV-enabled two-way relaying network with moving aerial relay has not well been studied and optimized. In addition, each two-way relaying network has its own traffic pattern which is defined as the ratio of traffic in two directions. For instance, gaming and online chatting are of symmetric pattern while the traffic pattern is extremely asymmetric in...
webpage browsing where the downlink traffic dominates. How the traffic pattern affects the performance of those three schemes and which scheme shows the best performance with symmetric and asymmetric traffic has not been investigated yet in the two-way relaying system.

Motivated by the mentioned above, in this paper, we consider a UAV-enabled two-way relaying network, where two GUs exchange information through a mobile UAV relay under three different information exchange schemes respectively. For each scheme, the rate region is analyzed and the average sum rate is maximized by jointly optimizing the time resources allocation (TRA), power allocation (PA) and the UAV trajectory subject to the constraints on rate region, UAV mobility, information-causality, and transmission powers. Besides, the system performance for different schemes with symmetric and asymmetric traffic is also analyzed, optimized and compared. It is observed from the numerical results that the three relaying schemes show great performance heterogeneity under different traffic patterns. Such analysis is appealing but has not been investigated in the existing literature to our best knowledge. Specifically, the main contributions of this paper are summarized as follows.

- We formulate network average sum rate maximization problems for three schemes, i.e., FSMH, NC, and PNC, by jointly optimizing the time resources allocation, the transmission powers of the transceivers, and the UAV trajectory subject to the UAV trajectory constraints, the information-causality constraints, as well as the peak and average transmission powers constraints. The optimization problem for each scheme is a non-convex problem which can not be solved directly because of the close coupling of the numerous optimization variables and the non-convexity brought by the information-causality constraints.

- To solve those problems above, we partition the entire optimization variables into three blocks, i.e., time-sharing parameters which are defined in Section II-B for TRA, transmission powers of GUs and the UAV for PA, and the UAV trajectory. Then, three sub-problems i.e., the TRA problem with fixed transmitting powers and UAV trajectory, the PA problem with fixed time-sharing parameters and UAV trajectory, and the UAV trajectory optimization problem with fixed time-sharing parameters and transmission powers are constructed. The TRA problem for each scheme is a typical linear programming and the corresponding PA problem can be transformed into standard convex optimization problem by introducing slack variables. However, even with given time-sharing parameters and transmission powers, the UAV trajectory optimization problem for each scheme is non-convex. This problem is tackled by successively solving an approximation convex problem by applying the successive approximation technique. Finally, an iterative algorithm is proposed to solve the joint optimization problems based on the block coordinate descent method by alternatively optimizing one block of variables in each iteration. The proposed algorithm is efficient and can converge after a few iterations shown in Section VI-D.

- To gain more insights, we also investigate the effects of traffic pattern on system performance for each scheme. Specifically, a new throughput maximization problem of this two-way relaying system for each scheme with symmetric and asymmetric traffic is formulated respectively by considering a new traffic pattern constraint which is defined in Section V. Those optimization problems can also be solved using the algorithms proposed above.

- Numerical results show that the proposed UAV-enabled two-way relaying system can achieve great throughput gains as compared to its counterparts with static relay for all schemes. Meanwhile, the three relaying schemes also show great performance heterogeneity under different traffic patterns, i.e., symmetric and asymmetric.

The rest of the paper is organized as follows. Existing literature related to the proposed work is discussed in Section II. Section III introduces the system model, the three information exchanging schemes and the problem formulation. In Section IV we propose an efficient algorithm for UAV trajectory optimization and an iterative algorithm based on block coordinate descent for the overall optimization. The traffic pattern parameter is defined and the corresponding optimization problems are presented in Section V. The numerical results are presented in Section VI. Finally, Section VII concludes the paper.

II. RELATED WORKS

For UAV-enabled wireless communications, since the highly controllable 3D mobility of UAV brings a new design DoF for enhancing the system performance, the optimization of UAV trajectory is of great importance in designing a UAV-enabled system. The authors in [30] give a tutorial overview of the recent advances in UAV communications and explore how to integrate UAVs into the forthcoming 5G communication and future cellular networks. In addition, a general framework for the co-design of UAV trajectory and communication is proposed. [31] studies the energy-efficient UAV communications in a system with only one UAV and one ground node. A theoretical model on the propulsion energy consumption of fixed-wing UAV as a function of UAV’s flying speed, direction and acceleration is derived. [32] considers a UAV-enabled two-user broadcast channel (BC) and characterizes the system capacity by jointly optimizing the UAV trajectory and the power allocation. By deploying the UAV as mobile BS, [33] studies the joint optimization of UAV trajectory and the resource allocation in an OFDMA network for maximizing the minimum downlink rate of all users. In [34], the authors propose a novel framework for attaining the 3-D deployment and dynamic movement of multiple UAVs in UAV communication system by applying the reinforcement learning method. In addition, the UAV can also play an important role in IoT networks. In [35], the UAV is employed as both a data collector and an aerial anchor node to assist terrestrial BSs in data collection and device positioning in an IoT network. The UAV trajectory and devices’ transmission schedule are jointly optimized to minimize the maximum energy consumption of
For UAV-enabled two-way relaying, [41] jointly optimizes the UAV positioning and transmission powers of users to maximize the sum rate of the system. In this relaying system, the UAV relay assists the communications between a group of GUs and BSs by applying the amplify-and-forward protocol. In [20], the minimum average rate of two downlinks is maximized by optimizing UAV trajectory (locations, velocity and acceleration), transmit power, and bandwidth in a UAV-enabled two-way relaying system with PNC scheme. A new surrogate function which enables the authors to optimize the UAV trajectory and transmit power jointly is proposed. The authors in [22] consider a two-way multi-hop UAV relaying network where multiple UAVs assist the information exchange between two GUs. They first provide an efficient algorithm to determine the location of UAVs, then study the energy efficiency in a UAV-IoT data collection system by optimizing the UAV flying speed and altitude. In [37], the authors consider a UAV assisted IoT network which consists of multiple UAVs and BSs. The access competition among UAVs and the bandwidth allocation among BSs are formulated as a dynamic evolutionary game and a non-cooperative game respectively.

For UAV-enabled one-way relaying, [17] studies the throughput maximization problem by jointly optimizing the source/relay transmission power and UAV trajectory. It is found that for the one-way relaying system, the transmission powers of the transceivers follow a modified Water-filling structure, and the optimal UAV trajectory without predetermined initial and final locations follows “Hovering-Flying-Hovering” pattern. [18] considers a kind of one-way relaying system with mobile devices (MDs). The transmission powers of UAV and MDs as well as the UAV trajectory are jointly optimized to minimize the outage probability. In [19], the beamforming technique is used for inter-user interference mitigation and the heading of the UAV relay is optimized to maximize the sum rate of the uplink channel. The authors in [38] study the energy-efficient UAV relaying communication by considering both the system throughput and the UAV energy consumption. Specifically, the transmit powers of UAV and BS, the UAV trajectory, acceleration, and speed are jointly optimized to maximize the energy efficiency. [39] proposes a cooperative UAV relaying network which includes multiple UAVs and multiple pairs of GUs. The authors study the minimum rate maximization problem by jointly optimizing the UAV relays’ locations, GUs’ transmission powers and the bandwidth allocation. In [40], an energy-efficient maneuvering and communication algorithm is proposed by considering that the small UAV flies in a circular trajectory.

For UAV-enabled two-way relaying, [41] jointly optimizes the UAV positioning and transmission power of users to maximize the sum rate of the system. In this relaying system, the UAV relay assists the communications between a ground BS and a group of GUs by applying the amplify-and-forward protocol. In [20], the minimum average rate of two downlinks is maximized by optimizing UAV trajectory (locations, velocity and acceleration), transmit power, and bandwidth in a UAV-enabled two-way relaying system with PNC scheme. A new surrogate function which enables the authors to optimize the UAV trajectory and transmit power jointly is proposed. The authors in [22] consider a two-way multi-hop UAV relaying network where multiple UAVs assist the information exchange between two GUs. They first provide an efficient two-way multi-hop UAV relaying pattern which is proved to show great performance and then the transmit powers and UAVs’ trajectories are jointly optimized to maximize the transmission rates between two GUs. [42] proposes a UAV-aided two-way relaying network which consists of one UAV relay and two group robot swarms. The UAV relay is deployed to expand the communication range of those two disconnected group robot swarms with decode-and-forward protocol.

However, [41] only adopts amplify-and-forward protocol without considering the effects of network coding. Though the PNC scheme is mentioned in [20], the capacity region of the PNC scheme is not taken into account in the formulated optimization problem. In addition, neither [41] nor [20] considers the effects brought by the traffic pattern. The relaying networks proposed in [22] and [42] include multiple UAV relays or GUs. Therefore, the methods proposed in [22] and [42] cannot be applied directly in the relaying system in this paper.

III. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

In this paper, we consider a UAV-enabled two-way relaying system, where the UAV is deployed as a relay assisting the information exchange between two GUs (GU1, GU2), as shown in Fig. 1(a). We assume that the direct communication links between these two GUs are negligible due to the block of mountains/high buildings. Without loss of generality, let $(0, 0, 0)$ and $(D, 0, 0)$ denote the locations of GU1 and GU2, respectively and $D > 0$ is the distance between them. In addition, the flight height of UAV is fixed at $H$, which can be regarded as the minimum altitude for avoiding obstacles. Generally, the UAV has a finite operation period, denoted with $T$, due to the limited on-board power. During this period, the instant position of UAV is $(x(t), y(t), H)$, $0 \leq t \leq T$, where $x(t)$ and $y(t)$ denote the time-varying x- and y-coordinates. Typically, the instant velocity of UAV cannot exceed a maximum and we have $v(t) = \sqrt{x'(t)^2 + y'(t)^2} \leq V_{\text{max}}$, where $V_{\text{max}}$ is the maximum velocity of UAV, $v(t)$ is the instant UAV velocity at time $t$, and $x'(t)$ and $y'(t)$ denote the time-derivatives of $x(t)$ and $y(t)$. For ease of exposition, we discretize $T$ into $N$ time segments, i.e., $T = N \delta_t$, where $\delta_t$ is the elemental time segment length. Denote $\delta_n, n \in \mathbb{N}, n \in (1, \ldots, N)$, as the $n$-th time segment. Note that the elemental segment length $\delta_t$ should be selected to be small enough so that the location of UAV can be regarded as constant within each time segment. In this case, the horizontal trajectory of
UAV can be approximated by \((x[n], y[n]), \forall n \in \mathcal{N}\), where \((x[n], y[n])\) represents the UAV horizontal position at \(n\)-th time segment. Obviously, by adopting this discrete-time approximation method, we can only approximately obtain some results satisfying certain accuracy. Theoretically, any required accuracy can be guaranteed by choosing sufficient large \(N\). However, the design complexity will be increased with \(N\) increasing. Therefore, one should choose proper \(N\) considering both the requirements of accuracy and complexity.

Then, the trajectory constraints can be rewritten as

\[
(x[n+1] - x[n])^2 + (y[n+1] - y[n])^2 \leq d_{\text{max}}^2, \; n = 1, \ldots, N-1,
\]

where \(d_{\text{max}} = V_{\text{max}} \times \delta_t\) is the maximal flying distance of UAV within each time segment.

For simplicity, the communication link between UAV relay and each GU is assumed to be dominated by LoS link. In addition, we assume that the Doppler effect caused by UAV’s mobility is perfectly compensated at the receivers. As a result, the channel power gain from UAV relay to GU_1 and GU_2 at \(n\)-th time segment \(\delta_n\) can be expressed as

\[
h_{r,1}[n] = \frac{\beta_0}{x^2[n] + y^2[n] + H^2}, \; \forall n \in \mathcal{N},
\]

\[
h_{r,2}[n] = \frac{\beta_0}{(D - x[n])^2 + y^2[n] + H^2}, \; \forall n \in \mathcal{N},
\]

where \(\beta_0\) is the channel power gain at a reference distance (1 m).

Let \(p_{r,k}[n], k = 1, 2\) denote the transmission power of the UAV relay to corresponding GU_k, and \(p_k[n], k = 1, 2\) is the transmission power of GU_k during \(n\)-th time segment \(\delta_n\), respectively. Then, the channel capacity from UAV relay to GU_1 in bits/second/Hz (bps/Hz) at \(n\)-th time segment \(\delta_n\) can be expressed as

\[
C_{r,1}[n] = \log_2(1 + \frac{p_{r,1}[n]h_{r,1}[n]}{\sigma^2}), \quad i = 1, 2, \forall n \in \mathcal{N},
\]

\[
C_{r,2}[n] = \log_2(1 + \frac{p_{r,2}[n]h_{r,2}[n]}{(D - x[n])^2 + y^2[n] + H^2}), \quad \forall n \in \mathcal{N},
\]

where \(\sigma^2\) represents the noise power and \(\beta_0 \triangleq \frac{\beta_0}{\sigma^2}\) denotes the reference signal-to-noise ratio (SNR).

Similarly, the channel capacity from UAV to GU_2 is expressed as

\[
C_{1,r}[n] = \log_2(1 + \frac{p_{1}[n]h_{1,r}[n]}{x^2[n] + y^2[n] + H^2}), \; \forall n \in \mathcal{N},
\]

\[
C_{2,r}[n] = \log_2(1 + \frac{p_{2}[n]h_{2,r}[n]}{(D - x[n])^2 + y^2[n] + H^2}), \; \forall n \in \mathcal{N},
\]

In addition, the channel power gain from GU_k to UAV relay is denoted by \(h_{k,r}[n] = h_{r,k}[n], k = 1, 2, \forall n\). Therefore, we can derive the uplink channel capacities from GU_1 and GU_2 to UAV relay respectively,

\[
C_{1,r}[n] = \log_2(1 + \frac{p_{1}[n]h_{1,r}[n]}{x^2[n] + y^2[n] + H^2}), \; \forall n \in \mathcal{N},
\]

\[
C_{2,r}[n] = \log_2(1 + \frac{p_{2}[n]h_{2,r}[n]}{(D - x[n])^2 + y^2[n] + H^2}), \; \forall n \in \mathcal{N},
\]

Note that we assume the link capacity can be achieved by a capacity-achieving code, e.g. LDPC or Turbo codes.

**B. Information Exchange Schemes**

In this two-way relaying system, GUs and UAV relay are considered as half-duplex, which means they cannot transmit and receive at the same time. In addition, the data buffer equipped on the UAV is with sufficiently large size and all the GUs and UAV operate in TDMA mode. For information exchanging between two GUs, a traditional approach is to use the time-division multi-hopping scheme, called FSMH scheme, requiring four time slots to finish a cycle of information exchange. In addition, some other schemes have been proposed for two-way relaying, such as the NC scheme. By adopting network coding, the information exchange process can be completed within only three time slots. Furthermore, by adopting physical network coding technique, the time cost for a cycle of information exchange can be further decreased to only two time slots and this scheme is called PNC scheme. In the following, the details of those three schemes, i.e., FSMH, NC and PNC, are introduced briefly for better understanding.

1) Four-slot Multi-hopping Scheme: Generally, in a two-way relaying system, the direct links between two GUs are generally omitted. In this case, the FSMH scheme, which is shown in Fig. 1(b), enables the two GUs to communicate with each other through a relay node. In this scheme, four time slots are needed to finish a cycle of information exchange through the relay node. Specifically, at the first slot GU_1 (GU_2) uploads information to the relay, then the relay forwards the information that received from GU_1 (GU_2) to GU_2 (GU_1) at the next time slot. In the same way, it needs two other time slots for GU_2 (GU_1) to transmit information to GU_1 (GU_2) through the relay.

Denote \(R_1\) and \(R_2\) as the information rate from GU_1 to GU_2 and from GU_2 to GU_1 respectively, shown in Fig. 1(b). Note that the information rate can be seen as the amount of information transmitted per second from each GU to another GU. The achievable rate pairs for FSMH in each time segment can be described by the following constraints

\[
R_1 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_1[n]C_{1,r}[n]), \quad R_1 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_2[n]C_{r,2}[n]),
\]

\[
R_2 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_3[n]C_{r,2}[n]), \quad R_2 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_4[n]C_{r,1}[n]),
\]

\[
\sum_{i=1}^{4} \lambda_i[n] \geq 0, \forall n \in \mathcal{N}, i \in \{1, 2, 3, 4\}.
\]
and the relay. The achievable information rate pairs are expressed as

$$C_{FSMH} = \{(R_1, R_2) : (8), (9), (10)\}. \tag{11}$$

2) Three-slot Network Coding Scheme: By exploiting the NC scheme, the efficiency of information transmission can be improved since the information exchange process can be completed within only three time slots, shown in Fig. 1(b). For ease of exposition, we assume that GU1 wants to send $D_1$ to GU2 while GU2 is expected to send $D_2$ to GU1 through the relay.

In the NC scheme, GU1 and GU2 transmit $D_1$ and $D_2$ to the relay in the first two time slots sequentially. Then, the relay will bit-wise XOR the received information and broadcast the XOR-ed information to both GU1. After receiving the XOR-ed information, each GU can get its expected packet by XOR-ing its own packet with the received one. The core idea of this scheme is to broadcast the coded packet to both GUs by taking advantage of the broadcast nature of wireless communication.

