Throughput maximization in a UAV-enabled Two-way Relaying System with Multi-pair Users

Xianzhen Guo, Bin Li, Jiayi Cong, and Ruonan Zhang

Abstract—In this letter, we propose a UAV-enabled two-way relaying system where a UAV relay assists the information exchange of multiple pairs of ground users (GUs). The minimum average information rate of each GU is maximized by jointly optimizing the user scheduling, transmission powers of the UAV and each GU, and the UAV trajectory. We formulate a mixed integer non-convex optimization problem which is hard to solve directly. To solve this optimization problem, we first divide all the optimization variables into three blocks and propose an iterative algorithm by adopting the block coordinate descent method and the successive convex approximation technique. The convergence of the proposed algorithm is also analyzed. The numerical results show that the proposed UAV-enabled relaying system outperforms its counterparts with static relay.

Index Terms—UAV, two-way relaying, multi-pair, user scheduling, trajectory optimization

I. INTRODUCTION

Recently, Wireless communications based on Unmanned aerial vehicles (UAVs) have attracted great attention due to the advantages brought by UAV [1], [2]. For example, the highly controllable 3D mobility of UAV provides a new design degree of freedom which enables the UAV-mounted base station (BS) to adjust its location adaptively according to the system requirements. The high altitude of UAV-BS is more likely to build line-of-sight (LoS) connections with ground users (GUs).

Accordingly, numerous UAV-enabled wireless communication systems have been proposed and studied. Firstly, the UAV-BS can be deployed to assist the existing terrestrial BS to provide ubiquitous coverage for certain areas or improve the quality of service of users [3]. The UAV can also be deployed as a data collector to collect delay-tolerant information from devices distributed in a wide area [4]. In addition, the UAV also plays an important role in relaying system [5], [6]. For UAV-enabled one-way relaying system, the UAV relay forwards the information from source station to destination station which cannot communicate with each other directly. [5] investigates a UAV-enabled one-way relaying system with one UAV relay, a source station and a destination station. The system throughput is maximized by jointly optimizing the transmission powers and the UAV trajectory. In [6], the authors derive the outage probability for communication links from the mobile device to the BS and minimize the outage probability by optimizing the transmission powers and the UAV trajectory.

Unlike in the one-way relaying system with unidirectional communications, the UAV relay is deployed to assist the bidirectional communications (information exchange) between each pair of GUs in a two-way relaying system. [8] investigates a UAV-enabled two-way relaying system which consists of one pair of GUs and one UAV relay. The authors optimize the transmit power, UAV trajectory and the bandwidth jointly to maximize the system throughput. The authors in [9] study a two-way relaying system which includes a ground base station and a set of distant GUs. They propose a novel concave surrogate function to tackle the proposed joint UAV positioning and power control problem.

In practical, there are usually more than one pair of GUs while the existing studies only focus on relaying system with only one pair of GUs. To the authors’ best knowledge, a UAV-enabled two-way relaying system with multiple pairs of GUs has not been investigated. Though [10] proposes a one-way relaying system with multi-pair GUs, the proposed methods cannot be applied in a two-way relaying system due to the difference between the one-way and the two-way relaying protocols.

In this letter, we propose a novel UAV-enabled two-way relaying system where the UAV relay assists the information exchange of multi-pair GUs in a TDMA mode by applying the decode-and-forward protocol. We maximize the system minimum average information rate by jointly optimizing the user scheduling variables, transmit power of each GU as well as the UAV, and the UAV trajectory. The formulated problem is a mixed integer non-convex problem which is hard to solve directly. By applying the block coordinate descent method and the successive approximation technique, we propose an iterative algorithm, which is proved to be convergent, to solve this non-convex problem. The numerical results show that the proposed UAV-based relaying system can achieve great performance improvement as compared to other benchmark relaying systems.

II. SYSTEM MODEL AND PROBLEM FORMULATION

A. System Model

In this paper, we consider a UAV-enabled two-way relaying system which consists of one UAV relay and $K>1$ pairs of GUs. The two GUs in the same pair exchange information through the UAV relay. We assume that the $k$-th pair of GU includes $G_U$ and $G_U^{K+k}$. In general, the mission period of
UAV is finite, denoted by $T$, due to the limited on-board power. By applying a 3D coordinate system, we denote $w_k = [x_k, y_k]^T$ as the fixed horizontal position of GU$_k$, $k \in K \triangleq \{1, 2, \ldots, 2K\}$. The UAV is assumed to fly in a fixed altitude $H$ above the ground and the horizontal coordinate of the UAV at time $t$ is $q(t)$, $0 \leq t \leq T$, which is time-varying due to the UAV’s mobility.

