Full-Duplex UAV Aided Communication in the Presence of Multiple Malicious Jammers

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Abstract. This paper studies a hybrid communication system, where the full-duplex unmanned aerial vehicle (UAV) communicates with the downlink users (DLUs) and uplink users (ULUs) simultaneously in the presence of multiple jammers. To improve quality of service of both ULUs and DLUs, we formulate an optimization problem, which maximizes the sum throughput of downlink and uplink by jointly designing the UAV trajectory , the scheduling of ULUs/DLUs, and the ULUs'transmit power. Notwithstanding, the formulated problem is non-convex hence computationally insoluble. We propose a low-complexity algorithm that is based on block coordinate descend and successive convex approximation techniques to effectively solve this problem. Numerical outcomes demonstrate that the proposed algorithm can improve throughput significantly comparing to the existing algorithm.

Keywords: Unmanned aerial vehicle (UAV) · Malicious jammer · Full-duplex · Non-convex

1 Introduction

Due to the adaptable capability and high maneuverability, unmanned aerial vehicle (UAV) has played an important role in the B5G/6G mobile network. Because the line-of-sight (LoS) links [1] is dominant when UAV works in the certain altitude, the channel path-loss is smaller than the one in the terrestrial communication. In addition, full-duplex (FD) technique providing approaches

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for simultaneous signal transmission and reception (STR), will be promising to combine with UAV to flexibly perform high-performance STR.

In [2], the FD secrecy communication for the UAV was studied, where the aim of the reseachers was to maximize the UAV's energy efficiency through jointly optimizing the UAV trajectory and transmit powers during a given duration. In [3], the authors studied FD UAV relaying multiple nodes to maximize the network's throughput by jointly optimizing the user scheduling, the UAV trajectory and the UAV transmit power. In [4], FD UAV aided uplink and downlink communication system was studied, where the UAV simultaneously communicates with ULUs and DLUs. An iterative algorithm has been propounded to maximize the throughput of the system through optimizing the UAV trajectory, DLU/ULU scheduling, and ULU transmit power. In [5], the authors studied the UAV that simultaneously communicated with DLUs and ULUs and propounded an iterative algorithm for throughput maximization through optimizing the communication scheduling, UAV transmit power and 3D UAV trajectory. The antecedent researches, nevertheless, have not investigated the transmission among the FD UAV, DLUs and ULUs in the existence of malicious jammers.

In this paper, we investigate FD UAV aided STR with time division Multiple Access (TDMA) manner in the existence of multiple malicious jammers. To improve the performance under malicious jammers, we concentrate on maximizing the aggregate throughput of both DLUs and ULUs through jointly optimizing DLU/ULU scheduling, the UAV trajectory, ULU transmit power. The formulated problem is a non-convex problem hence computationally insoluble. A low-complexity algorithm is proposed by utilizing both the block coordinate descent (BCD) and successive convex approximation (SCA) techniques. Numerical results illustrate that our propounded algorithm's performance is more effective than the existent solutions.

2 System Model and Problem Formulation

We suppose a UAV aided communication system, as demonstrated in Fig. 1, where the UAV tends to transmit signal to K_D single-antenna DLUs and receive signal from K_U single-antenna ULUs under M malicious jammers. Define $\mathcal{K}_D = \{1,2,...,K_D\}$, $\mathcal{K}_U = \{1,2,...,K_U\}$ and $\mathcal{M} = \{1,2,...,M\}$ as the series of DLUs, ULUs and malicious jammers, respectively. On the horizon, the location of DLU j is denoted as w_j, $j \in \mathcal{K}_D$, the location of ULU i is denoted as w_i, $i \in \mathcal{K}_U$, and the location of jammer m is denoted as w_m, $m \in \mathcal{M}$. The UAV is considered to fly at a fixed altitude H. The total flight duration T is equally divided into N time slots (TSs) δ. Let Q_{start} denotes the start point while Q_{end} denotes the end point, and the horizontal coordinate of UAV $Q[n]$ at TS n is supposed to satisfy the constrains:

$$\|Q[n] - Q[n-1]\| \leq V_{\max}\delta, \ n = 1, 2, 3, \ldots, N, \tag{1}$$

$$Q_{start} = Q[0], Q_{end} = Q[N], \tag{2}$$

where $V_{\max}$ is the maximum horizontal speed of the UAV.