For the NC scheme, the constraints for information rate $R_1$ and $R_2$ are

$$R_1 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_1[n]C_{1,r}[n]), \quad R_2 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_2[n]C_{1,r}[n]), \tag{12}$$

$$R_1 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_3[n]C_{r,2}[n]), \quad R_2 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_3[n]C_{r,1}[n]), \tag{13}$$

$$\sum_{i=1}^{3} \lambda_i[n] = 1, \lambda_i[n] \geq 0, \forall n \in \mathcal{N}, i \in \{1, 2, 3\}. \tag{14}$$

In this case, each time segment $\delta_n, \forall n$ is divided into 3 periods, i.e., $\lambda_1[n] \delta_n$, $\lambda_2[n] \delta_n$, and $\lambda_3[n] \delta_n$, as shown in Fig. 2(b). GU1 and GU2 upload information to the relay during $\lambda_1[n] \delta_n$ and $\lambda_2[n] \delta_n$, respectively. Then, $\lambda_3[n] \delta_n$ is used for the relay to broadcast the coded packets to both GUs. The achievable rate region for NC scheme is expressed as

$$C_{NC} = \{(R_1, R_2) : (12), (13), (14)\}. \tag{15}$$

3) Two-slot Physical Layer Network Coding Scheme: Fig. 1(c) indicates the simple process of the message exchange between GU1 and GU2 by using the PNC scheme. Specifically, the message exchange process for PNC scheme can be divided into two phases. In the first phase, GU1 and GU2 transmit their information ($D_1$ and $D_2$) to the relay simultaneously. Then, the relay encodes message $D_1$ to a channel code $X_{r,2}(D_1)$ according to the channel between the UAV relay and GU2. Assume that the channel between UAV and each GU are known at the relay and the GUs. Similarly, $D_2$ is encoded to a channel code $X_{r,1}(D_2)$ according to the channel between the relay and GU1. Then, the relay broadcasts the bit-wise XOR-ed packets $X_{r,2}(D_1) \oplus X_{r,1}(D_2)$ to both GUs. Finally, after receiving the broadcast information, each GU can decode its expected information by applying some proper operations. Note that we only give a brief introduction to the PNC scheme here for simplicity and one can refer to [27] for more details. We can see that only two time slots are needed to finish a cycle of information exchange by using the PNC scheme.

The achievable information rate pairs are expressed as

$$R_1 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_1[n]C_{1,r}[n]), \quad R_1 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_2[n]C_{1,r}[n]), \tag{16}$$

$$R_2 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_1[n]C_{2,r}[n]), \quad R_2 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_2[n]C_{2,r}[n]), \tag{17}$$

$$2 \lambda_i[n] = 1, \lambda_i[n] \geq 0, \forall n \in \mathcal{N}, i \in \{1, 2\}. \tag{18}$$

The information rate region for PNC scheme is denoted by

$$C_{PNC} = \{(R_1, R_2) : (16), (17), (18)\}. \tag{19}$$

In this scheme, each time segment $\delta_n, \forall n$ only needs to be divided into two parts, $\lambda_1[n] \delta_n$ and $\lambda_2[n] \delta_n$, shown in Fig. 2(c). The two GUs upload their information to the UAV simultaneously in the first period $\lambda_1[n] \delta_n$, and then the UAV forwards the PNC-modulated packets to both GUs in the rest time $\lambda_2[n] \delta_n$.

C. Problem Formulation

Let $\Lambda = \{\lambda_i[n], \forall i, n\}$, $P = \{p_w[n], p_k[n], \forall n, k\}$, $Q = \{x[n], y[n], \forall n\}$ denote the optimization parameters, i.e., time-sharing parameters, transmission powers and the UAV trajectory respectively. In this paper, we aim to maximize the average sum rate of the system by jointly optimizing the transmission powers $P$, time-sharing parameters, transmission powers and the UAV trajectory respectively. In this paper, we aim to maximize the average sum rate of the system by jointly optimizing the transmission powers $P$, time-sharing parameters, transmission powers and the UAV trajectory respectively. In this paper, we aim to maximize the average sum rate of the system by jointly optimizing the transmission powers $P$, time-sharing parameters, transmission powers and the UAV trajectory respectively.
For FSMH scheme, we formulate the optimization problem as

\begin{align}
\text{P1:} \quad & \max_{\Lambda, P, Q} R_1 + R_2, \\
\text{s.t.} \quad & (R_1, R_2) \in C_{FSMH}, \\
& \sum_{i=1}^{n} (\lambda_2[i] C_{r,2}[i]) \leq \sum_{i=1}^{n} (\lambda_1[i] C_{1,r}[i]), \forall n \in \mathcal{N}, \\
& \sum_{i=1}^{n} (\lambda_4[i] C_{r,1}[i]) \leq \sum_{i=1}^{n} (\lambda_3[i] C_{2,r}[i]), \forall n \in \mathcal{N}, \\
& \frac{1}{N} \sum_{n=1}^{N} (\lambda_2[n] p_{r,1}[n] + \lambda_4[n] p_{r,2}[n]) \leq P_r, \forall n \in \mathcal{N}, \\
& \frac{1}{N} \sum_{n=1}^{N} \lambda_1[n] p_{1}[n] \leq P_u, \frac{1}{N} \sum_{n=1}^{N} \lambda_3[n] p_{2}[n] \leq P_u, \forall n \in \mathcal{N}, \\
& 0 \leq p_{k}[n] \leq P_{\text{peak}}, \forall n \in \mathcal{N}, \forall k, \\
& (x[n+1] - x[n])^2 + (y[n+1] - y[n])^2 \leq \delta_{\text{max}}^2, \\
& n = 1, 2, ..., N-1,
\end{align}

where $P_r$ and $P_u$ denote the average transmission power limit for UAV and GU, respectively. $P_{\text{peak}}$ is the peak transmission power of all the transceivers. (21) indicates that the information rates $R_1$ and $R_2$ must be in the rate region. (24) and (25) give the average transmission power constraints over $T$ and (26) guarantees that the instant transmission powers of UAV and GUs are non-negative and no more than a maximum. Finally, (27) describes the constraints for UAV trajectory.

Similarly, we can also formulate the optimization problems for NC and PNC schemes by replacing the rate region in (21), constraints on transmission powers (24) and (25), as well as the information-causality constraints (22) and (23) in (P1).

For NC scheme, the problem is formulated as

\begin{align}
\text{P2:} \quad & \max_{\Lambda, P, Q} R_1 + R_2, \\
\text{s.t.} \quad & (R_1[n], R_2[n]) \in C_{NC}, \\
& \sum_{i=1}^{n} (\lambda_2[i] (C_{r,2}[i] + C_{r,1}[i])) \leq \sum_{i=1}^{n} (\lambda_1[i] C_{1,r}[i] + \lambda_2[i] C_{2,r}[i]), \forall n \in \mathcal{N}, \\
& \frac{1}{N} \sum_{n=1}^{N} (\lambda_3[n] p_{r,1}[n] + \lambda_3[n] p_{r,2}[n]) \leq P_r, \forall n \in \mathcal{N}, \\
& \frac{1}{N} \sum_{n=1}^{N} \lambda_1[n] p_{1}[n] \leq P_u, \frac{1}{N} \sum_{n=1}^{N} \lambda_3[n] p_{2}[n] \leq P_u, \forall n \in \mathcal{N}, \\
& 0 \leq p_{k}[n] \leq P_{\text{peak}}, \forall n \in \mathcal{N}, \forall k, \\
& (x[n+1] - x[n])^2 + (y[n+1] - y[n])^2 \leq \delta_{\text{max}}^2, \\
& n = 1, 2, ..., N-1,
\end{align}

Then, we formulate the joint optimization problem for PNC scheme.

\begin{align}
\text{P3:} \quad & \max_{\Lambda, P, Q} R_1 + R_2, \\
\text{s.t.} \quad & (R_1[n], R_2[n]) \in C_{PNC}, \\
& \sum_{i=1}^{n} (\lambda_2[i] (C_{r,2}[i] + C_{r,1}[i])) \leq \sum_{i=1}^{n} (\lambda_1[i] C_{1,r}[i] + \lambda_2[i] C_{2,r}[i]), \forall n \in \mathcal{N}, \\
& \frac{1}{N} \sum_{n=1}^{N} (\lambda_2[n] p_{r,1}[n] + \lambda_2[n] p_{r,2}[n]) \leq P_r, \forall n \in \mathcal{N}, \\
& \frac{1}{N} \sum_{n=1}^{N} \lambda_1[n] p_{1}[n] \leq P_u, \frac{1}{N} \sum_{n=1}^{N} \lambda_2[n] p_{2}[n] \leq P_u, \forall n \in \mathcal{N}, \\
& 0 \leq p_{k}[n] \leq P_{\text{peak}}, \forall n \in \mathcal{N}, \forall k, \\
& (x[n+1] - x[n])^2 + (y[n+1] - y[n])^2 \leq \delta_{\text{max}}^2, \\
& n = 1, 2, ..., N-1,
\end{align}

Note that the information-causality constraints for both NC and PNC are different from those for FSMH scheme, i.e., (22) and (23), because the relay broadcasts the coded packets to both GUs at the same time in NC and PNC schemes. The information-causality constraints for NC and PNC schemes are given in (30) and (36), respectively.

