Energy Efficient Communication of Fuel-Powered UAV Relay, Design of Positions and Power Allocation

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Abstract. In this paper, we study the energy efficient communication of a fuel-powered UAV relay. Since the fuel-power UAV has separate power supply for communication and operation, and the fuel can support hours' flight, we focus on the energy efficient communication of the UAV. We study two scenarios as a comparison, including the UAV working as a one-way relay and a two-way relay. The non-convex optimization problem is solved using successive convex approximation (SCA) method and difference of convex functions (DC) programming. The upper bounds and lower bounds of the data rates are proposed to transform the problem to an equivalent convex optimization problem. Numerical results show that the proposed upper bounds and lower bounds of the data rates converges to the same value. And the convergence of the objective function is also shown. The differences of the UAV's placement and power allocation as a one-way relay and a two-way relay are compared in the discussion.

Keywords: Energy efficient communication · Fuel-powered UAVs · One-way relay · Two-way relay

1 Introduction

In recent years, the application of unmanned aerial vehicles (UAVs) on communication networks has drawn wide attention [1,2,4]. Related studies focused on the UAV-assisted communication networks and UAVs in cellular networks [3,7,10]. Benefit from their high mobility, UAVs have bright prospect of working as relays or temporary base stations to build provisional communication networks for disaster recovery and wilderness exploration.

Unlike electric UAVs, which have short flight endurance, and fuel-cell UAVs, which requires high budget and long start-up time [5,6], fuel-powered UAVs have mature technologies, long endurance of flight and are adaptable to different environments. Fuel-powered UAVs are driven by internal combustion engines (ICEs) [8]. Although they also have drawbacks, such as noise and relatively

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lower efficiencies, they are still irreplaceable when high load, long endurance and low budget are required.

There are two categories of energy efficiencies related to UAV relays or base stations, energy efficient operation and energy efficiency communication [11]. When it comes to electric UAVs, the energy efficient operation is quite important because the communication module and operation are powered jointly by electric, and the operation consumes much more energy than the communication. As for fuel-powered UAVs, the energy efficient communication should be also considered, since the communication module is powered by batteries separately. The mission time is related to both the communication and the operation.

As for studies considering the problems of energy efficiency of UAVs, most of the studies focused on electricity-powered UAVs, of which the communication power and mechanical power are jointly provided by batteries [1,9]. The influence of the UAV's positions and communication power to the energy efficient of communication module on fuel-powered UAV relays has been left as unexplored questions. In this paper, we focus on the energy efficiency communication, related to the UAV positions. The UAV, working as a one-way relay and a two-way relay, are both studied, as a comparison.

2 System Model

We consider a three node communication system, consisting of a UAV and two ground nodes. The UAV flies at a fixed altitude as a relay. Denote the ground nodes as Node 1 and 2, and the UAV as A. Use k to denote the number of ground users, $k = 1, 2$. The positions of the ground users are $(x_k, y_k, 0)$. The UAV's position is (x_A, y_A, H). The power from the ground nodes is denoted as p_k. The power from the UAV to the two ground nodes is denoted as $p_{A,k}$. Suppose the UAV and the ground nodes have line of sight (LoS) channels, the channel gains between Node 1 and Node 2 and the UAV are $|h_{A,k}|^2 = C\sqrt{(x_A - x_k)^2 + (y_A - y_k)^2 + H^2}^{-\alpha}$, where C and α are the path loss at the reference distance, and path loss exponent, respectively. Then the data rate of from Node k to the UAV and the data rate from the UAV to the Node k are

$$R_{k,A} = \log_2\left(1 + \frac{p_k|h_{A,k}|^2|}{\sigma^2}\right), R_{A,k} = \log_2\left(1 + \frac{p_A|h_{A,k}|^2|}{\sigma^2}\right), \tag{1}$$

where σ^2 is the power of Gaussian white noise.

