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Mobile Edge Computing for Cellular-Connected UAV: Computation Offloading and Trajectory Optimization

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1. Introduction

Unmanned aerial vehicles (UAVs) have received growing interests in various applications such as cargo delivery, filming, rescue and search, as well as wireless platforms [1] [2]. To provide seamless communication for UAVs to maintain their safe cooperation, cellular-connected UAV communication has recently been emerging. UAVs can act as new aerial mobile users in cellular networks [3] [4]. Nevertheless, with their size, weight, and power (SWAP) limitations, UAVs usually have limited computation resources to handle computation-intensive and yet latency-critical tasks.

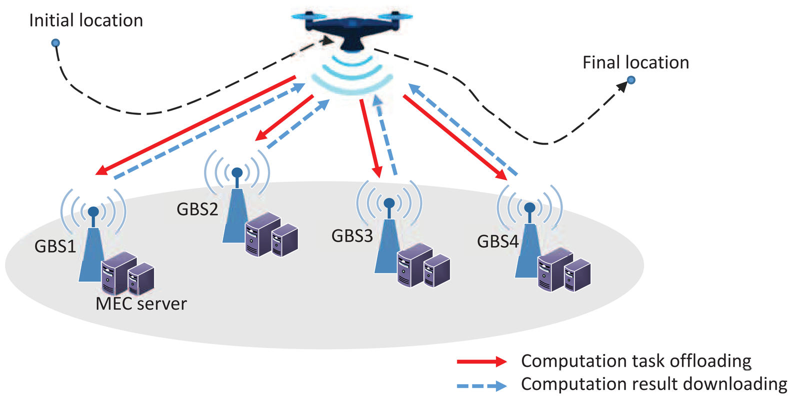
This paper proposes a new approach by jointly exploiting the techniques of mobile edge computing (MEC) and cellular-connected UAV communication. UAVs with cellular connection can offload their intensive computation tasks to ground base stations (GBSs) integrated with edge servers for remote execution. As GBSs are nowadays deployed almost everywhere, UAVs can connect to them with seamless communication and ubiquitous computation services. This helps increase their operation range and enlarge their application horizon.

With high-mobility UAV users in MEC system, some new opportunities and challenges are shown up.

- A UAV user in the sky usually possesses stronger and more reliable line-of-sight (LoS) links with many GBSs at the same time. This thus enables each UAV to simultaneously connect with multiple GBSs to exploit their distributed computing resources.
- With the controllable mobility in the three-dimensional (3D) airspace, UAV's trajectory can be jointly designed with its scheduling of computation offloading.

This paper studies a practical scenario where a UAV is served by cellular GBSs for computation offloading. The main results are summarized as follows.

- We aim to minimize the UAV's mission completion time by optimizing its trajectory jointly with the computation offloading scheduling, subject to the maximum speed constraint of the UAV, and the computation capacity constraints at GBSs.
- The formulated problem is non-convex and thus difficult to be solved optimally. Thus, we propose an efficient algorithm to obtain a high-quality suboptimal solution.
- Numerical results show that the proposed design significantly reduces the UAV's mission completion time, as compared to benchmark schemes.



