Secure Communications for Dual-UAV-MEC Networks

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Abstract. With the on-demand deployment and high flexibility of the unmanned aerial vehicle (UAV), carrying mobile edge computing (MEC) systems can efficiently relieve the pressure of the explosive growth of data traffic. UAVs adopt line-of sight (LOS) transmission with broadcast characteristics, the information they transmit to ground users (GUs) are easy to be eavesdrop by malicious eavesdroppers. Therefore, secure communication is worth studying in UAV-MEC networks. In this paper, we propose a Dual-UAV-MEC system where GUs offload part of the tasks to UAV server carrying MEC for calculation in the presence of the eavesdropping of offloading information by UAV Eavesdropper, Jammer on the ground sends interference signals to reduce eavesdropping. We propose a secure communication scheme with time division multiple access (TDMA) to maximum the GUs minimum secure calculation capacity. Specifically, we optimize the UAV Servers trajectory and allocate wireless resources which include time allocation factor and local calculation. Numerical results show that the method we proposed efficiently increases the secure calculation capacity of the system.

Keywords: UAV · Secure communication · MEC · Secure calculation capacity · TDMA

1 Introduction

Mobile edge computing (MEC) makes plenty of contribution for 5G era, e.g., reducing communication service latency, which has been extensively studied [1–8]. [2] proposed a scheme of collaborative computation to effectively reduce data redundancy pressure. As the on-demand deployment and high flexibility of UAVs, they can assist the MEC system in the Internet of things to help GUs with offloading calculation, which cannot only expand the converage of the MEC service, but also save the laying cost. [3] pointed out that the innovative study

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on interaction between UAV and MEC can improve the task computing efficiency and the wireless communication quality by signal blocking and shadow effect. [4] proposed a method with optimizing computation offloading and UAV trajectory to enhance the performance. UAV-MEC system can approach GUs to obtain efficient information transmission [5,6]. Physical layer security plays an indispensable role in the 5G era with the data's explosive growth [7,8].

In this paper, we propose a secure communication method for Dual-UAV-MEC networks based on TDMA to optimize UAVs' trajectory and wireless resources including time allocation and local calculation by combining block coordinate descent (BCD) and successive convex approximation (SCA) methods [9].

2 System Model and Problem Formulation

2.1 System Model

Figure 1 depicts a Dual-UAV-MEC secure communication system with two UAVs (UAV_S and UAV_E), K GUs and a ground jammer (GJ), where UAV_S assists GUs in completing the tasks for calculation, and UAV_E eavesdrops the offloading information by GUs to UAV_S as a mobile eavesdropper with given trajectory during the flight. In order to reduce the UAV_E eavesdropping, GJ sends interference signals. We assume that UAV_S has already known GJs interference signals, thus UAV_S is not disturbed by it. However, UAV_E knows nothing about it, thus the interference signals have noisy effects on UAV_E. UAVs, GUs and GJ are equipped with single antenna.

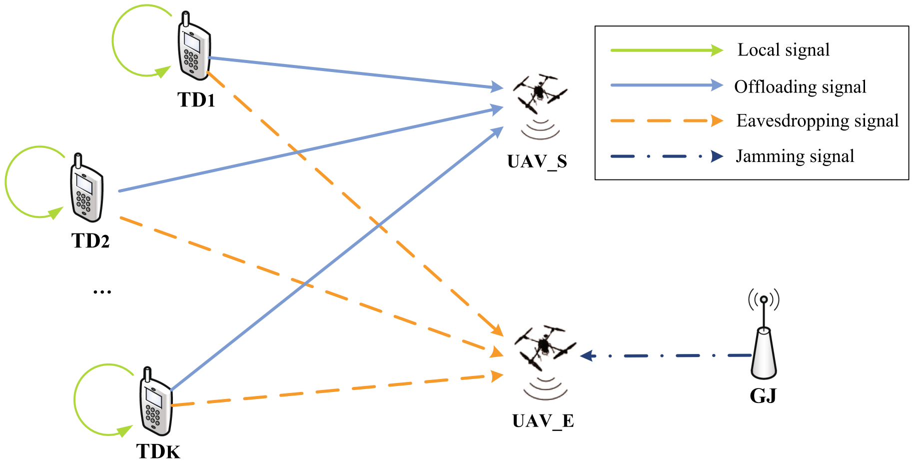

Fig. 1. Dual-UAV-MEC system model.