For ease of exposition, we can discretize the entire mission period of the UAV into $N$ time slots equally, indexed by $n = 1, \ldots, N$. The elemental time slot length is $\delta_t = \frac{T}{N}$ which is chosen to be sufficiently small so that the UAV’s location can be approximately regarded as unchanged during each time slot.

Denote $q[n]$ as the UAV’s location at time slot $n$. In practice, due to UAV’s physical characteristics or the mission requirements, the UAV’s trajectory should follow some rules following. Firstly, the initial and final locations of the UAV are usually predetermined [2] and we have

$$q[0] = q_0, \quad q[N] = q_f,$$  

where $q_0$ and $q_f$ are the predetermined initial and final locations of the UAV.

In addition, due to the UAV’s physical characteristics, the speed of UAV cannot exceed a maximum, which is expressed as

$$\|q[n] - q[n - 1]\|^2 \leq (V_{\text{max}}\delta_t)^2, \quad n = 1, \ldots, N,$$  

where $V_{\text{max}}$ is the maximal speed of UAV.

The distance from the UAV to GU$_k$ at time slot $n$ is expressed as $d_k[n] = \sqrt{\|q[n] - w_k\|^2 + H^2}$.

We assume that the communication links from the UAV to GUs are dominated by LoS links [11]. In addition, the Doppler effects caused by the UAV mobility is assumed to be well compensated at the receivers. Therefore, the channel power gain from UAV to GU$_k$ in each time slot $n$ follows the free space loss model, which can be expressed as

$$h_k[n] = \beta_0 d_k[n]^2 = \frac{\beta_0}{\|q[n] - w_k\|^2 + H^2},$$  

where $\beta_0$ is the channel power at the reference distance 1m.

Since there are $K$ pairs of GU and one UAV relay, we assume that the UAV serves the GUs via a periodic/cyclical time-division multiple access (TDMA). The UAV can only serve one pair of GU during each time slot. Denote a binary variable $a_k[n]$, $k = 1, \ldots, K$, which indicates that the UAV serves the $k$-th pair of GU (GU$_k$ and GU$_{K+k}$) during time slot $n$ if $a_k[n] = 1$; otherwise, if $a_k[n] = 0$. Accordingly, we have the following constraints

$$\sum_{k=1}^{K} a_k[n] \leq 1, \quad \forall n, \quad a_k[n] \in \{0, 1\}, \quad \forall k, n.$$  

Constraint (4) indicates that the UAV relay can only serve one pair of GUs during each time slot. In the two-way relaying system, we adopt the decode-and-forward protocol and the physical-layer network coding (PNC) technique is also applied. Specifically, during each time slot, the information process of the pair of GU served by the UAV is that both GUs firstly uploads information to the UAV simultaneously. Then, the GU encodes the received packets and broadcasts them to both GUs. After receiving the coded packets, both GU can decode its expected information after some proper operation. The detailed process of information exchanging by applying PNC technique can be referred to [12].

Then, the uplink capacity in bits/second/Hertz (bps/Hz) from GU$_k$ to the UAV relay at time slot $n$ can be expressed as

$$C_{u,k}[n] = \log_2 (1 + \frac{p_k[n]h_k[n]}{\sigma^2}),$$  

where $\sigma^2$ denotes noise power, $p_k[n]$ represents the transmission power of GU $k$ at time slot $n$ and $\gamma_0 \triangleq \beta_0/\sigma^2$ is the reference signal-to-noise ratio (SNR).

Similarly, the corresponding downlink capacity from UAV to GU$_k$ at time slot $n$ is

$$C_{d,k}[n] = \log_2 (1 + \frac{p_r[n]h_k[n]}{\sigma^2}),$$  

where $p_r[n]$ is the transmission power of the UAV relay at time slot $n$.

