Mobile Edge Computing via a UAV-Mounted Cloudlet: Optimization of Bit Allocation and Path Planning

§ Abstract

UAV: as means to enhance coverage or relaying services;

A moving UAV is endowed with computing capabilities to offer computation offloading opportunities; ⇒ aims at minimizing the total mobile energy consumption while satisfy the quality of services.

Problem: jointly optimizing the bit allocation along with the cloudlet's trajectory

§ I. Introduction

moving base stations or relays mounted on UAV ⇒ to extend coverage

Challenges: limited coverage and mobility of energy-constrained UAVs

A: State of the Art

* A UAV-enabled mobile relaying system ⇒ An iterative algorithm is proposed to alternatively optimize the power allocation and relay's trajectory.
  ↳ with the aim of maximizing the throughput [8]
* The efficient data delivery is sparse mobile ad hoc networks ⇒ to optimize the message drop rate under energy constraits [9]
* the deployment of UAV as relays to provide uplink transmition coverage ⇒ with the goal of maximizing the sum-rate [11]
* A scheduling and resource allocation framework ⇒ the minimum number of required UAVs [12]
* The optimal deployment of UAVs in the downlink scenario ⇒ To minimizing the required downlink transmit power for covering a target area. [13, 14]
* [14] the minimization of the total required downlink transmit power [14]

⇒ 以上为 communication scenarios.

Optimization of UAV path planning

* A ground vehicle and an aerial vehicle
* UAV trajectory optimization for drone delivery

⇒ 以上有关 Path Planning

B. UAV as a Moving Cloudlet

* A UAV-mounted cloudlet to provide application offloading opportunities ⇒ Specifically, MUs can offload computationally heavy tasks.

Fig. 1. Illustration of the considered mobile cloud computing system based on a UAV-mounted cloudlet that provides application offloading opportunities to MUs. The key design problem is the optimization of the bit allocation for communication in uplink (UL) and downlink (DL) and computing, as well as the cloudlet's trajectory with the goal of minimizing the mobile energy consumption.

Offloading Procedure

① uplink transmission
② Computation
③ downlink transmission

C. Main Contributions

* Scenario : A moving UAV is deployed to offer offloading opportunities to mobile devices ⇒ optimizing bit allocation for communication and computing as well as UAV's trajectory with the goal of minimizing the mobile energy consumption

① uplink/downlink transmission : orthogonal / non-orthogonal
② energy consumption : communication + computing + flying
↳ ① v
② v + acceleration

⇒ non-convex problem
⇓
successive convex approximation (SCA)

§II. System Model

A. Set-Up

Fig. 1. Illustration of the considered mobile cloud computing system based on a UAV-mounted cloudlet that provides application offloading opportunities to MUs. The key design problem is the optimization of the bit allocation for communication in uplink (UL) and downlink (DL) and computing, as well as the cloudlet's trajectory with the goal of minimizing the mobile energy consumption.

* consists of K MUs and a UAV-mounted cloudlet
  ⇒ Study the optimization of offloading process with the goal of minimizing the total energy consumption
* To enable offloading
  i. uplink transmission
  ii. execution on cloudlet
  iii. downlink transmission
* A three-dimension Cartesian coordinate system ⇐ $\begin{cases} p_k^m : \text{position of mobile } k \\ p_{(t)}^c : \text{position of UAV, fixed } H \end{cases}$
* the time horizon T is divided into N intervals : $T = N \cdot \Delta$

up/down link communication $\begin{cases} \text{orthogonal} \\ \text{non-orthogonal (in } \pm G \Rightarrow \text{NOMA)} \end{cases}$
↳ assume FDD with equal B