The energy efficiency of the one-way UAV relay can be formulated as

$$EE_o = \frac{R_{A,k}}{p_{A_k} + p_0}, \tag{2}$$

where p_0 is the circuit power of the communication module. Considering the information causality constraint, we have

$$R_{up} \leq R_{down}, \tag{3}$$

which means the information transmitted from UAV should be less than the information received by the UAV. We consider the constraints of communication power for the ground nodes and the UAV. The maximum power for a ground node is denoted as P_G, while the maximum power for the UAV is denoted as P_A. Then we have

$$p_1 \leq P_G, p_{A,2} \leq P_A. \tag{4}$$

The problem for power allocation and UAV's position is formulated as

$$\max_{p_1, p_A, x_A, y_A} EE_o \tag{5}$$
$$s.t. (3), (4)$$

The energy efficient problem of two-way relay is similar to the one way relay situation:

$$EE_t = \frac{1}{2} \sum_{k=1}^{2} \frac{R_{A,k}}{p_A + p_0} \tag{6}$$

$$s.t. (3),$$

$$p_k \leq P_G, \sum_{k=1}^{K} p_{A,k} \leq P_A \tag{7}$$

3 The Position and Power of the UAV

The energy-efficient problems are non-convex because of the non-concave objective functions and the constraint (3). To find the optimal power allocation scheme and the UAV's position, we refer to the successive convex approximation (SCA) method and difference of convex functions (DC) programming method.

We introduce the slake variables $\breve{\eta}_k$ for the energy efficiency. According to the SCA method, we consider the convex constraints

$$\ln \breve{\eta}_k^{(j-1)} + \frac{1}{\breve{\eta}_k^{(j-1)}} \delta_{\eta_k} + \ln \left(p_{A,k}^{(j-1)} + p_0 \right) + \frac{1}{p_{A,k}^{(j-1)} + p_0} \delta_{p_{A,k}} \leq \ln \left(\bar{R}_{A,k} \right), \tag{8}$$

$$\bar{R}_{A,k} \leq \check{R}_{A,k}, \tag{9}$$

where $\check{R}_{A,k}$, is the lower bound of $R_{A,k}$, we have

$$\check{R}_{A,k} = \log_2 \left(1 + \gamma_{A,k}^{(j)} \right), \check{R}_{k,A} = \log_2 \left(1 + \gamma_{k,A}^{(j)} \right), \tag{10}$$

where

$$\ln \gamma_{A,k}^{(j-1)} + \frac{\delta_{\gamma_{A,k}}}{\gamma_{A,k}^{(j-1)}} + f\left(\delta_{x_A}, \delta_{y_A}\right) \leq \ln \left[\left(p_{A,k}^{(j-1)} + \delta_{p_{A,k}} \right) C \right]. \tag{11}$$

$$\ln \gamma_{k,A}^{(j-1)} + \frac{\delta_{\gamma_{k,A}}}{\gamma_{k,A}^{(j-1)}} + f\left(\delta_{x_A}, \delta_{y_A}\right) \leq \ln \left[\left(p_k^{(j-1)} + \delta_{p_k} \right) C \right], \tag{12}$$

$$f\left(\delta_{x_A},\delta_{y_A}\right)=\ln\sigma^2+\frac{\alpha}{2}\ln\left[\left(x_A^{(j-1)}-x_k\right)^2+\left(y_A^{(j-1)}-y_k\right)^2+H^2\right]$$
$$+\frac{\alpha}{2}\frac{\left[\delta_{x_A}^2+\delta_{y_A}^2+2\left(x_A^{(j-1)}-x_k\right)\delta_{x_A}+2\left(y_A^{(j-1)}-y_k\right)\delta_{y_A}\right]}{\left(x_A^{(j-1)}-x_k\right)^2+\left(y_A^{(j-1)}-y_k\right)^2+H^2},\quad (13)$$