Denote $w_k = (x_k, y_k, 0), w_j = (x_j, y_j, 0)$ as the coordinates of the *k-th* GU and GJ, respectively. Define T as the UAV flight period, which is divided into N equal time slots, $\delta_t = N/T$, and UAV_$i(i \in \{S, E\})$'s location is denoted by $q_i(n) = (x_i[n], y_i[n], H_i), n \in \{1, 2, ..., N\}$, where H_i represents UAV_i's flight altitude. Define q_s^I, q_s^F and $V_s^{\max}$ as the start position, the end position and the maximum flight speed of UAV_S, respectively. Then, we have

$$q_s[1] = q_s^I \tag{1a}$$

$$q_s[N] = q_s^F \tag{1b}$$

$$||q_s[n+1] - q_s[n]|| \leq V_s^{\max}\delta_t, \forall n = 1, 2, ..., N-1 \tag{1c}$$

Denote $d_{\min}$ as the minimum anti-collision distance between UAV_S and UAV_E, which needs to satisfy

$$||q_s[n] - q_e[n]||^2 \geq d_{\min}^2, \forall n \in \{1, 2..., N\} \tag{2}$$

The distance between UAV_S and GU$_k, k \in \{1, 2, ..., K\}$, UAV_E and GJ, UAV_E and GU$_k$ in the time slot n are $d_{k,s}[n] = \sqrt{H_s^2 + ||q_s[n] - w_k||^2}, \forall k, n$ and $d_{j,e}[n] = \sqrt{H_e^2 + ||q_e[n] - w_j||^2}, \forall n$, respectively. We consider the channels between UAVs and GUs are modeled as LOS channels. The channel coefficient between GU$_k$ and UAV_S, GJ and UAV_E, GU$_k$ and UAV_E are expressed as

$$h_{k,s}[n] = \sqrt{\frac{\beta_0}{d_{k,s}^2[n]}}, \forall k, n \tag{3}$$

$$h_{j,e}[n] = \sqrt{\frac{\beta_0}{d_{j,e}^2[n]}}, \forall n \tag{4}$$

$$h_{k,e}[n] = \sqrt{\frac{\beta_0}{d_{k,e}^2[n]}}, \forall k, n \tag{5}$$

where β_0 represents the channel power gain at unit distance.

2.2 Problem Formulation

We utilize a TDMA scheme for GUs task offloading, in which we divide one time slot n into K sub-slots with $\tau_k[n]\delta_t, k \in \{1, 2, ...K\}$, where $\tau_k[n]$ represents the time allocation factor, which is given by

$$\sum_{k=1}^{K} \tau_k[n] \leq 1, \forall n \tag{6a}$$

$$0 \leq \tau_k[n] \leq 1, \forall k, n \tag{6b}$$

Communication Model

Since UAV_S has known GJs interference signals, UAV_S is not disturbed by it. Define $p_k[n]$ as the transmit power of GU$_k$, thus the signal-to-interference and noise ratio (SINR) of UAV_S in the time slot n is expressed as

$$r_{k,s}[n] = \frac{|h_{k,s}[n]|^2 p_k[n]}{\delta_s^2}, \forall k, n \tag{7}$$

While UAV_E knows nothing about the presence of GJ, UAV_E cannot determine who sent the received signals. Thus, the SINR of UAV_E is given by

$$r_{k,e}[n] = \frac{|h_{k,e}[n]|^2 p_k[n]}{|h_{j,e}[n]|^2 P_j + \delta_e^2}, \forall k, n \tag{8}$$

where P_j denotes the given transmit power of GJ, δ_s^2 and δ_e^2 denote the noise power of UAV_S and UAV_E, respectively. Thus, the task offloading rate from GU$_k$ to UAV_S and the task eavesdropping rate from GU$_k$ to UAV_E are given by

$$R_{k,s}[n] = \tau_k[n] \log_2 \left(1 + \frac{|h_{k,s}[n]|^2 p_k[n]}{\delta_s^2}\right), \forall k, n \tag{9}$$

$$R_{k,e}[n] = \tau_k[n] \log_2 \left(1 + \frac{|h_{k,e}[n]|^2 p_k[n]}{|h_{j,e}[n]|^2 P_j + \delta_e^2}\right), \forall k, n \tag{10}$$