2. System Model and Problem Formulation

2.1 System Setup:

- A system inclues one cellular-connected UAV user and a set $\mathcal{K} \triangleq \{1, \ldots, K\}$ of $K \geq 1$ GBSs.
- L: the number of task-input bits in the UAV;
  T: the mission completion time;
  $c_k > 0$: the execution of each task-input bit requires the same number of central frequency unit (CPU) cycles at GBS k.
- Each GBS has zero altitude and fixed horizontal location $\boldsymbol{\nu}_k = (x_k, y_k)$.
- The UAV flies at a fixed altitude $H \geq 0$ m, and $\boldsymbol{u}_I = (x_I, y_I)$ and $\boldsymbol{u}_F = (x_F, y_F)$ denote the UAV's initial and final locations, respectively.
- $\hat{\boldsymbol{u}}(t) = (\hat{x}(t), \hat{y}(t))$: the UAV's horizontal location at time instant $t \in [0, T]$.
- T can be discretized into N time slots each with duration δ_t, i.e. $T = N\delta_t$, where δ_t is sufficiently small and N is to be optimized. Thus the UAV's horizontal location at time slot n is $\boldsymbol{u}[n] \triangleq \hat{\boldsymbol{u}}(n\delta_t), n \in \mathcal{N} \triangleq \{1, ..., N\}$, with $\boldsymbol{u}[0] \triangleq \hat{\boldsymbol{u}}(0) = \boldsymbol{u}_I$ and $\boldsymbol{u}[N] \triangleq \hat{\boldsymbol{u}}(T) = \boldsymbol{u}_F$.
- The distance between the UAV and GBS k is
  $$d_k(\boldsymbol{u}[n]) = \sqrt{H^2 + \|\boldsymbol{u}[n] - \boldsymbol{\nu}_k\|^2},$$
  where $\|\cdot\|$ denotes the Euclidean norm.
- The channel power gain from the UAV to GBS k is
  $$h_k(\boldsymbol{u}[n]) = \frac{\beta_0}{d_k^2(\boldsymbol{u}[n])} = \frac{\beta_0}{H^2 + \|\boldsymbol{u}[n] - \boldsymbol{\nu}_k\|^2},$$
  where β_0 denotes the channel power gain at a reference distance of 1 m.

2.2 UAV's Flying:

- $V_{\max} > 0$: the UAV's maximum speed;
  $S_{\max} = \delta_t V_{\max}$: the maximum UAV displacement during each time slot.
- The maximum UAV speed and initial/final location constraints are
  $$\|\boldsymbol{u}[n] - \boldsymbol{u}[n-1]\|^2 \leq S_{\max}^2, \forall n \in \mathcal{N}, \quad (1)$$
  $$\boldsymbol{u}[0] = \boldsymbol{u}_I,\ \boldsymbol{u}[N] = \boldsymbol{u}_F. \quad (2)$$

2.3 UAV's Computation Offloading:

- Time-division-multiple-access (TDMA) protocol is considered to implement the UAV's computation offloading. By dividing each time slot $n \in \mathcal{N}$ into K sub-slots each with duration $\tau_k[n] \geq 0$, we have
  $$\sum_{k \in \mathcal{K}} \tau_k[n] = \delta_t, \ \forall n \in \mathcal{N}, \quad (3)$$
  $$\tau_k[n] \geq 0, \ \forall k \in \mathcal{K}, n \in \mathcal{N}. \quad (4)$$
- The achievable offloading rate from the UAV to GBS k is
  $$R_k(\boldsymbol{u}[n]) = B \log_2\left(1 + \frac{P h_k(\boldsymbol{u}[n])}{\sigma^2}\right),$$
  $$= B \log_2\left(1 + \frac{\rho}{H^2 + \|\boldsymbol{u}[n] - \boldsymbol{\nu}_k\|^2}\right),$$
  where $P > 0$, σ^2 and B are the transmit power, noise power at the receiver of each GBS and the bandwidth, respectively, and $\rho = \frac{P\beta_0}{\sigma^2}$ is the reference signal-to-noise ratio (SNR).
- In order for the UAV to offload all the L task-input bits to the K GBSs, we have
  $$\sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} \tau_k[n] R_k(\boldsymbol{u}[n]) \geq L. \quad (5)$$
- As for the remote task execution at each GBS k, we have the following computation capacity constraint over time:
  $$\sum_{j=n}^{N} c_k \tau_k[j] R_k(\boldsymbol{u}[j]) \leq (N-n) f_k \delta_t, \quad (6)$$
  where f_k is the maximum CPU frequency at GBS k, and $f_k \delta_t$ represents the per-slot computation capacity of GBS k.

2.4 Problem Formulation:

The joint UAV trajectory and computation offloading optimization problem is formulated as

$$(\mathbf{P1}): \min_{\{\boldsymbol{u}[n], \tau_k[n]\}, N \in \mathbb{Z}^+} N$$
$$\text{s.t.} \quad (1), (2), (3), (4), (5), \text{and } (6),$$

where $\mathbb{Z}^+$ is the set of all strictly positive integers.