Then we derive an upper bound of $R_{A,k}$ as

$$\widehat{R}_{A,k}=\log_2\left(1+\phi_{A,k}^{(j-1)}\right)+\frac{\delta_{\phi_{A,k}}}{\ln 2\left(1+\phi_{A,k}^{(j-1)}\right)},\quad (14)$$

where

$$\ln\left(\phi_{A,k}^{(j-1)}+\delta_{\phi_{A,k}}\right)+\ln\left(\beta_k\right)\geq\ln\left(\frac{p_{A,k}^{(j-1)}C}{\sigma^2}\right)+\frac{1}{p_{A,k}^{(j-1)}}\delta_{p_{A,k}},\quad (15)$$

$$\beta_k\leq X^{\frac{\alpha}{2}}+\frac{\alpha}{2}X^{\frac{\alpha}{2}-1}\Delta_X,\quad (16)$$

$$X=\left(x_A^{(j-1)}-x_k\right)^2+\left(y_A^{(j-1)}-y_k\right)^2+H^2,\quad (17)$$

$$\Delta_X=\delta_{x_A}^2+\delta_{y_A}^2+2\left(x_A^{(j-1)}-x_k\right)\delta_{x_A}+2\left(y_A^{(j-1)}-y_k\right)\delta_{y_A}.\quad (18)$$

According to SCA method, as for the one-way relay, in the jth iteration, $\check{\eta}_2^{(j)}$, $p_{A,2}^{(j)}$, $p_1^{(j)}$, $\gamma_{A,2}^{(j)}$, $\gamma_{1,A}^{(j)}$, $x_A^{(j)}$, $y_A^{(j)}$, and $\phi_{A,k}^{(j)}$ are updated. The update increment $\boldsymbol{\delta}_1=\left\{\delta_{\check{\eta}_2},\delta_{p_{A,2}},\delta_{p_1},\delta_{\gamma_{A,2}},\delta_{\gamma_{1,A}},\delta_{x_A},\delta_{y_A},\delta_{\phi_{A,k}}\right\}$ are given by solving (P1)

$$\max_{\boldsymbol{\delta}_1,\bar{R}_{A,k}}\ \check{\eta}_2^{(j-1)}+\delta_{\check{\eta}_2}\quad \text{(P1)}$$
$$s.t. (8), (9), (11), (12), (15), (16)$$

$$\widehat{R}_{A,2}\leq\check{R}_{1,A}\quad (19)$$
$$p_1^{(j-1)}+\delta_{p_1}\leq P_G\quad (20)$$
$$p_{A,2}^{(j-1)}+\delta_{p_{A,2}}\leq P_A.\quad (21)$$

The algorithm to solve the UAV's position and power allocation is given in Algorithm 1. In each iteration, (P1) is solved. With the algorithm converges, the solution converges to the optimal solution of the energy efficient problem. The way to solve the energy efficient problem of two-way relay is similar, thus is omitted for simplicity.

Algorithm 1. Trajectory and Power Solution for One-way UAV Relay

1: Initialize the iteration number j=0, and $\check{\eta}_2^{(0)}$, $p_{A,2}^{(0)}$, $p_1^{(0)}$, $\gamma_{A,2}^{(0)}$, $\gamma_{1,A}^{(0)}$, $x_A^{(0)}$, $y_A^{(0)}$, and $\phi_{A,k}^{(0)}$;
2: **repeat**
3: Solve the convex optimization problem (P1) to obtain $\boldsymbol{\delta_1}$;.
4: Update the variables $\check{\eta}_2^{(j)}$, $p_{A,2}^{(j)}$, $p_1^{(j)}$, $\gamma_{A,2}^{(j)}$, $\gamma_{1,A}^{(j)}$, $x_A^{(j)}$, $y_A^{(j)}$, and $\phi_{A,k}^{(j)}$.
5: Update the iteration number $j = j + 1$.
6: **until** The value of the objective function reaches a convergence

4 Numerical Results and Discussion

In this section, we show the numerical results of the proposed algorithms. The ground nodes are fixed at $(0, 0, 0)$ and $(2000, 0, 0)$. The height of the UAV is set to be $H = 100$ m. The communication system's bandwidth is 20 MHz, and works at 5 GHz. The parameter of LoS path-loss at reference distance is -46 dB, the path-loss exponent is set to be 2. The noise spectrum density is -169 dBm/Hz [10]. The circuit power is set to be 0.02 Watt.