In practice, there are some constraints on transmission powers of the GUs and the UAV relay. Here, we consider the peak transmission power constraints which are

$$0 \leq p_r[n] \leq P_{\text{peak}}, \quad 0 \leq p_k[n] \leq P_{\text{peak}}, \forall k, n,$$  

where $P_{\text{peak}}$ is the peak transmission power of both UAV and each GU.

Accordingly, the achievable uplink and downlink information rates of GU$_k$ in time slot $n$ in bps/Hz can be expressed as

$$R_{u,k}[n] = a_k[n]\log_2 (1 + \frac{p_k[n]h_k[n]}{\|q[n] - w_k\|^2 + H^2}),$$  

$$R_{d,k}[n] = a_k[n]\log_2 (1 + \frac{p_r[n]\gamma_0}{\|q[n] - w_k\|^2 + H^2}).$$  

In UAV-enabled relaying, we need to consider the information-causality constraint, which implies that the UAV relay can only forward the information which has been received [7]. The information causality constraint is expressed as

$$\sum_{i=1}^{n} R_{d,k}[i] \leq \sum_{i=1}^{n} R_{u,k'}[i], \quad \forall n, k, k',$$  

where $R_{u,k'}$ indicates the uplink information rate of the GU which is in the same pair with GU$_k$.

The achievable average rate of GU$_k$ during the whole mission period $T$ is

$$\bar{R}_k = \frac{1}{N} \sum_{n=1}^{N} R_{d,k}[n].$$  

B. Problem Formulation

Let $A = \{a_k[n], \forall k, n\}$, $Q = \{q[n], \forall n\}$, and $P = \{p_r[n], p_k[n], \forall k, n\}$. In this paper, we aim to maximize the minimum achievable rate of GUs, i.e., $\min_{k \in K} \bar{R}_k$, by jointly optimizing the user scheduling parameter ($A$), transmission
powers of the GU s and the UAV \((P, Q)\), and the UAV trajectory \((Q)\). Then, the optimization problem can be formulated as

\[
(P1) : \max_{A, P, Q} \min_{k \in K} \bar{R}_k
\]

s.t. (1), (2), (3), (4), (5), (6), (11). (14)

It is hard to solve problem (P1) directly due to two main reasons. Firstly, the optimization variables for user scheduling \(A\) are binary, resulting in the integer constraints (5). Second, even with fixed user scheduling, the objective function of (P1) and the information constraints are non-convex constraints with respect to transmit power variables \(P\). Therefore, problem (P1) is a mixed-integer non-convex problem, which is difficult to be optimally solved efficiently.

III. PROPOSED ALGORITHM

To make the original problem more tractable, we first rewrite the problem as

\[
(P2) : \max_{A, P, Q, \eta} \eta
\]

s.t.

\[
\frac{1}{N} \sum_{n=1}^{N} R_{d,k}[n] \geq \eta, \forall k,
\]

\[
0 \leq a_k[n] \leq 1, \forall k, n,
\]

(15), (16), (17), (18)

where \(\eta(A, P, Q)\) is defined as a function of \(A, P, Q\).

Compare (P1) with (P2), we can see that we introduce a slack variable \(\eta\) to make the objective function an affine function. In addition, we relax the binary variables in (5) into continuous variables as expressed in (17). Such relaxation implies that the objective value of (P2) serves as an upper bound for that of problem (P1). In spite of the relaxation and the transformation, the resulted problem (P2) is still non-convex due to the non-convexity of (11). Therefore, there is no standard method to solve this problem efficiently. In the following, we introduce the proposed algorithm for solving the problem (P2). Specifically, we firstly divide the entire optimization variables into three blocks, i.e., GU scheduling variables \(A\), the transmit power variables \(P\), and the UAV trajectory variable \(Q\). Then, we optimize each block of variables with the other two blocks of variables fixed. Finally, based on the block coordinate descent technique, we propose an iterative algorithm to solve the original problem.

A. USER SCHEDULING OPTIMIZATION

With any given UAV trajectory and transmit powers \(\{Q, P\}\), the user scheduling optimization problem can be formulated as

\[
(P2.1) : \max_{A, \eta} \eta
\]

s.t. (4), (11), (16), (17). (19)

We can see that this problem (P2.1) is a standard linear programming which can be solved efficiently using existing optimization tools such as CVX. In addition, it is easy to verify that the equality in (4) holds at the optimal \(A^*\) with given UAV trajectory and transmit powers.