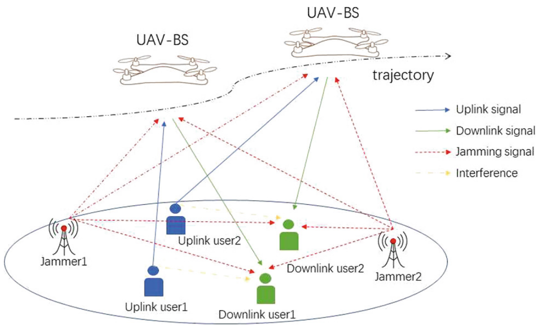

Fig. 1. Full-duplex UAV aided STR system under malicious jamming.

As shown in the 3GPP, The air-to-ground communication channel between the UAV and the user is mostly influenced by LoS, particularly in rural and suburban area [1]. Consequently, the channel power gains from the UAV to the j-th DLU, i-th ULU, m-th jammer, respectively, can be given by

$$g_{b,j} = \frac{\beta_0}{\|Q[n] - w_j\|^2 + H^2}, j \in \mathcal{K}_D, \tag{3}$$

$$g_{i,b} = \frac{\beta_0}{\|Q[n] - w_i\|^2 + H^2}, i \in \mathcal{K}_U, \tag{4}$$

$$g_{m,b} = \frac{\beta_0}{\|Q[n] - w_m\|^2 + H^2}, m \in \mathcal{M}, \tag{5}$$

where β_0 denotes the channel power gain at the reference distance and H is the altitude of the UAV.

The channel model between the m-th jammer and j-th DLU is influenced by Rayleigh fading, and the channel gain is set as $h_{m,j}[n] = \beta_0 d_{m,j}^{-\alpha} \varrho$ [7], where $d_{m,j}$ is the distance between the m-th jammer and the j-th DLU, ϱ is a random variable, and α denotes the path loss exponent. Also, the channel gain between the i-th ULU and the j-th DLU is denoted as $h_{i,j}[n] = \beta_0 d_{i,j}^{-\alpha} \varrho$.

To mitigate interference, a TDMA protocol based transmission is considered where the UAV can communicate with a DLU and a ULU over single TS. Such a protocol has to satisfy:

$$\sum_{j=1}^{K_D} x_j^d[n] \leq 1, \forall n, \tag{6}$$

$$x_j^d[n] \in \{0, 1\}, \forall j, n, \tag{7}$$

$$\sum_{i=1}^{K_U} x_i^u[n] \leq 1, \forall n, \tag{8}$$

$$x_i^u[n] \in \{0, 1\}, \forall i, n, \tag{9}$$

where (6) and (7) denote the scheduling constrains of the DLUs, while (8) and (9) denote the scheduling constrains of the ULUs.

The achievable throughput of the j-th DLU over TS n is given by

$$R_j^d[n] = \log_2(1 + \frac{p_b g_{b,j}[n]}{\sum_{i=1}^{K_U} x_i^u[n]\beta_0 d_{i,j}^{-\alpha} p_i[n] + \sum_{m=1}^{M} P_m \beta_0 d_{m,j}^{-\alpha} + \sigma^2}), \tag{10}$$

where σ^2 denotes the value of white Gaussian noise power, p_b represents UAV transmit power and P_m is the transmit power of m-th jammer. Again, the throughput of the UAV from i-th ULU is as follows

$$R_i^u[n] = \log_2(1 + \frac{p_i[n] g_{i,b}[n]}{f_b[n] + \sum_{m=1}^{M} P_m g_{m,b} + \sigma^2}), \tag{11}$$

where $f_b[n]$ is the self-interference over TS n from other ULUs to the FD UAV [4]. $p_i[n]$ denotes the uplink transmit power of i-th ULU at TS n.