Figure 1 shows the convergence of the proposed algorithms. Figure 2 shows the influence of available power for the ground nodes and the UAV. The results imply that with more power available, the energy efficiency of the one-way relay increases, while for the two-way relay, the energy efficiency increases first and then keeps stable.

The upper bounds and the lower bounds of the data rates are shown in Fig. 3 and Fig. 4. With the algorithms converges, the upper bound of data rates, $\widehat{R}_{A,k}$ and the lower bounds of the data rates $\check{R}_{A,k}$, as well as the slake variables $\bar{R}_{A,k}$ converges to the same value. In fact, since we only focus on the energy efficiency of the UAV, the power from the ground nodes is not specially considered. When the available power for the ground nodes is limited, $\check{R}_{k,A}$ and the upper bound of $R_{A,k}$ converge to the same value. But if the ground nodes have superfluous power, the results of $\check{R}_{k,A}$ may be higher than what is needed. This is because we did not focus on the energy efficiency of the users, thus as long as it dose not violate the information causality constraints, $\check{R}_{k,A}$ is not specially minimized. This part will be discussed in the future work.

The communication power from the UAV can be seen in Fig. 5. The communication power of the one-way relay decreases when more power is available, because the UAV is near Node 2 to maintain better channel conditions. In Fig. 6 that with more power available, the UAV, as a one-way relay, moves to near Node 2, while the two-way relay stays in the center between the two ground nodes. This is because for the one-way relay, with more power available, Node 1 can transmit with higher power to the UAV to maintain the information causality, the UAV can move near to the destination node for better channel so as to save its communication power. But as for the two-way relay, UAV needs to communicate with both of the two ground nodes, thus neither moving to Node 1 nor moving to Node 2 helps to save energy.

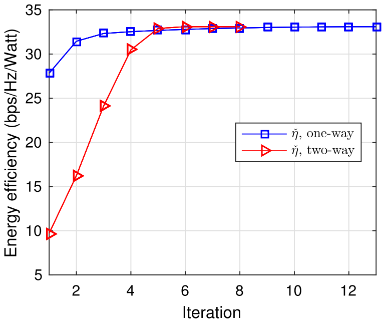

Fig. 1. The convergence of the proposed algorithms.

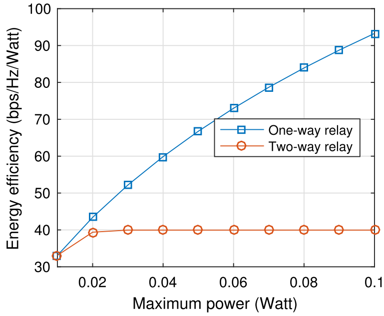

Fig. 2. The influence of the communication power on energy efficiencies.

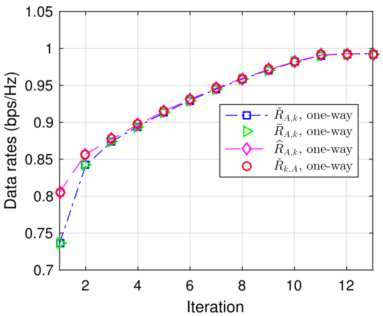

Fig. 3. Convergence of $\check{R}_{A,k}$, $\bar{R}_{A,k}$, $\widehat{R}_{A,k}$ and $\check{R}_{k,A}$ of one-way relay.

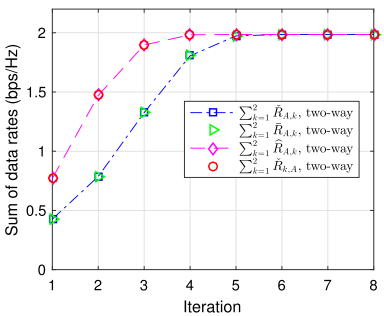

Fig. 4. Convergence of $\check{R}_{A,k}$, $\bar{R}_{A,k}$, $\widehat{R}_{A,k}$ and $\check{R}_{k,A}$ of two-way relay.