It is difficult to solve those problems (P1), (P2) and (P3) directly due to two reasons. Firstly, there are large numbers of optimization variables which are closely coupled, making the optimization problems extremely intractable. Secondly, problems (P1), (P2) and (P3) are both non-convex optimization problems due to the non-convexity of rate region constraints (21), (29) and (35), the information-causality constraints (22) and (23), (30), (36), respectively. Therefore, there are no efficient algorithms to solve them directly.

In the following, we first divide the optimization variables into three blocks, i.e., time-sharing parameters $\Lambda$, transmission powers $P$, and the UAV trajectory $Q$. Then we construct a sub-problem for each block of optimization variables while keeping other variables fixed, namely time-sharing parameters optimization with fixed transmission powers and UAV trajectory, trajectory optimization with fixed transmission powers and time-sharing parameters, power allocation optimization with fixed time-sharing parameters and UAV trajectory. Each block of variables is optimized by solving its corresponding optimization sub-problem. Then, an overall iterative algorithm, which solves those three sub-problems iteratively, based on block coordinate descent method is proposed to solve the origin joint optimization problem.

### IV. PROPOSED ALGORITHMS

In this section, we first introduce the three constructed sub-problems for (P1), (P2) and (P3). Then, the algorithms or methods for solving the sub-problems are given. Finally, we introduce the overall iterative optimization algorithm which solves the joint optimization problem based on block coordinate descent method.
A. Time Resources Allocation

With Given transmission powers and fixed UAV trajectory \( \{P, Q\} \), the sub-problem for TRA under FSMH scheme can be formulated as

\[
(P1.1) : \max_\lambda R_1 + R_2, \\
\text{s.t. } (21), (22), (23), (24), (25).
\]

It is observed that only the constraints related to time-sharing parameters are considered in (P1.1). The constraints on UAV trajectory and transmission powers are ignored in this sub-problem. However, in order to guarantee that the solutions of (P1.1) are feasible to (P1), the given transmission powers and UAV trajectory should also satisfy their corresponding constraints.

In addition, the corresponding sub-problems for NC and PNC schemes are expressed as

\[
(P2.1) : \max_\lambda R_1 + R_2, \\
\text{s.t. } (29), (30), (31), (32).
\]

\[
(P3.1) : \max_\lambda R_1 + R_2, \\
\text{s.t. } (33), (36), (37), (38).
\]

With any given UAV trajectory and power allocation, \( C_{k,r}[n], C_{r,k}[n], \forall k, n \) are constants. In this case, all the constraints in both (P1.1), (P2.1) and (P3.1) are linear constraints with respect to \( \lambda_i, \forall i \). As a result, all the sub-problems are standard linear programming and thus can be solved efficiently using existing convex optimization tools such as CVX [43].

B. Power Allocation Optimization

Similarly, to formulate the power allocation problem, we only need to consider the constraints related to transmission powers. Denote the sub-problems of power allocation for FSMH, NC, and PNC schemes with (P1.2), (P2.2) and (P3.2) respectively which are expressed as

\[
(P1.2) : \max_P R_1 + R_2, \\
\text{s.t. } (21), (22), (23), (24), (25), (26).
\]

\[
(P2.2) : \max_P R_1 + R_2, \\
\text{s.t. } (29), (30), (31), (32), (26).
\]

\[
(P3.2) : \max_P R_1 + R_2, \\
\text{s.t. } (33), (36), (37), (38), (26).
\]

Those sub-problems are both non-convex optimization problems due to the non-convexity of the corresponding information-causality constraints, i.e., (22) and (23), (30), (36). However, we can transform all those problems to equivalent convex optimization problems by introducing some slack variables.

Firstly, for the FSMH scheme, problem (P1.2) can be reformulated as

\[
(P1.3) : \max_{P,W_1,W_2} R_1 + R_2, \\
\text{s.t. } R_1 \leq \frac{1}{N} \sum_{n=1}^{N} W_1[n], R_2 \leq \frac{1}{N} \sum_{n=1}^{N} W_2[n], \\
W_1[n] \leq \lambda_2[n] \log_2(1 + p_{r,2}[n] \gamma_{r,2}[n]), \forall n \in \mathcal{N}, \\
W_2[n] \leq \lambda_4[n] \log_2(1 + p_{r,1}[n] \gamma_{r,1}[n]), \forall n \in \mathcal{N}, \\
\sum_{i=1}^{n} (W_1[i]) \leq \sum_{i=1}^{n} (\lambda_1[i] \log_2(1 + p_{1,r}[i] \gamma_{1,r}[i])), \forall n \in \mathcal{N}, \\
\sum_{i=1}^{n} (W_2[i]) \leq \sum_{i=1}^{n} (\lambda_3[i] \log_2(1 + p_{2,r}[i] \gamma_{2,r}[i])), \forall n \in \mathcal{N},
\]

where \( \gamma_{1,r}[n] = \gamma_{r,1}[n] = \frac{\lambda_1[n] C_{r,1}[n]}{x_0^2 + \gamma_{1,r}[n] + H^2}, \gamma_{2,r}[n] = \frac{\lambda_2[n] C_{r,2}[n]}{x_0^2 + \gamma_{1,r}[n] + H^2}, \mathbf{W}_1 = \{W_1[n], \forall n\} \) and \( \mathbf{W}_2 = \{W_2[n], \forall n\} \) are the slack variables. Note that at the optimal of (P1.2), the equality in (54) and (55) always holds. Otherwise, if there exists a slot \( n' \), the inequality in (54) and (55) is satisfied. Then we can always decrease \( p_{r,2}[n'] \) and \( p_{r,1}[n'] \) without decreasing the objective value. As a result, with fixed UAV trajectory and time-sharing parameters, (P1.3) is equivalent to (P1.2).

For the NC scheme, we can rewrite optimization problem (P2.2) as

\[
(P2.3) : \max_P R_1 + R_2, \\
\text{s.t. } R_1 + R_2 \leq \frac{1}{N} \sum_{n=1}^{N} (\lambda_3[n] C_{r,2}[n] + \lambda_3[n] C_{r,1}[n]),
\]

\[
(P2.4) : \max_P R_1 + R_2, \\
\text{s.t. } R_1 + R_2 \leq \frac{1}{N} \sum_{n=1}^{N} W_3[n], \\
W_3[n] \leq \lambda_3[n] C_{r,2}[n] + \lambda_3[n] C_{r,1}[n], \forall n \in \mathcal{N},
\]

\[
\sum_{i=1}^{n} W_3[i] \leq \sum_{i=1}^{n} \lambda_1[i] C_{1,r}[i] + \lambda_2[i] C_{2,r}[i], \forall n \in \mathcal{N},
\]

\[
\sum_{i=1}^{n} W_3[i] \leq \sum_{i=1}^{n} \lambda_3[i] C_{3,r}[i], \forall n \in \mathcal{N},
\]

\[
\sum_{i=1}^{n} W_3[i] \leq \sum_{i=1}^{n} \lambda_3[i] C_{3,r}[i], \forall n \in \mathcal{N},
\]

\[
\sum_{i=1}^{n} W_3[i] \leq \sum_{i=1}^{n} \lambda_3[i] C_{3,r}[i], \forall n \in \mathcal{N},
\]

\[
\sum_{i=1}^{n} W_3[i] \leq \sum_{i=1}^{n} \lambda_3[i] C_{3,r}[i], \forall n \in \mathcal{N},
\]

\[
\sum_{i=1}^{n} W_3[i] \leq \sum_{i=1}^{n} \lambda_3[i] C_{3,r}[i], \forall n \in \mathcal{N},
\]

\[
\sum_{i=1}^{n} W_3[i] \leq \sum_{i=1}^{n} \lambda_3[i] C_{3,r}[i], \forall n \in \mathcal{N},
\]

\[
\sum_{i=1}^{n} W_3[i] \leq \sum_{i=1}^{n} \lambda_3[i] C_{3,r}[i], \forall n \in \mathcal{N},
\]
where $W_3 = \{W_3[n], \forall n\}$ is a slack variable. Note that at an optimal of (P2.3), the inequality in (64) is always active. Otherwise, we can always increase $W_3$ to make it active without decreasing the objective value. Therefore, (P2.4) is equivalent to (P2.3). With (P2.3) being equivalent to (P2.2), we can conclude that (P2.4) is equivalent to the original problem (P2.2). (P2.4) is a convex optimization problem which can be solved using standard convex optimization techniques or tools.