As a result, the secrecy offloading rate from GU$_k$ to UAV_S with UAV_E participation is formulated as

$$R_{k,\mathrm{sec}}[n] = (R_{k,\mathrm{s}}[n] - R_{k,e}[n])^+, \forall k, n \tag{11}$$

Computing Model

The tasks of GUs can be completed by local calculation and offloading to UAV_S for calculation. Let c_k and c_s describe the CPU cycles for GU$_k$ and UAV_S computing one bit of task respectively. Let $F_k^{\max}$ and $F_s^{\max}$ represent GU$_k$ and UAV_Ss maximum CPU frequency. Define B as the bandwidth. Both of the local calculation bits $l_{loc,k}[n]$ of GU$_k$ and the secure calculation bits of UAV_S cannot exceed their respective maximum calculation capability, which meet the constraints as

$$c_k l_{loc,k}[n] \le F_k^{\max} \delta_t, \forall k, n \tag{12}$$

$$B \delta_t c_s R_{k,\mathrm{sec}}[n] \le \tau_k[n] \delta_t F_s^{\max}, \forall k, n \tag{13}$$

The total calculation of GU$_k$ consists of the local calculation and offloading calculation. Since GU$_k$ have a secure task requirements Q_m to calculate, it needs to satisfy the following minimum secure calculation constraints

$$l_{loc,k}[n] + B \tau_k[n] \delta_t R_{k,\mathrm{sec}}[n] \ge Q_m, \forall k, n \tag{14}$$

The energy consumption calculated locally by GU$_k$ is expressed as

$$E_{loc,k}[n] = \frac{k_k (c_k l_{loc,k}[n])^3}{\delta_t^2}, \forall k, n \tag{15}$$

where k_k denotes the effective capacitance of GU_k.

The energy consumption calculated by offloading to UAV_S is $\tau_k[n]\delta_t p_k[n]$. Define P_{ave}^k as GU_k's average power budget, the GU_k energy constraint over T is limited as

$$\sum_{n=1}^{N}\left(\tau_k[n]\delta_t p_k[n]+\frac{k_k(c_k l_{loc,k}[n])^3}{\delta_t^2}\right)\leq P_{ave}^k T, \forall k, n \tag{16}$$

Problem Formulation

In order to ensure GUs fairness and enhance the Dual-UAV-MEC systems secure calculation capacity, define GU_k average secure calculation bits as the objective,

$$\overline{R}_{k,\mathrm{sec}}=\frac{1}{T}\left(\sum_{n=1}^{N} l_{loc,k}[n]+B\delta_t\sum_{n=1}^{N}\tau_k[n]R_{k,\mathrm{sec}}[n]\right), \forall k, n \tag{17}$$

Under the constraints of the maximum flight speed of UAVs, anti-collision between UAV_S and UAV_E, GU_k average power budget, GUs and UAV_S calculating capability and GU_k secure task calculation requirements, we optimize the time allocation factor $\tau_k[n]$, the local calculation $l_{loc,k}[n]$ and the trajectory of UAV_S $q_s[n]$ to maximize the minimum GU_k average secure calculation capacity, as follows,

$$\begin{aligned}&(\mathrm{P1}):\max_{\{\tau_k[n],l_{loc,k}[n],q_s[n]\}}\min_{\forall k}\overline{R}_{k,\mathrm{sec}} \\ &s.t.(1),(2),(6),(12),(13),(14),(16)\end{aligned} \tag{18}$$

The problem (P1) is hard to solve as the non-convexity of (2), (13) and (14).