3. Proposed Solution to (P1)

We sub-optimally solve (P1) equivalently by first optimizing over $\{\boldsymbol{u}[n]\}$ and $\{\tau_k[n]\}$ under any given N, and then using a bisection search to find the optimal N. Let N^* denote the optimal solution of N to (P1).

3.1 Feasibility Checking Problem:

Under any given N, (P1) becomes the following feasibility checking problem:

$$(\mathbf{P2}): \text{find } \{\boldsymbol{u}[n]\} \text{ and } \{\tau_k[n]\}$$
$$\text{s.t. } (1), (2), (3), (4), (5), \text{and } (6).$$

If (P2) is feasible under N, then it follows that $N^* \leq N$; otherwise, we have $N^* \geq N$.

3.2 Solving (P2) Under Given N:

Note that solving (P2) is equivalent to solving the following problem (P3) to maximize the number of computation task-input bits $\tilde{L}$.

$$(\mathbf{P3}): \max_{\{\boldsymbol{u}[n]\}, \{\tau_k[n]\}, \tilde{L} \geq 0} \tilde{L}$$
$$\text{s.t.} \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} \tau_k[n] R_k(\boldsymbol{u}[n]) \geq \tilde{L}, \quad (7)$$
$$(1), (2), (3), (4), \text{and } (6).$$

If $\tilde{L}^* \geq L$, then (P2) is feasible; otherwise, (P2) is infeasible.

3.3 Suboptimal Solution to (P3):

We jointly optimize the time allocation $\{\tau_k[n]\}$ and the UAV trajectory $\{\boldsymbol{u}[n]\}$ in an alternating manner to solve (P3).

- **Time Allocation for (P3) Under Given UAV Trajectory:**
  Under given $\{\boldsymbol{u}[n]\}$, (P3) is reduced to
  $$(\mathbf{P3.1}): \max_{\{\tau_k[n]\}, \tilde{L} \geq 0} \tilde{L} \text{ s.t. } (3), (6), (4), \text{and } (7).$$
  (P3.1) is a linear program (LP), which can be solved by CVX.

- **UAV Trajectory Optimization for (P3) Under Given Time Allocation:**
  Under given $\{\tau_k[n]\}$, (P3) is reduced to
  $$(\mathbf{P3.2}): \max_{\{\boldsymbol{u}[n]\}, \tilde{L} \geq 0} \tilde{L} \text{ s.t. } (1), (2), (6), \text{and } (7).$$
  (P3.2) is non-convex. We use the successive convex approximation (SCA) technique iteratively to solve (P3.2), and denote $\{\boldsymbol{u}^{(i)}[n]\}$ as the local point at the i-th iteration, $i \geq 0$.

  First, consider constraint (6). By checking the first-order Taylor expansion of the convex term $H^2 + \|\boldsymbol{u}[n] - \boldsymbol{\nu}_k\|^2$ with respect to $\boldsymbol{u}[n]$ at the local point $\boldsymbol{u}^{(i)}[n]$, we have
  $$H^2 + \|\boldsymbol{u}[n] - \boldsymbol{\nu}_k\|^2 \geq q_k^{(i)}[n] + 2(\boldsymbol{\omega}^{(i)}[n])^T \boldsymbol{u}[n],$$
  with $\boldsymbol{\omega}^{(i)}[n] = \boldsymbol{u}^{(i)}[n] - \boldsymbol{\nu}_k$ and $q_k^{(i)}[n] = H^2 + \|\boldsymbol{u}^{(i)}[n] - \boldsymbol{\nu}_k\|^2 - 2(\boldsymbol{\omega}^{(i)}[n])^T \boldsymbol{u}^{(i)}[n]$, where $(\cdot)^T$ indicates the transpose. Then, we obtain an upper bound of $R_k(\boldsymbol{u}[n])$ as
  $$R_k(\boldsymbol{u}[n]) \leq R_{k,\text{up}}^{(i)}(\boldsymbol{u}[n])$$
  $$\triangleq B \log_2\left(1 + \frac{\rho}{q_k^{(i)}[n] + 2(\boldsymbol{\omega}^{(i)}[n])^T \boldsymbol{u}[n]}\right),$$
  where $R_{k,\text{up}}^{(i)}(\boldsymbol{u}[n])$ is convex with respect to $\boldsymbol{u}[n]$. Replacing $R_k(\boldsymbol{u}[n])$ in (6) as $R_{k,\text{up}}^{(i)}(\boldsymbol{u}[n])$, we have
  $$\sum_{j=n}^{N} c_k \tau_k[n] R_{k,\text{up}}^{(i)}(\boldsymbol{u}[n]) \leq (N-n) f_k \delta_t. \quad (9)$$