For the PNC scheme, we can also formulate the power allocation problem (P3.2) to a convex optimization problem (P3.4) by rewriting a (P3.3) applying the same method as that used for NC scheme. For simplicity, (P3.3) is not presented and the convex optimization problem (P3.4) is expressed as

\[
(P3.4) : \max_{P,W_4} R_1 + R_2,
\]

subject to
\[
R_1 + R_2 \leq \frac{1}{N} \sum_{n=1}^{N} (W_4[n]), \quad (68)
\]
\[
W_4[n] \leq \lambda_2[n]C_{r,2}[n] + \lambda_2[n]C_{r,1}[n], \forall n \in \mathcal{N}, \quad (69)
\]
\[
\sum_{i=1}^{n} W_4[i] \leq \sum_{i=1}^{n} \lambda_1[i]C_{r,1}[i] + \lambda_1[i]C_{r,2}[i], \forall n \in \mathcal{N}, \quad (70)
\]
\[
\{26, 65, 67, 68\}, \quad (71)
\]

where $W_4 = \{W_4[n], \forall n\}$ is the slack variable introduced for PNC scheme.

\[\text{C. UAV Trajectory Optimization}\]

In this section, we formulate the sub-problems for UAV trajectory optimization with fixed power allocation and time resources allocation. Note that the information-causality constraints are also non-convex for trajectory optimization. To tackle the non-convexity, we also need to adopt slack variables. Then, for FSMH scheme, the optimization problem can be expressed as

\[
(P1.4) : \max_{Q,W_5,W_6} R_1 + R_2,
\]

subject to
\[
R_1 \leq \frac{1}{N} \sum_{n=1}^{N} W_5[n], R_2 \leq \frac{1}{N} \sum_{n=1}^{N} W_6[n], \quad (72)
\]
\[
W_5[n] \leq \lambda_2[n]C_{r,2}[n], W_6[n] \leq \lambda_4[n]C_{r,1}[n], \forall n \in \mathcal{N}, \quad (73)
\]
\[
\sum_{i=1}^{n} (W_5[i]) \leq \sum_{i=1}^{n} (\lambda_1[i]C_{r,1}[i]), \forall n \in \mathcal{N}, \quad (74)
\]
\[
\sum_{i=1}^{n} (W_6[i]) \leq \sum_{i=1}^{n} (\lambda_3[i]C_{r,2}[i]), \forall n \in \mathcal{N}, \quad (75)
\]
\[
\{10, 27\}, \quad (76)
\]

where $W_5 = \{W_5[n], \forall n\}$ and $W_6 = \{W_6[n], \forall n\}$ are both slack variables.

(P1.4) is a non-convex optimization problem due to the non-convex feasible set caused by constraints (74), (75) and (76). In the following, we will introduce how we solve this non-convex problem. Specifically, we first construct an approximate convex optimization problem denoted by (P1.5) for (P1.4). Then (P1.4) is solved by successively solving (P1.5). Specifically, the approximate solutions can be obtained by successive optimizing the incremental of the UAV trajectory at each iteration.

The non-convexity of constraints (74), (75) and (76) comes from the right side hand (RHS), i.e. $C_{r,1}[n]$, $C_{r,2}[n]$, $C_{r,1}[n]$ and $C_{r,2}[n]$ which are not concave functions of $Q$. Thus, we only need to focus on the transformation of the RHS.

Firstly, let $\{y_i[n], \phi_i[n]\}, \forall n \in \mathcal{N}$ denote the trajectory incremental from the l-th iteration to $(l+1)$-th iteration. The resulting horizontal trajectory after l-th iteration is denoted by $\{x_i[n], y_i[n]\}, \forall n \in \mathcal{N}$. Therefore, we can derive the UAV trajectory at $(l+1)$-th iteration, i.e., $x_{l+1}[n] = x_l[n] + \eta_l[n]$, $y_{l+1}[n] = y_l[n] + \phi_l[n], \forall n \in \mathcal{N}$. In addition, the corresponding uplink and downlink channel capacities at l-th iteration can be expressed as

\[
C_{r,1,l}[n] = \log_2(1 + \frac{p_{r,1}[n] \gamma_0}{x_l^2[n] + y_l^2[n] + H^2}), \forall n \in \mathcal{N}, \quad (78)
\]
\[
C_{r,2,l}[n] = \log_2(1 + \frac{p_{r,2}[n] \gamma_0}{(D - x_l[n])^2 + y_l^2[n] + H^2}), \forall n \in \mathcal{N}, \quad (79)
\]
\[
C_{r,1,l}[n] = \log_2(1 + \frac{p_1[n] \gamma_0}{x_l^2[n] + y_l^2[n] + H^2}), \forall n \in \mathcal{N}, \quad (80)
\]
\[
C_{r,2,l}[n] = \log_2(1 + \frac{p_2[n] \gamma_0}{(D - x_l[n])^2 + y_l^2[n] + H^2}), \forall n \in \mathcal{N}. \quad (81)
\]

We then have the following results.

Lemma 1: For any trajectory incremental $\eta_l[n], \phi_l[n], \forall n \in \mathcal{N}$, the inequalities hold

\[
C_{r,1,l+1}[n] \geq C_{r,1,l+1}^b[n] = C_{r,1,l}[n] - a_{1,1,l}[n](\eta_{l}[n]^2 + \phi_{l}[n]^2) - b_{1,1,l}[n](\eta_{l}[n] - c_{1,1,l}[n]\phi_{l}[n]), \quad (82)
\]

where $C_{r,1,l+1}^b[n]$ is the lower bound of $C_{r,1,l+1}[n]$, $a_{1,1,l}[n]$, $b_{1,1,l}[n]$ and $c_{1,1,l}[n]$ are coefficients which are explained and given in Appendix A.

Proof 1: Please refer to Appendix A.

Similarly, we can also derive the lower bound for $C_{r,2,l+1}$

\[
C_{r,2,l+1}^b[n] = a_{2,2,l}[n] \eta_l[n] + b_{2,2,l}[n] y_l[n], \quad (83)
\]

In this case, the coefficients can be obtained

\[
a_{2,2,l}[n] = \frac{-2 \log_2 e \gamma_2}{d_{2,2,l}[n](\frac{d_{2,2,l}[n]}{2} + \gamma_2)}, \quad (84)
\]
\[
b_{2,2,l}[n] = -2 a_{2,2,l}[n](D - x_l[n]), \quad (85)
\]
\[
c_{2,2,l}[n] = 2 a_{2,2,l}[n] y_l[n], \quad (86)
\]

where $d_{2,2,l}[n] = (D - x_l[n])^2 + y_l^2[n] + H^2$ is the square of distance between the UAV relay to GU2 at time segment $\delta_l$.

By replacing the corresponding parameters in (82) and (83), we can also derive the lower bounds $C_{r,1,l+1}^b$ and $C_{r,2,l+1}^b$ for $C_{r,1,l+1}$ and $C_{r,2,l+1}$, respectively.

From Lemma 1, we can see that for any trajectory incremental $\eta_l[n], \phi_l[n]$ and trajectory $x_{l}[n], y_{l}[n], \forall n \in \mathcal{N}$, the
resulting uplink and downlink capacities are lower bounded by
\( C_{2,r,l+1}, C_{1,r,l+1}, C_{b,l,1,l+1} \) and \( C_{b,2,r,l+1} \), respectively.