3 Problem Solution

We introduce $\{t, t_{1,k}[n], t_{2,k}[n]\}$ as auxiliary variables to convexify the problem (P1), which can be solved by optimizing $S=\{\tau_k[n], l_{loc,k}[n], q_s[n], t, t_{1,k}[n], t_{2,k}[n]\}$, which is rewritten as

$$(\mathrm{P2}):\max_{S} t \tag{19a}$$

$$s.t.(1),(2),(6),(12),(16)$$

$$t\leq\frac{1}{T}\left(\sum_{n=1}^{N} l_{loc,k}[n]+B\delta_t\sum_{n=1}^{N}\left(t_{1,k}[n]-t_{2,k}[n]\right)\right), \forall k, n \tag{19b}$$

$$t_{1,k}[n]\leq\tau_k[n]\log_2\left(1+\frac{|h_{k,s}[n]|^2 p_k[n]}{\delta_s^2}\right), \forall k, n \tag{19c}$$

$$\tau_k[n]\log_2\left(1+\frac{|h_{k,e}[n]|^2 p_k[n]}{|h_{j,e}[n]|^2 P_j+\delta_e^2}\right)\leq t_{2,k}[n], \forall k, n \tag{19d}$$

$$c_s B\left(t_{1,k}[n]-t_{2,k}[n]\right)\leq\tau_k[n]F_s^{\max}, \forall k, n \tag{19e}$$

$$l_{loc,k}[n]+B\delta_t\left(t_{1,k}[n]-t_{2,k}[n]\right)\geq Q_m, \forall k, n \tag{19f}$$

The lower bound of the objective function $\overline{R}_{k,\text{sec}}$ is represented by t. $t_{1,k}[n]$ and $t_{2,k}[n]$ are expressed as the lower bound of $R_{k,s}[n]$ and the upper bound of $R_{k,e}[n]$, respectively. Then the secrecy offloading rate $R_{k,sec}[n]$ is represented as $(t_{1,k}[n] - t_{2,k}[n])$. We can omit $(\cdot)^+$ because it is guaranteed that the objective is non-negative, $p_k[n]$ is given which is non-negative, and at least $l_{loc,k}[n]$ can be set to 0. The problem (P1) is equivalently formulated as (19).

Since constraints (2), (19c) and (19d) is non-convex, we utilize BCD and SCA algorithms to solve problem (P2) in two steps, i.e., step 1, with given UAV_S trajectory to optimize time allocation factor and local calculation, and step 2, with given time allocation factor and local calculation to optimize UAV_S trajectory.

3.1 Step 1: Time Allocation and Local Calculation Allocation

For any given trajectory of UAV_S, the problem (P2) is rewritten as

$$\begin{aligned}(\text{P3.1}): & \max_{\{\tau_k[n], l_{loc,k}[n], t_{1,k}[n], t_{2,k}[n]\}} t \\ & s.t. (6), (12), (16), (19b) - (19f)\end{aligned} \tag{20}$$

Note that the optimization problem (P3.1) is typically convex as the constraints of (P3.1) are linear, which can be effectively solved by utilizing standard optimization software e.g., CVX [10].

3.2 Step 2: Trajectory Optimization

For any given trajectory of time allocation factor and local calculation, the problem (P2) is rewritten as

$$\begin{aligned}(\text{P3.2}): & \max_{\{q_s[n], t_{1,k}[n], t_{2,k}[n]\}} t \\ & s.t. (1), (2), (19b) - (19f)\end{aligned} \tag{21}$$

Since (P3.2) is a non-convex problem as the non-convexity of the constraints (2) and (19c), we apply SCA to solve (P3.2). (P3.2) is an approximately convex in r-th iteration. Then, we update the trajectory of UAV_S iteratively to obtain $q_s[n]$.