  Next, consider constraint (7). By taking the first-order Taylor expansion of $R_k(\boldsymbol{u}[n])$ with respect to $\|\boldsymbol{u}[n] - \boldsymbol{\nu}_k\|^2$, we can obtain a lower bound of $R_k(\boldsymbol{u}[n])$.
  $$R_k(\boldsymbol{u}[n]) \geq R_{k,\text{low}}^{(i)}(\boldsymbol{u}[n])$$
  $$\triangleq R_k(\boldsymbol{u}^{(i)}[n]) + b_k^{(i)}[n](\|\boldsymbol{u}^{(i)}[n] - \boldsymbol{\nu}_k\|^2)$$
  $$- b_k^{(i)}[n](\|\boldsymbol{u}[n] - \boldsymbol{\nu}_k\|^2),$$
  where $b_k^{(i)}[n] = B\rho/(\ln 2 d_k^2(\boldsymbol{u}^{(i)}[n])(\rho + d_k^2(\boldsymbol{u}^{(i)}[n])))$. Replacing $R_k(\boldsymbol{u}[n])$ in constraint (7) as $R_{k,\text{low}}^{(i)}(\boldsymbol{u}[n])$, we have
  $$\sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} \tau_k[n] R_{k,\text{low}}^{(i)}(\boldsymbol{u}[n]) \geq \tilde{L}. \quad (10)$$

  Finally, (P3.2) is approximated as (P3.3). It can be solved optimally via CVX.
  $$(\mathbf{P3.3}): \max_{\{\boldsymbol{u}[n]\}, \tilde{L} \geq 0} \tilde{L} \text{ s.t. } (1), (2), (9), \text{and } (10).$$
  In each iteration $i \geq 1$, the UAV trajectory is updated as $\{\boldsymbol{u}^{(i)*}[n]\}$ by solving (P3.3) at local point $\{\boldsymbol{u}^{(i)}[n]\}$, i.e. $\boldsymbol{u}^{(i+1)}[n] = \boldsymbol{u}^{(i)*}[n], \forall n \in \mathcal{N}$, where $\{\boldsymbol{u}^{(0)}[n]\}$ denotes the initial UAV trajectory. Thus (P3.2) is solved.