By defining \( I = \{ n, \phi_{I[n]} \} \), for all \( n \in \mathcal{N} \), we can reformulate (P1.4) as
\[
\begin{align*}
(P1.5) & : \max_{I, W_5, W_6} R_1 + R_2, \\
\text{s.t.} & \quad R_1 \leq \frac{1}{N} \sum_{n=1}^{N} W_5[n], R_2 \leq \frac{1}{N} \sum_{n=1}^{N} W_6[n], \\
& \quad W_5[n] \leq \lambda_2[n] C_{2,r}[n], W_6[n] \leq \lambda_4[n] C_{b,l}[n], \forall n \in \mathcal{N}, \\
& \quad \sum_{i=1}^{n} (W_5[i] + \sum_{i=1}^{n} (\lambda_1[i] C_{1,r}[i]), \forall n \in \mathcal{N}, \\
& \quad \sum_{i=1}^{n} (W_6[i] + \sum_{i=1}^{n} (\lambda_3[i] C_{2,r}[i]), \forall n \in \mathcal{N}.
\end{align*}
\]

Denote (P2.5) and (P3.5) as the sub-problems of UAV trajectory optimization for NC and PNC schemes respectively. Similarly, the formulation of the lower bound (P2.6) and (P3.6) for problem (P2.5) and (P3.5) can be easily obtained by replacing \( C_{1,r}, C_{2,r}, C_{r,1} \) and \( C_{r,2} \) with corresponding lower bounds \( C_{b,1,r}, C_{b,2,r}, C_{b,l} \) and \( C_{b,2,r} \) respectively. In case of redundancy, we do not present (P2.6) and (P3.6).

In rate region constraints (89), (90) and (91), \( C_{2,r,l+1}, C_{b,l,1,l+1} \) and \( C_{b,2,r,l+1} \), are concave quadratic functions with respect to \( \{ n[n], \phi_{n[n]} \}_{n=1}^{N} \) with given trajectory \( \{ x[i,n], y[i,n] \}_{n=1}^{N} \). The rest constraints are also convex over \( \{ n[n], \phi_{n[n]} \}_{n=1}^{N} \). Therefore, (P1.5), (P2.6) and (P3.6) are convex optimization problems which can be solved directly using standard convex optimization techniques. Furthermore, we can approximately solve (P1.4), (P2.5) and (P3.5) by successively solving (P1.5), (P2.6) and (P3.6), respectively. The detail process is shown in Algorithm 1.

Algorithm 1 Successive Trajectory Optimization Algorithm for (P1.4), (P2.5) and (P3.5)

*Initialize UAV trajectory \( \{ x_0[n], y_0[n] \} \), \( \forall n \in \mathcal{N} \) and \( l = 0 \).*

*repeat* Solve problem (P1.5)/(P2.6)/(P3.6) for optimal trajectory incremental \( I^* = \{ n^*_i[n], \phi_{n^*_i[n]} \}, \forall n \in \mathcal{N} \).

Update UAV trajectory \( x_{i+1}[n] = x_i[n] + n^*_i[n], y_{i+1} = y_i[n] + \phi_{n^*_i[n]} \).

Update \( l = l + 1 \).*

*until* Convergence or a maximum number of iterations has been reached.

D. Overall Iterative Algorithm

According to the analysis of those sub-problems, we propose an overall iterative algorithm for problem (P1), (P2) and (P3) by using the block coordinate descent method [14]. For the FSMH/NC/PNC scheme, we partition the entire optimization variables in problem (P1)/(P2)/(P3) into three blocks \( \{ \Lambda \}, \{ P \}, \{ Q \} \). Then, the time-sharing parameters \( \Lambda \) and power allocation \( P \) are optimized by solving convex optimization problem (P1.1)/(P2.1)/(P3.1) and (P1.2)/(P2.2)/(P3.2) respectively. The UAV trajectory \( Q \) is optimized by solving (P1.4)/(P2.5)/(P3.5). The obtained solution in each iteration is used as the input of the next iteration. The details of the algorithm are presented in Algorithm 2. Note that only convex optimization problem needs to be solved in each iteration in Algorithm 2. Therefore, the algorithm is of polynomial complexity in the worst situation [3]. The proposed algorithm converges quickly and can give a good lower bound for the original problems, which is shown in Section VI-D.

Algorithm 2 Overall Iterative Algorithm

*Initialize \( \{ \Lambda_0, P_0, Q_0 \} \) and \( r = 0 \).*

*repeat* Solve problem (P1.1)/(P2.1)/(P3.1) with given \( \{ P_r, Q_r \} \), and denote the optimal solution as \( \Lambda_{r+1} \).

Solve problem (P1.3)/(P2.4)/(P3.4) with given \( \{ \Lambda_{r+1}, Q_r \} \), and denote the optimal solution as \( P_{r+1} \).

Solve problem (P1.4)/(P2.5)/(P3.5) with given \( \{ \Lambda_{r+1}, P_{r+1} \} \), and denote the optimal solution as \( Q_{r+1} \).

Update \( r = r + 1 \).

*until* Convergence or a maximum number of iterations has been reached.

V. EFFECTS OF TRAFFIC PATTERN

In this section, we investigate how the traffic pattern, which is defined as the ratio between two rates \( R_1 \) and \( R_2 \), affects the performance of each scheme.

Firstly, we define the traffic pattern parameter as
\[
\mu = \frac{R_1}{R_2}, \tag{93}
\]
which is the ratio between \( R_1 \) and \( R_2 \).

This traffic pattern can describe different use cases. For example, if we denote \( R_1 \) as the downlink traffic while \( R_2 \) as the uplink traffic. Then, we have \( \mu \to 0 \) for webpage downloading while \( \mu \to 1 \) for gaming traffic. In addition, if \( R_1 \) and \( R_2 \) represent the traffic of two users who are chatting online with each other, we also have \( \mu \to 1 \). To explore the effects of the traffic pattern on the system performance for each scheme, we only need to reconstruct the joint optimization problems (P1), (P2) and (P3) by adding a new traffic pattern constraint
\[
R_1 = \mu R_2, \tag{94}
\]

The newly constructed problems for FSMH, NC and PNC scheme are denoted by (P4), (P5) and (P6), which are expressed as
\[
(P4) : \max_{\Lambda, P, Q} R_1 + R_2, \tag{95}
\]
\[
s.t. \quad R_1 = \mu R_2, \tag{96}
\]
\[
(21), (22), (23), (24), (25), (26), (27). \tag{97}
\]
Fig. 3. Time resources allocation with given UAV trajectory and transmission powers.

Fig. 4. Power allocation with given UAV trajectory and time-sharing parameters.

(P5) : \[
\max_{\Lambda, P, Q} R_1 + R_2,
\]
s.t. \[
R_1 = \mu R_2, \tag{29}
\]
(P6) : \[
\max_{\Lambda, P, Q} R_1 + R_2,
\]
s.t. \[
R_1 = \mu R_2, \tag{30}
\]

Since we only add an affine constraints in (P4),(P5) and (P6), those three problems can also be solved using the same methods or algorithms proposed for (P1), (P2) and (P3) respectively.

VI. NUMERICAL RESULTS

In this section, we give the simulation results for different schemes. The distance \( D \) between GU1 and GU2 is assumed to be 1000 m. The maximum UAV velocity \( V_{\text{max}} = 50 \text{ m/s} \) and the elemental time segment length \( \delta_t = 1 \text{ s} \), resulting that \( d_{\text{max}} = V_{\text{max}} \delta_t = 50 \text{ m} \). In addition, the reference channel power and the noise power are assumed to be \( \beta_0 = -50 \text{ dB} \) and \( \sigma^2 = -130 \text{ dB} \), respectively. Then, the reference signal-to-noise ratio \( \gamma_0 = 80 \text{ dB} \). Assume \( P_r = P_u = 10 \text{ dBm} \) (0.01 W) and the peak transmission power \( P_{\text{peak}} = 10P_r/10P_u = 0.1 \text{ W} \), except as otherwise noted.

A. Time resources allocation

In this section, we give the time resources allocation results with UAV flying from (0,0,100) towards (1000,0,100) in m with a constant velocity \( v = 20 \text{ m/s} \) and \( T = 50 \text{ s} \).

Fig. 3 indicates how the time resources are allocated to each communication link along with UAV flying from GU1 towards GU2 for different schemes. According to Fig. 3 we can describe the communication process for all schemes. Firstly, for the FSMH scheme, it is observed from Fig. 3(a) that all the time resources in each time segment are allocated to links GU1-to-UAV and UAV-to-GU2 during 0-25 s and 27-50 s, respectively. GU1 uploads information to the relay during 0-25 s and the relay forwards the information from GU1 to GU2 in 27-50 s. However, \( \lambda_3 \) and \( \lambda_4 \) are 0 during the whole mission period except in 25-27 s, which means that GU2 only has few opportunities to transmit information. In this case, the traffic from GU1 to GU2 (\( R_1 \)) and from GU2 to GU1 (\( R_2 \)) are extremely asymmetric. In some ways, the two-way relaying system can be regarded as a kind of one-way relaying system with GU1 being the source station while GU2 being the destination station. For the NC scheme, we can see from Fig. 3(b) that the GU1 first transmits information to the relay during 0-15s while all the time resources are allocated to the uplink GU2-to-relay during 15-33 s. Then, during 33-50 s, about 60 percent of the time resources in each time segment are allocated to the relay to broadcast the coded packets to both GUs while the rest time is used by GU2 to send information.
to the relay. It is also observed that $\lambda_3$ is always 0 until 33 s, indicating that the downlinks are inactive during 0-33 s. As a result, each GU can only receive its expected information after 33 s and there exists a transmission delay in this case. For the PNC scheme, the time resources allocation results are presented in Fig. 5(c). We can see that $\lambda_1$ and $\lambda_2$ are non-increasing and non-decreasing respectively. In addition, $\lambda_1$ is bigger than $\lambda_2$ during the first 27 s. It is expected because the information-causality constraints require that the UAV can only transmit the information it has been received. Therefore, more time resources should be allocated to the uplink channels in the first period. It is also observed that $\lambda_1$ and $\lambda_2$ are both non-zero during the whole mission period, which means that all the downlinks and uplinks are active in each time segment, guaranteeing instant information exchanging between two GUs.