Constraint (2) can be transformed as the following expression in terms of UAV_S flight trajectory in the $r-$th iteration, $\{q_s^r[n]\}$, by first-order Taylor expansion, given by

$$||q_s^r[n] - q_e[n]||^2 + 2||q_s^r[n] - q_e[n]||||q_s[n] - q_s^r[n]|| \geq d_{\min}^2, \forall n \in \{1, 2..., N\} \tag{22}$$

According to (19c), similarly we have

$$t_{1,k}[n] \leq A_{1,k}[n] - A_{2,k}[n], \forall k, n \tag{23}$$

where $A_{1,k}[n] - A_{2,k}[n]$ represent the lower-bounded of the right term in (19c) approximately. $A_{1,k}[n]$ and $A_{2,k}[n]$ are as follows, respectively,

$$\begin{aligned} A_{1,k}[n] &= \log_2\left(\left(||q_s^r[n]-w_k||^2\right)\delta_s^2 + H_s^2 + \beta_0 p_k[n]\right) \\ &+ \frac{2}{\ln 2}\frac{\left(||q_s^r[n]-w_k||\right)\delta_s^2\left(q_s[n]-q_s^r[n]\right)}{\left(\delta_s^2\left(||q_s^r[n]-w_k||^2+H_s^2\right)+\beta_0 p_k[n]\right)}, \forall k, n \end{aligned} \tag{24}$$

$$\begin{aligned} A_{2,k}[n] &= \log_2\left(\left(||q_s^r[n]-w_k||^2\right)\delta_s^2 + H_s^2\right) \\ &+ \frac{2}{\ln 2}\frac{\left(||q_s^r[n]-w_k||\right)\delta_s^2\left(q_s[n]-q_s^r[n]\right)}{\delta_s^2\left(||q_s^r[n]-w_k||^2+H_s^2\right)}, \forall k, n \end{aligned} \tag{25}$$

Problem (P3.2) can be optimized by solving

$$\begin{aligned} (\text{P3.3}): &\max_{\{q_s[n]\},\{t_{1,k}[n],t_{2,k}[n]\}} t \\ &s.t.(1),(19b),(19d),(19e),(19f),(22),(23) \end{aligned} \tag{26}$$

Note that (P3.3) is convex, which can be solved by using standard optimization software effectively.

As a result, we can optimize the problem (P1) by solving (P3.1) and (P3.3) alternatively in the case of updating all optimizing variables, which is concluded in Algorithm 1.

Algorithm 1. Proposed algorithm based on BCD to optimize (P1)

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1: Initialize Given $\tau_k^r[n], q_s^r[n], l_{loc,k}^r[n]$, $r = 0$ and $\theta$, $\theta > 0$.
2: Repeat
3:     Given $q_s^r[n]$, and obtain the time allocation factor $\tau_k[n]$ and local calculation $l_{loc,k}[n]$ to solve (P3.1).
4:     Update $\tau_k^r[n] = \tau_k[n]$, $l_{loc,k}^r[n] = l_{loc,k}[n]$.
5:     Given $\tau_k^r[n]$ and $l_{loc,k}^r[n]$, and obtain UAV_S trajectory optimization $q_s[n]$.
6:     Update $q_s^r[n] = q_s[n]$.
7:     Update $r = r + 1$.
8: Until Objective increase is less than $\theta$ or $r$ is equal to $r_{max}$.
9: Output $\tau_k[n], l_{loc,k}[n], q_s[n], t, t_{1,k}[n]$ and $t_{2,k}[n]$.
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4 Simulation Results

In this section, we present simulation results of the optimization objective by our proposed algorithm. In the Dual-UAV-MEC system, GJ is set at $[0,0,0]^T$, and 5 GUs are randomly fixed in a $400 \times 400\,\text{m}^2$ area. UAV_E flies at a constant speed from $[200,-10,100]^T$ to $[-200,50,100]^T$ with given trajectory, and UAV_S flies from $[-200, -10, 100]^T$ to $[200, -10, 100]^T$. UAV_i's maximum flight speed is 50 m/s. UAV_S and UAV_E anti-collision minimum distance is 1 m.