Define $\mathcal{X}_D = \{x_j^d[n], \forall j, n\}$, $\mathcal{X}_U = \{x_i^u[n], \forall i, n\}$, $\mathcal{P} = \{p_i[n], \forall i, n\}$, $\mathcal{Q} = \{Q[n], \forall n\}$, then a throughput maximization problem subject to the UAV mobility constrains, the transmit power of ULUs constrains and the scheduling constrains is formulated as:

$$\max_{\mathcal{X}_D, \mathcal{X}_U, \mathcal{Q}, \mathcal{P}} \sum_{n=1}^{N} \sum_{j=1}^{K_D} x_j^d[n] R_j^d[n] + \sum_{n=1}^{N} \sum_{i=1}^{K_U} x_i^u[n] R_i^u[n] \tag{12a}$$

$$\text{s.t.} \quad 0 \leq p_i[n] \leq P_{\max}, \forall i, n, \tag{12b}$$

$$(1), (2), (6) - (9), \tag{12c}$$

where $P_{\max}$ denotes the transmit power budget of ULUs.

3 Proposed Algorithm

By virtue of the non-concave objective function, the problem is non-convex and is not solvable efficiently. Besides, the existence of the binary constrains (7) and (9) makes the problem computationally intractable. Firstly, we transform the constrains into the linear constrains [6], which can be expressed as follows

$$0 \leq x_j^d[n] \leq 1, \forall j, n, \tag{13}$$

$$0 \leq x_i^u[n] \leq 1, \forall i, n. \tag{14}$$

Subsequently by applying BCD, we propound an algorithm to solve the problem (12a) through alternatively optimizing $\mathcal{X}_D$, $\mathcal{X}_U$, $\mathcal{Q}$, and $\mathcal{P}$.

3.1 Design for DLU Scheduling

We suppose that ULU scheduling $\mathcal{X}_U$, UAV trajectory $\mathcal{Q}$, and ULU transmit power $\mathcal{P}$ have been given. And, the problem is given by

$$\max_{\mathcal{X}_D} \sum_{n=1}^{N}\sum_{j=1}^{K_D} x_j^d[n]R_j^d[n] \tag{15a}$$

$$\text{s.t.} \ (6), (13). \tag{15b}$$

The problem (15) has satisfied the condition of the linear programming and we can obtain the solution efficiently.

3.2 Design for ULU Scheduling

Similarly, we assume that DLU scheduling $\mathcal{X}_D$, trajectory of UAV $\mathcal{Q}$, and ULU transmit power $\mathcal{P}$ have been given, the problem for DLU scheduling is written as

$$\max_{\mathcal{X}_U} \sum_{n=1}^{N}\sum_{j=1}^{K_D} x_j^d[n]R_j^d[n] + \sum_{n=1}^{N}\sum_{i=1}^{K_U} x_i^u[n]R_i^u[n] \tag{16a}$$

$$\text{s.t.} \ (8), (14). \tag{16b}$$

With respect to the variable $x_i^u[n]$, the throughput of downlink $R_j^d[n]$ is non-concave so that problem (16) cannot be solved effectively. In the sequel, we adopt SCA to derive the lower bound with a feasible point $\{x_i^{u,r}\}$,

$$\begin{aligned} R_j^d[n] &\geq \log_2(1 + \frac{p_b g_{b,j}}{T_j^r[n]}) - \sum_{i=1}^{K_U} \frac{\beta_0 d_{i,j}^{-\alpha} p_i[n] p_b g_{b,j} \log_2^e}{T_j^r[n](T_j^r[n] + p_b g_{b,j})}(x_i^u[n] - x_i^{u,r}[n]), \\ &\triangleq \mathcal{R}_j^d[n] \end{aligned} \tag{17}$$

where $T_j^r[n] = \sum_{i=1}^{K_U} x_i^{u,r} \beta_0 d_{i,j}^{-\alpha} p_i[n] + \sum_{m=1}^{M} P_m \beta_0 d_{m,j}^{-\alpha} + \sigma^2$. Then, the problem (16) can be reconstruct as:

$$\max_{\mathcal{X}_U} \sum_{n=1}^{N}\sum_{j=1}^{K_D} x_j^d[n]\mathcal{R}_j^d[n] + \sum_{n=1}^{N}\sum_{i=1}^{K_U} x_i^u[n]R_i^u[n] \tag{18a}$$

$$\text{s.t.} \ (8), (14). \tag{18b}$$

We can update the ULU scheduling $\mathcal{X}_U$ by optimizing problem (18).