B. Power allocation

In this section, we give the power allocation results with the same UAV trajectory in Section VI-A and set $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \frac{1}{4}$ for FSMH, $\lambda_1 = \lambda_2 = \lambda_3 = \frac{1}{3}$ for NC, $\lambda_1 = \lambda_2 = \frac{1}{2}$ for PNC when $T = 50$ s. Fig. 6 gives the power allocation results for different schemes. First, it is observed that GU2 transmits with a peak transmission power when the UAV is close to GU1 for the FSMH scheme shown in Fig. 6a. It is expected because we set $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \frac{1}{4}$ which means all the communications links, i.e., GU1-to-UAV, UAV-to-GU2, GU2-to-UAV, UAV-to-GU1, are active for the same time in each time segment. In order to improve the system sum rate, the GU with weak channels should increase its transmission power. At the beginning, GU2 is far away from the relay. Thus, it should increase its transmission power $p_{r,2}$ to compensate for the path loss caused by the long distance. In addition, because of the information-causality constraints, the total amount of information transmitted through downlinks should be no more than those received through the uplinks. Therefore, the transmission power of the uplinks should be high enough at the beginning of the mission period. This is the reason why $p_1$ and $p_2$ follows a non-increasing pattern and are higher than $p_{r,1}$ and $p_{r,2}$ for a period firstly for all schemes, as shown in Fig. 6a, Fig. 6b and Fig. 6c). Furthermore, we can see that the power allocation results for NC and PNC are similar while the transmission power in NC scheme are bigger than those in PNC scheme. With fixed UAV trajectory and time sharing parameters, the power allocation is mainly affected by the information-causality constraints. The power allocation problems (P2.4) and (P3.4) for NC and PNC have similar information-causality constraints. Therefore, the power allocation results for those two problems follow similar patterns.

C. UAV trajectory optimization

In this section, we give some results of UAV trajectory optimization with fixed power, i.e., $p_1 = p_2 = p_{r,1} = p_{r,2} = 10$ dBm, fixed time resources allocation, i.e., $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \frac{1}{4}$ for FSMH, $\lambda_1 = \lambda_2 = \lambda_3 = \frac{1}{3}$ for NC, $\lambda_1 = \lambda_2 = \frac{1}{2}$ for PNC when $T = 50$ s.

We compare the system performance under three different UAV trajectories with that under the optimal UAV trajectory obtained from Algorithm 1 for different schemes. The three trajectories are (1) Towards GU1: the UAV starts from the right above GU2 and flies in a line trajectory towards GU1 with a constant speed $v = \frac{D}{T}$. (2) Towards GU2: the UAV starts from the right above GU1 and flies in a line trajectory towards GU2 with a constant speed $v = \frac{D}{T}$. (3) Cyclic: the UAV flies between (400,0,100) and (600,0,100) cyclically in a line trajectory with the same velocity $v = \frac{D}{T}$.

From the results in Fig. 5a, (b) and (c), we can see that the system has the same performance with trajectory (1) and (2) for all the schemes. It is reasonable because the transmission powers and time resources allocation are the same for both GUs. In addition, the UAV will fly over the same location and stay for the same time over each location no matter in trajectory (1) or (2). Therefore, the channel capacities in each time segment are the same when UAV flies in those two trajectories. For example, When UAV is in trajectory (1), at the $n$-th time segment, the channel capacities for all the links are $C_{1,r}[n]$, $C_{2,r}[n]$, $\hat{C}_{r,1}[n]$, $\hat{C}_{r,2}[n]$ and information rates are $R_1$ and $R_2$. Then, with UAV flying in trajectory (2), at the $n$-th time segment, the corresponding channel capacities are $\check{C}_{1,r}[n]$, $\check{C}_{2,r}[n]$, $\check{C}_{r,1}[n]$, $\check{C}_{r,2}[n]$ and information rates are $\check{R}_1$ and $\check{R}_2$. Then, according to the symmetry of GUs’ locations, it is easy to obtained that $C_{1,r}[n] = C_{2,r}[n]$, $C_{1,r}[n] = C_{2,r}[n]$, $\check{C}_{r,1}[n] = \check{C}_{r,2}[n]$, $\check{C}_{r,1}[n] = \check{C}_{r,2}[n]$ and $R_1 = R_2$ and
$\hat{R}_2 = \hat{R}_1$. As a result, the system sum rate is the same under those two trajectories, i.e., $\hat{R}_1 + \hat{R}_2 = \hat{R}_1 + \hat{R}_2$.

In addition, the system performance with optimal UAV trajectory is better than those with other trajectories which indicates the necessity of the UAV trajectory optimization.

**D. Overall optimization**

In this section, the overall optimization results are presented. The transmission power is initialized as $p_1 = p_2 = 0.01$ W, $p_{r,1} = p_{r,2} = 0.005$ W and $P_r = P_u = 0.01$ W. The initial UAV trajectory is assumed to be a line trajectory named Towards GU$_2$ in Section VI-C. In addition, for each scheme, the initial time resources are average allocated to each link as described in Section VI-C.

Fig. 6 indicates the iteration process of the Algorithm 2 for different schemes. From this figure, we can see that the proposed algorithm is efficient since the fact that it converges after only 11, 17 and 9 iterations for FSMH, NC and PNC schemes, respectively.

Before presenting the UAV optimal trajectory, we have this lemma following.

**Lemma 2:** For (P1.1), (P2.1) and (P3.1), the optimal UAV trajectory satisfies that $x[n] \in [0, D]$, $y[n] = 0 \forall n \in N$, which indicates that the UAV should fly above the line segment connecting the two GUs to achieve maximum sum rate.

**Proof 2:** Assume the optimal UAV trajectory $x[n_1] < 0$ or $x[n_1] > D$ at some time segment $n_1$. Then, we can always construct a new trajectory with $x[n_1] \in [0, D]$ which can simultaneously decrease the distances between UAV to both GUs, resulting in better channel capacities for uplinks and downlinks. Thus, the system sum rate can be improved. Similarly, with optimal UAV trajectory $y[n_2] \neq 0$ at time segment $n_2$, then we can always replace it with another trajectory with $y[n_2] = 0$ to decrease the distance from UAV to each GU simultaneously and improve the system performance.

According to Lemma 2, we only need to give the UAV’s x-coordinate since the y-coordinate is always 0 during the whole mission period. Fig. 7 gives the optimal UAV trajectories for all schemes when $T = 30$ s, 70 s and Fig. 8 indicates the corresponding instant UAV speed with $T = 70$ s. Combining those two figures, we can see that the optimal UAV trajectories for all schemes follow the same pattern, i.e., hovering above GU$_1$ for a period firstly, then flying at a maximum speed towards GU$_2$ and hovering above GU$_2$ in the rest time.

In Fig. 9 we plot the system sum rate versus mission period $T$ with $P_r = P_u = 20$ dBm. Firstly, it is observed that for all schemes the system sum rate increases with the increase of mission period until saturation. By comparing the UAV optimal trajectories when $T = 30$ s, 70 s in Fig. 7 and Fig. 8, we can explain the reasons. The UAV-GU communication links are of the best quality when the UAV is right above some GUs because the distance between them is the shortest at that time. Thus, the system performance can be increased if the UAV relay can hover right above each GU for a longer time. From Fig. 7 we can see that the time UAV spends on flying from GU$_1$ to GU$_2$ are the same, i.e., $\frac{D}{V_{max}}$. Therefore, longer mission period enables the UAV hover right above each GU.
The maximum velocity is a system with a static relay. It is worth noting that if the sum rate of system is a constant just like that of GU for longer time. As a result, the system performance (sum rate) can be improved with mission period $T$ increasing. When $T$ becomes sufficient large, the time spent on flying between two GUs is negligible. In this case, the UAV trajectory can be regarded as hovering over GU$_1$ and GU$_2$ for $\frac{T}{2}$ sequentially and the sum rate of system is a constant just like that of a system with a static relay. It is worth noting that if the maximum velocity is $V_{\text{max}} \to \infty$, we have $\frac{D}{V_{\text{max}}} \to 0$ and the optimal UAV trajectory can be regarded as hovering over each GU for $\frac{T}{2}$, respectively. Though this setting is impractical, it can give us an upper bound for the average sum rate of this two-way relaying system. The upper bound for each scheme is shown in Fig. 9.