Figure 2 shows the convergence of our proposed algorithm with different T and p_k. We can find from Fig. 2 that the algorithm we proposed is converged and the secure calculation capacity of the system is better with larger T and P_k.

Figure 3 shows the UAV_S and UAV_E trajectory after optimization when $T = 20$ s. In Fig. 3, UAV_E files with a constant speed to eavesdrop GUs offloading information, and we can find that UAV_S flies as close to GUs as possible to get better channel condition to obtain GUs offloading information.

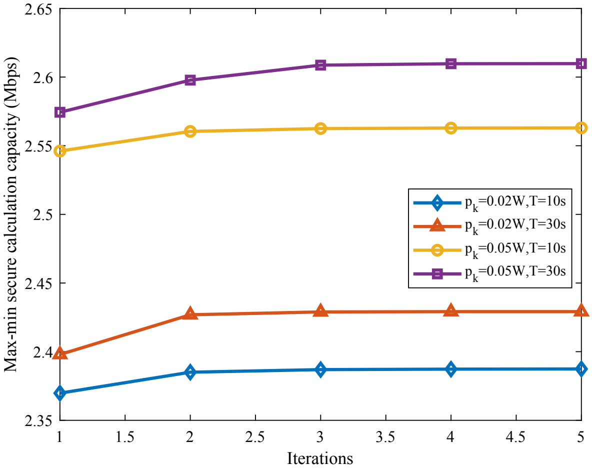

Fig. 2. Convergence.

Figure 4 shows the objective, max-min secure calculation capacity, versus T with different GUs' transmit power p_k. In Fig. 4, we find that the secure performance becomes better with the increase of T. This is because that UAV_S has more chance and time to get closer to GUs to improve get more GUs offloading information when T increases. And when p_k is larger, the more energy GUs could get, thus GUs is able to send more information offloading and the objective is larger.

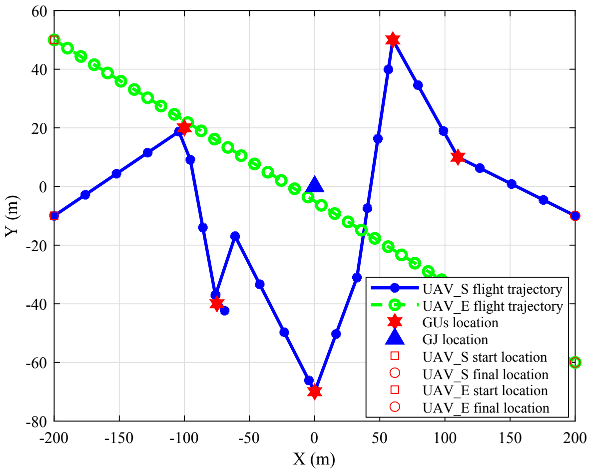

Fig. 3. The optimization trajectory of UAV_S and UAV_E.

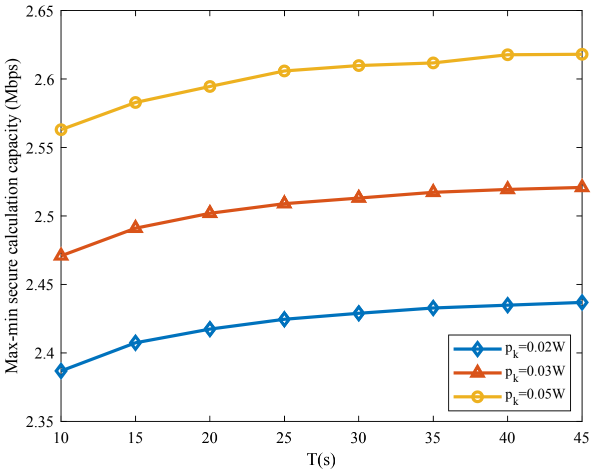

Fig. 4. The objective comparison versus T.

Figure 5 depicts the objective changes in case of time and local calculation allocation without trajectory optimization, trajectory optimization without time and local calculation allocation and joint optimization we proposed. It is clear to find that joint optimization scheme outperforms the other schemes, which proves greatly the significant effect of the algorithm we proposed.