3.3 Design for UAV Trajectory

In like manner, with the given DLU scheduling $\mathcal{X}_D$, ULU scheduling $\mathcal{X}_U$, and ULU transmit power P, the problem for the UAV trajectory is formulated as follows

$$\max_{\mathcal{Q}} \sum_{n=1}^{N}\sum_{j=1}^{K_D} x_j^d[n]R_j^d[n] + \sum_{n=1}^{N}\sum_{i=1}^{K_U} x_i^u[n]R_i^u[n] \tag{19a}$$

$$\text{s.t.} \quad (1), (2). \tag{19b}$$

In the first part, the downlink throughput expression of problem (19) is non-convex. Then, we take the first-order Taylor expansion at TS n $||Q^r[n]-w_j||$ to get the lower bound:

$$\begin{aligned} R_j^d[n] &\geq \log_2(1+\frac{D_j[n]}{||Q^r[n]-w_j||^2+H^2}) - \varGamma_j[n] \times (||Q[n]-w_j||^2 - ||Q^r[n]-w_j||^2) \\ &\triangleq \varPhi^{lb}(R_j^d[n]), \end{aligned} \tag{20}$$

where

$$\varGamma_j[n] = \frac{D_j[n]\log_2^e}{(D_j[n]+||Q^r[n]-w_j||^2+H^2)(||Q^r[n]-w_j||^2+H^2)}$$

and

$$D_j[n] = \frac{p_b\beta_0}{\sum_{i=1}^{K_U} x_i^u[n]\beta_0 d_{i,j}^{-\alpha} p_i[n] + \sum_{m=1}^{M} P_m\beta_0 d_{m,j}^{-\alpha} + \sigma^2}.$$

The uplink throughput expression of problem (19) is also non-convex. Introduce slack variables $L_{i,b}[n]$ and $I_b[n]$ then the uplink throughput expression is rewritten as

$$\bar{R}_i^u[n] = \log_2(1+\frac{1}{L_{i,b}[n]I_b[n]}), \forall n, \tag{21}$$

with additional constraints

$$p_i[n]g_{i,b}[n] \geq L_{i,b}[n]^{-1}, \forall n, \tag{22}$$

and

$$f_b[n] + \sum_{m=1}^{M} P_m g_{m,b}[n] + \sigma^2 \leq I_b[n], \forall n. \tag{23}$$

However, the problem (21) cannot be solved effectively due to the non-concave objective function and the non-convex constrains (23). To handle the problem (21), we apply the following lemma to derive an approximate result.

Lemma. *With any given achievable point* $(L^r_{i,b}[n], I^r_b[n])$, $\bar{R}_{i,b}$ *should be lower bounded by*

$$\bar{R}^{lb}_{i,b}[n] = \log_2\left(\frac{1}{L^r_{i,b}[n]I^r_b[n]}\right) + \phi_{i,b}(L_{i,b}[n] - L^r_{i,b}[n]) + \psi_{i,b}(I_b[n] - I^r_b[n]), \quad (24)$$

where $\phi_{i,b} = -\frac{\log_2^e}{(L^r_{i,b}[n]+(L^r_{i,b}[n])^2 I^r_b[n])}$ and $\psi_{i,b} = -\frac{\log_2^e}{(I^r_b[n]+(I^r_b[n])^2 L^r_{i,b}[n])}$

Through introducing slack variable $d_m[n]$, the constrains (23) can be substituted by

$$f_b[n] + \sum_{m=1}^{M} P_m \beta_0 d_m[n]^{-1} + \sigma^2 \leq I_b[n], \forall n, \quad (25)$$

$$d_m[n] \leq ||Q[n] - w_m||^2 + H^2, \forall n, \quad (26)$$

$$d_m[n] \geq 0, \forall n. \quad (27)$$

Next, by taking the first-order Taylor expansion, we can derive the lower bound of right hand side (RHS) of constrains (26)