B. POWER ALLOCATION

With any given UAV trajectory and user scheduling \(\{Q, A\}\), the optimal transmit powers of all the GU and the UAV can be obtained by solving the following problem.

\[
(P2.2) : \max_{\eta, P} \eta
\]

s.t. (5), (11), (16). (20)

This problem is still non-convex since the left-hand-side of (11) is not convex with respect to \(\eta\). Therefore, there is no existing method to solve this problem efficiently. In spite of the relaxation and the transformation, the resulted problem (P2.2) is still a non-convex problem since the left-hand-side of (25) and (26) are not concave with respect to \(\eta\). Therefore, there is no existing method to solve this problem efficiently. In the following, we adopt the successive convex optimization technique to solve this problem. Though the right-hand side of (25) is not concave with respect to \(q[n]\), it is a convex function of \(\|q[n] - w_{k'}\|^2\). Recall that the first-order Taylor expansion of any convex
function provides a global under-estimator \[13]. Therefore, at any given local point \(Q^* = \{q^*[n]\}\) in the \(s\)-th iteration, we can obtain the lower bound \(C_{u,k}^{lb}[n]\) for \(C_{u,k}[n]\) as 
\[ C_{u,k}^{lb}[n] = \log_2(1 + \frac{p_k[n]r_{0}}{||q[n] - w_k||^2 + H^2}), \]
where \(A_{u,k}^{lb}[n]\) and \(B_{u,k}^{lb}[n]\) are constants that are

\[ A_{u,k}^{lb}[n] = \frac{1}{1 + \frac{p_k[n]r_{0}}{||q[n] - w_k||^2 + H^2}}, \]

satisfying

\[ B_{u,k}^{lb}[n] = \log_2(1 + \frac{p_k[n]r_{0}}{||q[n] - w_k||^2 + H^2}), \]

with the other two block of variables fixed, shown in Algorithm \[1\]. Let \(\eta_i\) denote the objective values of problem (P2) based on \(A^s, P^s, Q^s\). Since that problems (P2.1) can be solved optimally with given \(Q^s, P^s\) respectively, we have

\[ \eta(A^s, P^s, Q^s) \leq \eta(A^{s+1}, P^s, Q^s). \] (43)

Similarly, optimal solution of (P2.2) can also be obtained with given \(A^{s+1}, Q^s\) and we have

\[ \eta(A^{s+1}, P^{s+1}, Q^s) \leq \eta(A^{s+1}, P^{s+1}, Q^s). \] (44)

Then, with given \(A^{s+1}, P^{s+1}\) and \(Q^s\), it follows that

\[ \eta(A^{s+1}, P^{s+1}, Q^s) \leq \eta(A^{s+1}, P^{s+1}, Q^s). \] (45)

where (a) holds since that the first-order Taylor expansion in (22) is tight at the given local points \[13\]; (b) holds since that with given \(A^{s+1}, P^{s+1}\), problem (P2.5) is solved optimally with solution \(Q^{s+1}\); (c) holds since that the objective value of (P2.5) is a lower bound of that of (P2.4).

Combining (43), (44) and (45), we can obtain that

\[ \eta(A^s, P^s, Q^s) \leq \eta(A^{s+1}, P^{s+1}, Q^s), \] (46)

which indicates that the objective value of (P2) is non-decreasing after each iteration in Algorithm \[1\]. In addition, the objective value of problem (P2) is upper bounded by a finite value. Thus, the proposed Algorithm is guaranteed to converge.

**IV. NUMERICAL RESULTS**

In this section, we give the numerical results to analyze the performance of this proposed UAV-based relaying system. We consider a system with \(K = 3\) pairs of GUs (6 GUs). The locations of the first, second and third pair of GUs are \(w_1 = [-1000, 100]^T\) and \(w_2 = [1000, 100]^T\), \(w_2 = [-1000, 0]^T\) and \(w_5 = [1000, 0]^T\), \(w_3 = [-1000, -1000]^T\) and \(w_6 = [1000, -1000]^T\) respectively. In addition, we set \(H = 100m, V_{max} = 50m/s, \beta_0 = -60dB, \sigma^2 = -110dBm, \delta_t = 1s.\)
It is first observed that the system throughput increases until saturation with $T$ increasing. This is expected since that longer mission period enables the UAV to fly closer to each GU and shorter distance brings better channel condition and greater channel capacity. In addition, we can see that the max-min average rate with $P_{\text{peak}} = 20 \text{ dBm}$ is much bigger than that with $P_{\text{peak}} = 10 \text{ dBm}$. It is reasonable since that with bigger peak transmission powers, the channel capacity can be improved according to (6) and (7). Furthermore, we can see that by jointly optimizing the user scheduling, power allocation and UAV trajectory, the UAV-enabled two-way relaying system with multi-pair users can achieve great throughput gains over other systems with static relay.