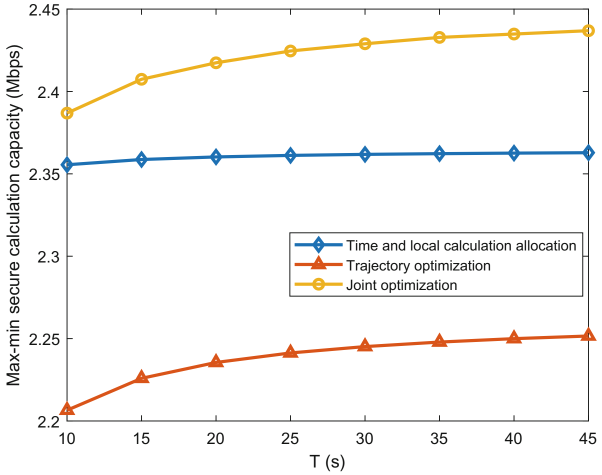

Fig. 5. The objective versus T.

5 Conclusion

This paper investigated the secure calculation capacity of the Dual-UAV-MEC system, in which multiple GUs offload partial tasks to UAV_S for calculation with the presence of UAV_E eavesdropping. In order to enhance the security communication performance, we set GJ to send interference information to disturb UAV_E. To maximize the minimum objective, the secure calculation capacity, we optimize time allocation factor, local calculation and the trajectory of UAV_S with the constraints of UAVs maximum flight speed, the anti-collision between UAV_S and UAV_E, GU_k average power budget, GUs and UAV_S calculating capability and GU_k secure task calculation requirements. We proposed the efficient algorithm to solve the optimization problem by combining BCD and SCA methods. Simulation results show that the algorithm can enhance the security communication performance of the system effectively.

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References

1. Lee, S., Lee, S., Shin, M.-K.: Low cost MEC server placement and association in 5G networks. In: 2019 International Conference on Information and Communication Technology Convergence (ICTC), Jeju, Korea (South), pp. 879–882 (2019)
2. Nguyen, T.D.T., Nguyen, V., Pham, V.-N., Huynh, L.N.T., Hossain, M.D., Huh, E.-N.: Modeling data redundancy and cost-aware task allocation in MEC-enabled Internet-of-vehicles applications. IEEE Internet Things J. **8**(3), 1687–1701 (2021)

3. Yu, Z., Gong, Y., Gong, S., Guo, Y.: Joint task offloading and resource allocation in UAV-enabled mobile edge computing. IEEE Internet Things J. **7**(4), 3147–3159 (2020)
4. Guo, F., Zhang, H., Ji, H., Li, X., Leung, V.C.M.: Joint trajectory and computation offloading optimization for UAV-assisted MEC with NOMA. In: IEEE INFOCOM 2019 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), Paris, France (2019)
5. Du, Y., Yang, K., Wang, K., Zhang, G., Zhao, Y., Chen, D.: Joint resources and workflow scheduling in UAV-enabled wirelessly-powered MEC for IoT systems. IEEE Trans. Veh. Technol. **68**(10), 10187–10200 (2019)
6. Zhou, F., Wu, Y., Hu, R.Q., Qian, Y.: Computation rate maximization in UAV-enabled wireless-powered mobile-edge computing systems. IEEE J. Sel. Areas Communi. **36**(9), 1927–1941 (2018)
7. Lu, W., Wu, W., Qian, L., Wu, Y., Yu, N., Huang, L.: Optimal power allocation for secure non-orthogonal multiple access transmission. In: 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall), Victoria, BC, Canada (2020)
8. Zhao, N., et al.: Security enhancement for NOMA-UAV networks. IEEE Trans. Veh. Technol. **69**(4), 3994–4005 (2020)
9. Marks, B., Wright, G.P.: A general inner approximation algorithm for nonconvex mathematical programs. Oper. Res. **26**(4), 681–683 (1978)
10. Boyd, S., Vandenberghe, L.: Convex Optimization. Cambridge University Press, Cambridge (2004)