In addition, we also compare the system performance when UAV flies in an optimal trajectory with those when UAV stays static at (500,0,100) in Fig. 9 i.e., right above the middle of the line connecting two GUs. We can see that the system performance is greatly improved by jointly optimizing the UAV trajectory with transmission power and time-sharing parameters. On the other hand, the two-way relaying system with UAV staying static can be regarded as a kind of conventional two-way relaying system with a fixed terrestrial relay at a height of 100 m. The UAV-enabled two-way relaying system outperforms the conventional relaying system which indicates that by exploiting the new DoF brought by UAV’s mobility, the system performance can be improved greatly.

In Fig. 10 we give the ratio of $R_1$ and $R_2$, i.e., $\frac{R_1}{R_2}$, versus $T$ with $P_r = P_u = 0.1W$. We can see that for NC and PNC schemes, the ratio $\frac{R_1}{R_2}$ is no more than 2, which means that those schemes can keep a good balance between the traffic in links GU$_1$-to-UAV-to-GU$_2$ and GU$_2$-to-UAV-to-GU$_1$. Both GUs can send and receive a certain amount of information by adopting those two schemes during the whole process. However, for the FSMH scheme, we can see that this ratio is about 10 when $T = 20$ s and rapidly increases to 250 when $T = 70$ s. In this case, most of the time resources are assigned to links GU$_1$-to-UAV-to-GU$_2$ and this relaying system degenerates to a kind of one-way relaying system with only GU$_1$-to-UAV-to-GU$_2$ active at the most time. However, it is important to note that it is not a pure one-way relaying system since the fact that GU$_2$ can also transmit a little information to GU$_1$ through the relay.

Fig. 11 plots the system sum rate versus maximum transmission power. We can see that the system sum rate increases with the increase of maximum transmission power. It is reasonable because that bigger transmission power brings greater SNR as well as greater channel capacity. It is then observed that the system performance with PNC scheme is the best and that with FSMH scheme is the worst while UAV keeps static. However, with optimal trajectories, the FSMH scheme outperforms the NC scheme when the maximum transmission power is relatively low, i.e., 0.01-0.03W. With low SNR (or transmission power), when the UAV hovers above GU$_1$, the distance between UAV and GU$_2$ is relatively long, leading to bad channel conditions for links, GU$_2$-to-UAV and UAV-to-GU$_1$. For FSMH scheme, the two-way relaying can be approximately regraded as a kind of one-way relaying system and all the time resources is allocated to GU$_2$-to-UAV while the NC
scheme assigned the time resources to all the links. Therefore, the performance of the NC scheme is more likely to be affected by the weak channel capacities. Though the UAV can assign more time resources to both links with NC scheme than with the FSMH scheme in each time segment, it cannot compensate for the loss caused by the weak links GU2-to-UAV and UAV-to-GU1 when the SNR is relatively low. As a result, the sum rate is the worst in NC scheme with low transmission powers. However, with large transmission power, the channel gains of GU2-to-UAV and UAV-to-GU1 are improved and the loss can be well compensated. Thus, NC scheme is better than the FSMH scheme with higher maximum transmission power.

E. Effects of traffic pattern

To gain more insights, we explore the performance of all the schemes when $R_1$ and $R_2$ are symmetric $\mu = 1$ or asymmetric $\mu = 10$ respectively. It is observed that the PNC scheme outperforms the other schemes when the traffic $R_1$ and $R_2$ are symmetric. However, when $R_1 = 10R_2$ and the traffic is asymmetric, the FSMH becomes the one achieving best performance. It is expected because that even without traffic pattern the NC and PNC scheme achieve a balance between $R_1$ and $R_2$. Thus, the system sum rate only decreases a little after adding the traffic pattern constraints ($R_1 = R_2$) for those two scheme. However, with asymmetric traffic constraints, $R_2$ should be decreased a lot in order to guarantee $R_1 = 10R_2$ for NC and PNC scheme. For FSMH scheme, the traffic is extremely asymmetric even without the traffic pattern. Therefore, the asymmetric pattern has little influence on the performance of FSMH scheme. As a result, FSMH scheme has the best performance with asymmetric traffic. Finally, for use cases such as online chatting or gaming, the NC and PNC schemes are of priority while the FSMH scheme should be selected for use cases with asymmetric traffic like webpage downloading.

VII. CONCLUSION

In this paper, we propose a UAV-enabled two-way relaying system with one UAV relay and two GUs. We maximize the system throughput (average sum rate) by jointly optimizing the UAV trajectory, time-sharing parameters and the transmission powers for different schemes, i.e., FSMH, NC, PNC within a finite mission period. It is found that for all the schemes, the optimal UAV trajectory follows the same patterns, i.e., hovering over one GU for a period, then flying with maximum velocity to another GU and finally hovering over another GU. In addition, the system performance with asymmetric and symmetric traffic for all schemes is also investigated. The NC and PNC schemes have better performance than the FSMH scheme with symmetric traffic while the FSMH outperforms other two schemes when the traffic is extremely asymmetric.

APPENDIX A

PROOF OF LEMMA 1

Here, we define a function $f(z) = \log_2(1 + \frac{\gamma}{w + z})$ with constants $\gamma \geq 0$ and $w$, which can be proved convex in terms of $z \geq -w$. For any convex function, its first-Taylor approximation is in fact a global under-estimator of the function, i.e., $f(z) \geq f(z_0) + f'(z_0)(z - z_0)$, where $f'(z_0) = -\frac{\log_2 e \gamma}{w + z_0}$ is the derivative of $f(z)$ at point $z_0$. Therefore, we can obtain the following result by letting $z_0 = 0$

$$f(z) \geq \log_2(1 + \frac{\gamma}{w}) - \frac{\log_2 e \gamma}{w(w + \gamma)} z. \quad (104)$$

In addition, we have

$$C_{1,r,t+1}[n] = \log_2(1 + \frac{p_1[n]\gamma_0}{x_{t+1}[n] + y_{t+1}[n] + H^2}),$$

$$= \log_2(1 + \frac{p_1[n]\gamma_0}{(x_1[n] + y_1[n])^2 + (y_1[n] + \phi_1[n])^2 + H^2}),$$

$$= \log_2(1 + \frac{\gamma_1[n]}{\rho_{1,r,l}[n] + \Omega[n]}), \forall n \in \mathcal{N},$$

where $d_{1,r,l}^2[n] = x_1^2[n] + y_1^2[n] + H^2, \Omega[n] = \eta_1^2[n] + \phi_1^2[n] + 2\eta_1[n]x_1[n] + 2\phi_1[n]y_1[n]$. With a slight abuse of notation, we define $\gamma_1[n] \equiv p_1[n]\gamma_0, \gamma_2[n] \equiv p_2[n]\gamma_0, \gamma_3[n] \equiv p_{r,1}[n]\gamma_0$ and $\gamma_4[n] \equiv p_{r,2}[n]\gamma_0$.

Therefore, by letting $d_{1,r,l}^2[n] = w, \gamma_1[n] = \gamma$ and $\Omega[n] = z$, we can derive the following result

$$C_{1,r,t+1}[n] \geq \log_2(1 + \frac{\gamma_1[n]}{d^2_{1,r,l}[n]}) - \frac{\log_2 e \gamma_1[n]}{d^2_{1,r,l}[n](d^2_{1,r,l}[n] + \gamma_1[n])(\eta_1^2[n] + \phi_1^2[n] + 2\eta_1[n]x_1[n] + 2\phi_1[n]y_1[n])}$$

$$= C_{1,r,t}[n] - a_{1,r,l}[n]\eta_1[n] - b_{1,r,l}[n], \quad (106)$$

where

$$a_{1,r,l}[n] = \frac{\log_2 e \gamma_1[n]}{d^2_{1,r,l}[n](d^2_{1,r,l}[n] + \gamma_1[n])}, \quad b_{1,r,l}[n] = 2a_{1,r,l}[n]x_1[n], \quad c_{1,r,l}[n] = 2a_{1,r,l}[n]y_1[n].$$

So far, Lemma 1 has been proved.
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