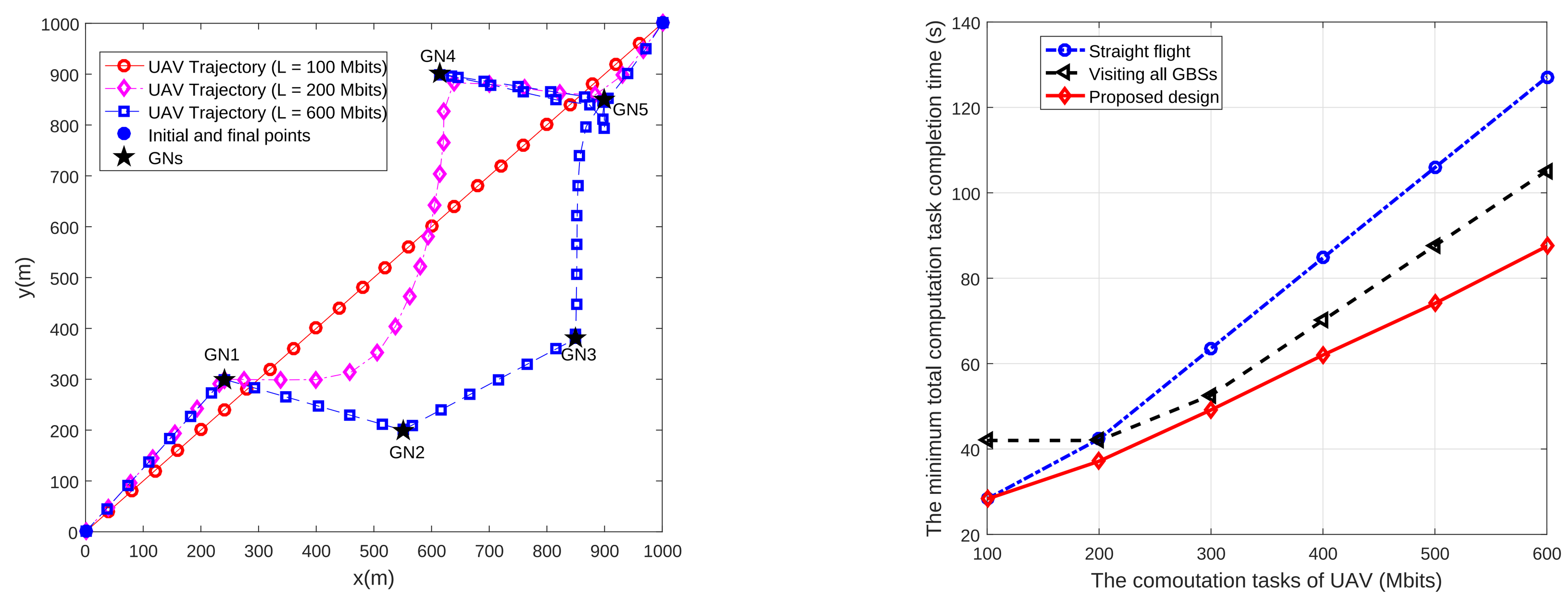
- **Complete Algorithm to Solve (P3):**
  With (P3.1) and (P3.2) solved, we solve (P3) by iteratively updating $\{\boldsymbol{u}[n]\}$ and $\{\tau_k[n]\}$. In each iteration, we first solve (P3.1) under given $\{\boldsymbol{u}[n]\}$ to update $\{\tau_k[n]\}$, and then solve (P3.2) under $\{\tau_k[n]\}$ to update $\{\boldsymbol{u}[n]\}$.

With (P3) solved, the feasibility of (P2) is accordingly checked. By combing this together with the bisection search over N, problem (P1) can be efficiently solved.

4. Numerical Results

There are $K = 5$ GBSs that are distributed within a geographic area of size 1×1 km^2. At each GBS, we set $f_k = 2.5$ GHz and $c_k = 10^3$ cycles/bit. Let $B = 1$ MHz, $H = 50$ m, $V_{\max} = 50$ m/s, and $P = 0.1$ W. The channel power gain at the reference distance of 1 m is $\beta_0 = -30$ dB and the noise power is $\sigma^2 = -60$ dBm. We validate the performance of our proposed design comparing with the following benchmark schemes.

- *Straight flight:* the UAV flies straight from the initial to the final location.
- *Successive hover-and-fly:* the UAV flies to successfully reach at the top of the K GBSs at the maximum speed, and hovers above each of them for computation offloading.



(a) Optimized UAV trajectory projected on the horizontal plane under different values of L.

(b) The minimum mission completion time T versus the number of task-input bits L.

5. Conclusion

This paper investigates a new MEC application scenario where a cellular-connected UAV offloads its computation tasks to multiple GBSs along its trajectory.

- The UAV trajectory is jointly designed with the computation offloading scheduling, to minimize the mission completion time, subject to the UAV's maximum speed and initial/final location constraints, as well as the GBSs' individual computation capacity constraints.
- By exploiting alternating optimization and SCA techniques, an efficient algorithm is proposed to solve the formulated problem sub-optimally.
- Numerical results show a prominent performance gain of our design over the benchmark schemes.

References

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