$$C^l_{m,b} = ||Q^r[n] - w_m||^2 + 2(Q^r[n] - w_m)^T (Q[n] - Q^r[n]) + H^2, \quad (28)$$

then, the constrains (26) can be rebuilt as

$$d_m[n] \leq C^l_{m,b}, \forall n, \quad (29)$$

As a result, the original problem (19) is approached as follows:

$$\max_{\mathcal{Q}} \sum_{n=1}^{N} \sum_{j=1}^{K_D} x^d_j[n] \varPhi^{lb}(R^d_j[n]) + \sum_{n=1}^{N} \sum_{i=1}^{K_U} x^u_i[n] \bar{R}^{lb}_{i,b}[n] \quad (30a)$$

$$\text{s.t.} \quad (1), (2), (22), (25), (27), (29). \quad (30b)$$

Solve the convex problem (30) to update the UAV trajectory Q.

3.4 Design for ULU Transmit Power Control

With the given DLU scheduling $\mathcal{X}_D$, ULU scheduling $\mathcal{X}_U$, and the UAV trajectory $\mathcal{Q}$, the problem for the ULU transmit power P is written as:

$$\max_{\mathcal{P}} \sum_{n=1}^{N} \sum_{j=1}^{K_D} x^d_j[n] R^d_j[n] + \sum_{n=1}^{N} \sum_{i=1}^{K_U} x^u_i[n] R^u_i[n] \quad (31a)$$

$$\text{s.t.} \quad (12b). \quad (31b)$$

With respect to $p_i[n]$, the expression $R^d_j[n]$ in the first part is convex. Thus, the problem (31) is a non-convex problem. We also apply the first-order Taylor expansion at achievable point $\{p^r_i[n]\}$ to be approximated as:

$$R_j^d[n] \geq \log_2\Big(1 + \frac{p_b g_{b,j}[n]}{E_j^r[n]}\Big) - \sum_{i=1}^{K_U} \frac{\beta_0 d_{i,j}^{-\alpha} x_i^u[n] p_b g_{b,j} \log_2^e}{E_j^r[n](E_j^r[n] + p_b g_{b,j}[n])}(p_i[n] - p_i^r[n]),$$
$$\triangleq \Upsilon^{lb}(R_j^d[n]) \tag{32}$$

where $E_j^r[n] = \sum_{i=1}^{K_U} x_i^u[n]\beta_0 d_{i,j}^{-\alpha} p_i^r[n] + \sum_{m=1}^{M} P_m \beta_0 d_{m,j}^{-\alpha} + \sigma^2$.

The objective function (31a) can be rewritten as:

$$\max_{\mathcal{P}} \sum_{n=1}^{N}\sum_{j=1}^{K_D} x_j^d[n]\Upsilon^{lb}(R_j^d[n]) + \sum_{n=1}^{N}\sum_{i=1}^{K_U} x_i^u[n] R_i^u[n] \tag{33a}$$
$$\text{s.t.} \quad (12c). \tag{33b}$$

Then, the problem (31) can be approximately solved by solving problem (33).

Algorithm 1. Algorithm Proposed for Solving (12)

1: **Initialization:** Set $r = 0$. Find initial feasible points $\{Q^r[n]\}$, $\{x_i^{u,r}[n]\}$, $\{x_j^{d,r}[n]\}$, $\{p_i^r[n]\}$ for (12), set $\epsilon > 0$.
2: **repeat.**
3: Solve the problem (15) to update the optimum point as $\{x_j^{d,r+1}[n]\}$ with $\{Q^r[n]\}$, $\{x_i^{u,r}[n]\}$, $\{p_i^r[n]\}$.
4: Solve the problem (16) to update the optimum point as $\{x_i^{u,r+1}[n]\}$ with $\{Q^r[n]\}$, $\{x_j^{d,r+1}[n]\}$, $\{p_i^r[n]\}$.
5: Solve the problem (19) to update the optimum point as $\{Q^{r+1}[n]\}$ with $\{x_i^{u,r+1}[n]\}$, $\{x_j^{d,r+1}[n]\}$, $\{p_i^r[n]\}$.
6: Solve the problem (31) to update the optimum point as $\{p_i^{r+1}[n]\}$ with $\{x_i^{u,r+1}[n]\}$, $\{x_j^{d,r+1}[n]\}$, $\{Q^{r+1}[n]\}$.
7: Set $r := r + 1$
8: **Until** the fractional growth of the objective value of (12) is within the tolerance ϵ