V. CONCLUSION

In this letter, we consider a UAV-enabled two-way relaying system where the UAV relay assists the information exchange among multi-pair users. The minimum average rate is maximized by jointly optimizing the user scheduling, transmission powers and the UAV trajectory. An iterative algorithm is proposed to solve the formulated mixed-integer non-convex problem. The numerical results show that a great throughput gain is achieved by the proposed relaying design. In addition, the proposed method can be extended to two-way relaying system with multiple UAV relays and multi-pair users, which will be left as future work.

REFERENCES

[1] Y. Zeng, R. Zhang, and T. J. Lim, “Wireless communications with unmanned aerial vehicles: opportunities and challenges,” IEEE Commun. Mag., vol. 54, no. 5, pp. 36–42, May 2016.
[2] Y. Zeng, Q. Wu, and R. Zhang, “Accessing from the sky: A tutorial on uav communications for 5g and beyond,” Proc. IEEE, vol. 107, no. 12, pp. 2327–2375, Dec 2019.
[3] M. Alzenad, A. El-Keyi, F. Lagum, and H. Yanikomeroglu, “3-d placement of an unmanned aerial vehicle base station (uav-bs) for energy-efficient maximal coverage,” IEEE Wireless Commun. Lett., vol. 6, no. 4, pp. 434–437, Aug 2017.
[4] C. Zhan and Y. Zeng, “Completion time minimization for multi-uav-enabled data collection,” IEEE Trans. Wireless Commun., vol. 18, no. 10, pp. 4859–4872, Oct 2019.
[5] Y. Zeng, R. Zhang, and T. J. Lim, “Throughput maximization for uav-enabled mobile relaying systems,” IEEE Trans. Commun., vol. 64, no. 12, pp. 4983–4996, Dec 2016.
[6] S. Zeng, H. Zhang, K. Bian, and L. Song, “Uav relaying: Power allocation and trajectory optimization using decode-and-forward protocol,” in Proc. IEEE ICC Workshops, 2018, pp. 1–6.
[7] S. Ahmed, M. Z. Chowdhury, and Y. M. Jang, “Energy-efficient uav relaying communications to serve ground nodes,” IEEE Commun. Lett., vol. 24, no. 4, pp. 849–852, 2020.
[8] S. Eom, H. Lee, J. Park, and I. Lee, “Uav-aided two-way mobile relaying systems,” IEEE Commun. Lett., vol. 24, no. 2, pp. 438–442, 2020.
[9] L. Li, T. Chang, and S. Cai, “Uav positioning and power control for two-way wireless relaying,” IEEE Trans. Wireless Commun., vol. 19, no. 2, pp. 1008–1024, 2020.
[10] R. Fan, J. Cui, S. Jin, K. Yang, and J. An, “Optimal node placement and resource allocation for uav relaying network,” IEEE Commun. Lett., vol. 22, no. 4, pp. 808–811, 2018.
[11] Y. Zeng and R. Zhang, “Energy-efficient uav communication with trajectory optimization,” IEEE Trans. Wireless Commun., vol. 16, no. 6, pp. 3747–3760, 2017.
[12] B. Nazer and M. Gastpar, “Reliable physical layer network coding,” Proc. IEEE, vol. 99, no. 3, pp. 438–460, 2011.
[13] S. Boyd and L. Vandenberghe, Convex Optimization. Cambridge, U.K.: Cambridge Univ. Press, 2004.
[14] Q. Wu, Y. Zeng, and R. Zhang, “Joint trajectory and communication design for multi-uav enabled wireless networks,” IEEE Trans. Wireless Commun., vol. 17, no. 3, pp. 2109–2121, 2018.