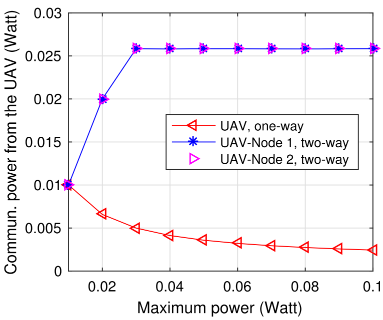

Fig. 5. The influence of the maximum power on the UAV's communication power.

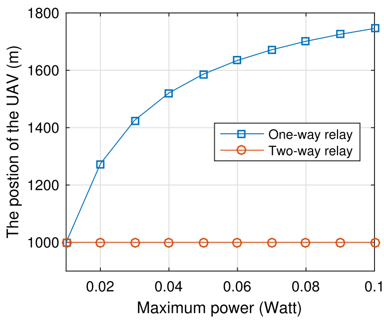

Fig. 6. The influence of the communication power on the UAV's positions.

5 Conclusion

In this paper, we studied the communication systems with fuel-powered UAV working as a one-way relay and a two-way relay, as a comparison. To maximize the energy efficiency of the communication for the UAV relay, we solve the non-convex problem by referring to SCA method and DC programming. Results show the convergence of the proposed algorithms and the efficiency of the upper bounds and lower bounds of the data rates. The positions and communication power of the UAV working as a one-way relay and a two-way relay are different when the communication power supply increases. The future work will be extended to the energy-efficient UAV trajectory design and power allocation for multi-users, and multiplexing techniques will be also taken into consideration.

References

1. Ahmed, S., Chowdhury, M.Z., Jang, Y.M.: Energy-efficient uav relaying communications to serve ground nodes. IEEE Commun. Lett. **24**(4), 849–852 (2020). https://doi.org/10.1109/LCOMM.2020.2965120
2. Ahmed, S., Chowdhury, M.Z., Jang, Y.M.: Energy-efficient uav-to-user scheduling to maximize throughput in wireless networks. IEEE Access **8**, 21215–21225 (2020). https://doi.org/10.1109/ACCESS.2020.2969357
3. Eom, S., Lee, H., Park, J., Lee, I.: UAV-aided two-way mobile relaying systems. IEEE Commun. Lett. **24**(2), 438–442 (2020)
4. Jiang, H., Zhang, Z., Wu, L., Dang, J.: Three-dimensional geometry-based uav-mimo channel modeling for A2G communication environments. IEEE Commun. Lett. **22**(7), 1438–1441 (2018)
5. Kaya, K., Hames, Y.: A study on fuel cell electric unmanned aerial vehicle. In: 2019 4th International Conference on Power Electronics and their Applications (ICPEA), pp. 1–6 (2019)
6. Savvaris, A., Xie, Y., Malandrakis, K., Lopez, M., Tsourdos, A.: Development of a fuel cell hybrid-powered unmanned aerial vehicle. In: 2016 24th Mediterranean Conference on Control and Automation (MED), pp. 1242–1247 (2016)
7. Wang, H., Wang, J., Chen, J., Gong, Y., Ding, G.: Network-connected uav communications: potentials and challenges. China Commun. **15**(12), 111–121 (2018)
8. Wang, Y., Shi, Y., Cai, M., Xu, W., Pan, T., Yu, Q.: Study of fuel-controlled aircraft engine for fuel-powered unmanned aerial vehicle: energy conversion analysis and optimization. IEEE Access **7**, 109246–109258 (2019)
9. Zeng, Y., Zhang, R.: Energy-efficient UAV communication with trajectory optimization. IEEE Trans. Wirel. Commun. **16**(6), 3747–3760 (2017). https://doi.org/10.1109/TWC.2017.2688328
10. Zeng, Y., Zhang, R., Lim, T.J.: Throughput maximization for UAV-enabled mobile relaying systems. IEEE Trans. Commun. **64**(12), 4983–4996 (2016)
11. Zeng, Y., Zhang, R., Lim, T.J.: Wireless communications with unmanned aerial vehicles: opportunities and challenges. IEEE Commun. Mag. **54**(5), 36–42 (2016)