4 Numerical Results

In this segment, numerical outcomes are obtained to demonstrate our proposed algorithm's performance. We think about multiple ULUs, jammers and DLUs. Locations of DLUs and ULUs are set as $D_1 = (200, 700)$, $D_2 = (600, 200)$, $U_1 = (200, 800)$ and $U_2 = (600, 150)$, jammers in $(200, 200)$ and $(700, 700)$. The value of the self-interference is $f_b[n] - 130$ dB and the value of the tolerance is $\epsilon = 10^{-3}$ [4]. Besides, the UAV altitude is fixed at $H = 100$ m. The bandwidth is $B = 1$ MHz and the UAV maximal horizontal speed is $V_{max} = 50$ m/s. The UAV maximal transmit power, the ULU maximal transmit power and the transmit power of jammers are respectively assumed as $p_b = 0.1$ W, $P_{max} = 0.1$ W and $P_m = 0.05$ W. We assume that $\alpha = 3, \delta = 0.5$, $\beta_0 = -60$ dB and $\sigma^2 = -110$ dBm [6].

Figure 2 plots the UAV trajectories based on our algorithm versus flight time T. The UAV flight start point and end point respectively are set as $Q_s = (0, 500)$

and $Q_e = (1000, 500)$. Apparently, UAV flies away from jammer1 and reaches D_1 in three cases. However, when flight time is small, i.e., $T = 30\,\mathrm{s}$, $T = 50\,\mathrm{s}$, it can be observed that UAV has to reach final point in an arc path due to the constrains of the trajectory design after passing D_1. If T is sufficiently large, i.e., $T = 110\,\mathrm{s}$, UAV not only flies to the D_1, but also flies to the U_2 away from jammer2 and finally reaches the final point for maximizing the throughput.

In following simulations, "Our proposed Algorithm 1" refers to the proposed algorithm, while "Baseline algorithm" refers to the benchmark algorithm without the presence of jammers. Figure 3 shows that the throughput of both downlink and uplink versus flight time T. As the time T increasing, the performance of our algorithm is better than the benchmark algorithm. Figure 4 and 5 show the UAV throughput of algorithms versus the number of jammers M and jammers transmit power P_m. Observe that the throughput of algorithms decrease gradually, because the denominator of objective function (12a) increases when the number of jammers or the transmit power of jammers increases. The simulation outcomes illustrate that our proposed algorithm is superior over the benchmark algorithm.

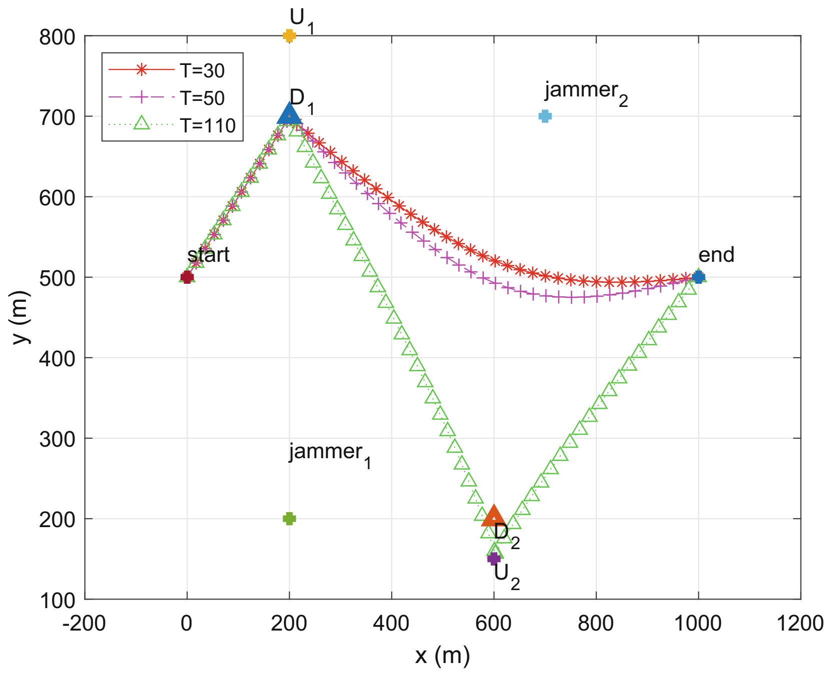

Fig. 2. Trajectory of UAV for different period T.

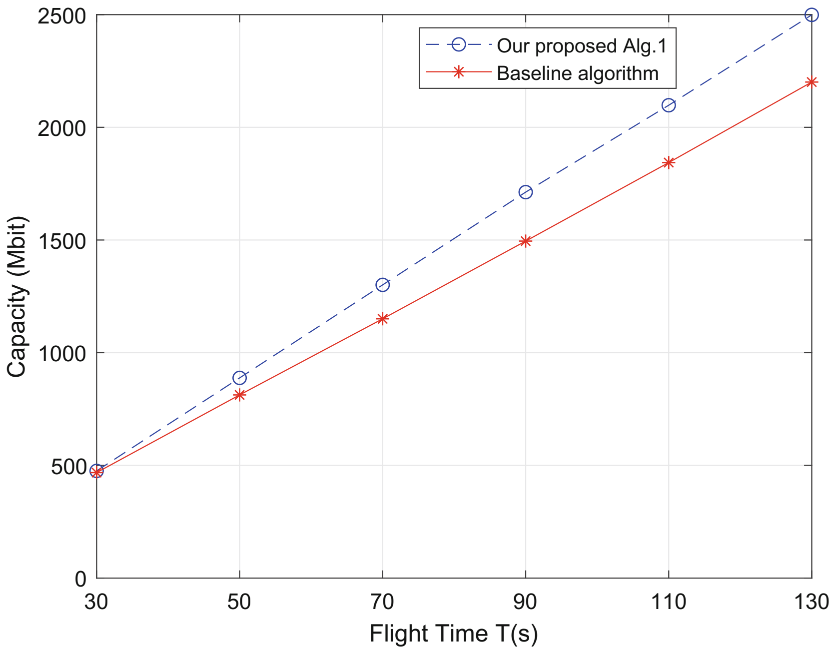

Fig. 3. Capacity of UAV versus different period T.

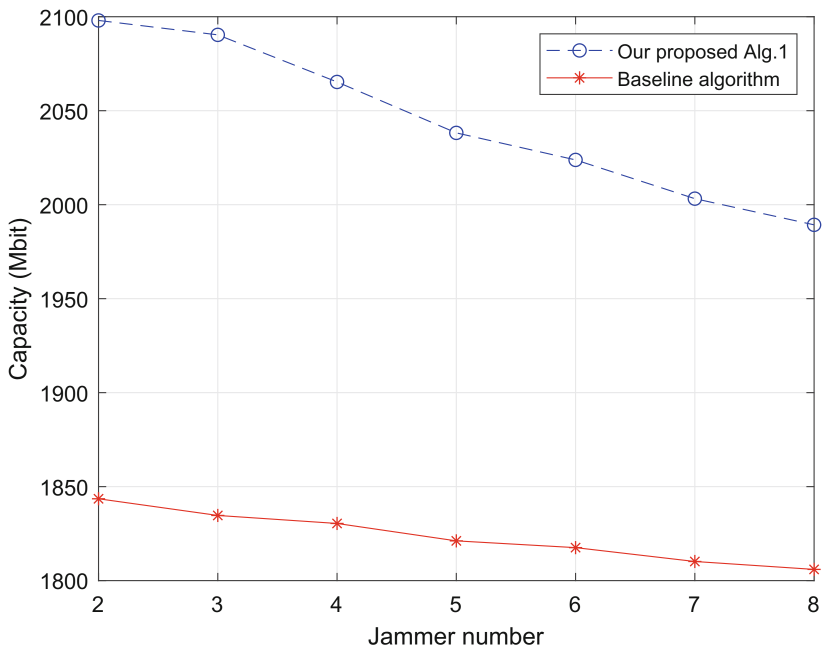

Fig. 4. Capacity of UAV versus the number of malicious jammers.

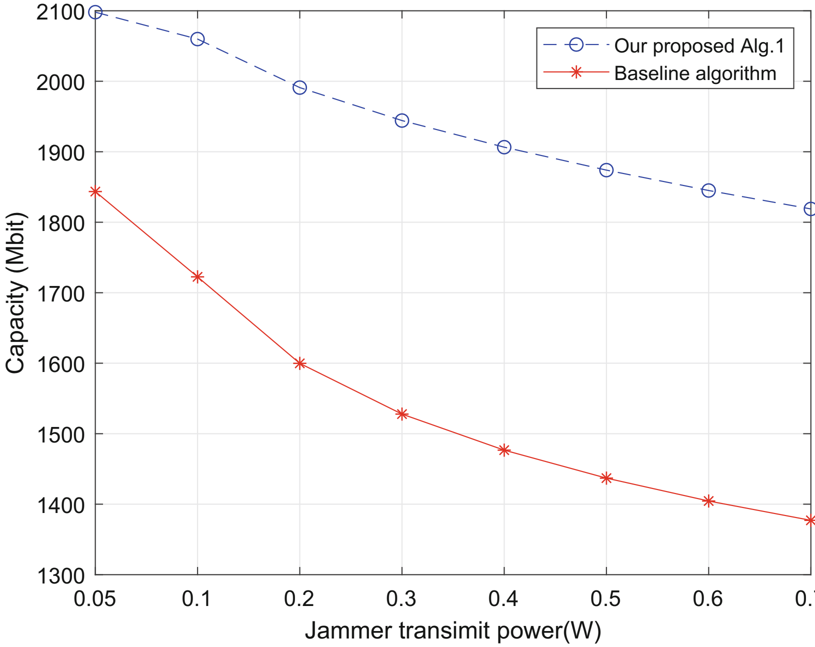

Fig. 5. Capacity of UAV versus the transmit power of malicious jammers.

5 Conclusion

In this research, a FD UAV communication scheme has been studied, where a FD UAV is used to communicate with DLUs and ULUs in the presence of malicious jammers. A throughput maximization problem has been formulated by iteratively optimizing the scheduling of ULUs/DLUs, the UAV trajectory, and the transmit power of ULUs. Because the proposed problem is non-convex and computationally insoluble, a low-complexity algorithm based on BCD and SCA techniques has been propounded. Our numerical results have illustrated that our algorithm outperforms than the existent algorithm.

References

1. Lin, X., et al.: The sky is not the limit: LTE for unmanned aerial vehicles. IEEE Commun. Mag. **56**(4), 204–210 (2018). https://doi.org/10.1109/MCOM.2018.1700643
2. Duo, B., Wu, Q., Yuan, X., Zhang, R.: Energy efficiency maximization for full-duplex UAV secrecy communication. IEEE Trans. Veh. Technol. **69**(4), 4590–4595 (2020). https://doi.org/10.1109/TVT.2020.2977948
3. Li, B., Zhao, S., Zhang, R., Yang, L.: Full-duplex UAV relaying for multiple user pairs. IEEE Internet Things J. **8**(6), 4657–4667 (2021). https://doi.org/10.1109/JIOT.2020.3027621

4. Hua, M., Yang, L., Pan, C., Nallanathan, A.: Throughput maximization for full-duplex UAV aided small cell wireless systems. IEEE Wireless Commun. Lett. **9**(4), 475–479 (2020). https://doi.org/10.1109/LWC.2019.2959527
5. Hua, M., Yang, L., Wu, Q., Swindlehurst, A.L.: 3D UAV trajectory and communication design for simultaneous uplink and downlink transmission. IEEE Trans. Wirel. Commun. **68**(9), 5908–5923 (2020). https://doi.org/10.1109/TCOMM.2020.3003662
6. Wu, Q., Zeng, Y., Zhang, R.: Joint trajectory and communication design for Multi-UAV enabled wireless networks. IEEE Trans. Wirel. Commun. **17**(3), 2109–2121 (2018). https://doi.org/10.1109/TWC.2017.2789293
7. 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