$M_k(I_k, C_k, D_k)$ with in time T

B. Energy Consumption Model for Offloading

* Computation Energy at the cloudlet

$$E_k^c(l, f^c) = \gamma^c C_k l (f^c)^2, \tag{5}$$

* Communication Energy at the mobile and UAV

{ orthogonal access
non-orthogonal access

① Orthogonal

$$E_{O,k,n}^d(L_{k,n}^d, \boldsymbol{p}_n^c) = \frac{N_0 B\Delta/K}{g_{k,n}(\boldsymbol{p}_n^c)} \left(2^{\frac{L_{k,n}^d}{B\Delta/K}} - 1\right), \tag{6}$$

where we recall that $g_{k,n}(\boldsymbol{p}_n^c)$ in (4) is the path loss between the MU k and cloudlet at the nth frame, and $d = \mathrm{m}$ for uplink while $d = \mathrm{c}$ for downlink.

② Non-orthogonal (cf. NOMA in 5G)

$$E_{N,k,n}^m(L_n^m, \boldsymbol{p}_n^c) = \frac{1}{g_{k,n}(\boldsymbol{p}_n^c)} \Bigg(N_0 B\Delta + \sum_{k'=1, k'\neq k}^{K} g_{k',n}(\boldsymbol{p}_n^c) E_{N,k',n}^m(L_n^m, \boldsymbol{p}_n^c)\Bigg) \left(2^{\frac{L_{k,n}^m}{B\Delta}} - 1\right) \tag{7a}$$

⇒ for uplink

and

$$E_{N,k,n}^c(L_n^c, \boldsymbol{p}_n^c) = \Bigg(\frac{N_0 B\Delta}{g_{k,n}(\boldsymbol{p}_n^c)} + \sum_{k'=1, k'\neq k}^{K} E_{N,k',n}^c(L_n^c, \boldsymbol{p}_n^c)\Bigg) \left(2^{\frac{L_{k,n}^c}{B\Delta}} - 1\right), \tag{7b}$$

⇒ for downlink

* Flying Energy

① model 1: Energy depends only on velocity

$$\text{(Model 1)} E_{F,n}^c(\boldsymbol{v}_n^c) = \kappa \left\|\boldsymbol{v}_n^c\right\|^2, \tag{8}$$

② model 2: velocity + acceleration vector

C. Energy consumption Model for Mobile Execulation

$$E^m \triangleq \sum_{k=1}^{K} E_k^m(I_k, f_k^m) = \sum_{k=1}^{K} \frac{\gamma_k^m C_k^3}{T^2} I_k^3, \tag{10}$$

⇒ The total energy consumption for all mobile users.

§III. Optimal Energy Consumption of Orthogonal Access (orthogonal access + Model 1) ⇓ velocity

A. Problem Formulation

MUs ⇐ UAVs ⇐

$$\underset{\{L^m_{k,n}\},\{l_{k,n}\},\{L^c_{k,n}\},\{\boldsymbol{p}^c_n\}}{\text{minimize}} \sum_{k=1}^{K}\sum_{n=1}^{N-2} E^m_{O,k,n}(L^m_{k,n},\boldsymbol{p}^c_n) \tag{13a}$$

Energy needed for uplink

$$\text{s.t.} \sum_{k=1}^{K}\sum_{n=1}^{N-2} E^c_{k,n+1}(l_{n+1}) + E^c_{O,k,n+2}(L^c_{k,n+2},\boldsymbol{p}^c_{n+2})$$

Computation Energy Consumption

Transmission Energy for downlink

orthogonal

$$+\sum_{n=1}^{N} E^c_{F,n}(\boldsymbol{v}^c_n) \le \mathcal{E} \tag{13b}$$

→ UAV energy constraint

→ Flying Energy

$$\sum_{i=1}^{n} l_{k,i+1} \le \sum_{i=1}^{n} L^m_{k,i},$$

$$\text{for } k\in\mathcal{K} \text{ and } n=1,\dots,N-2 \tag{13c}$$

$$\sum_{i=1}^{n} L^c_{k,i+2} \le O_k \sum_{i=1}^{n} l_{k,i+1},$$

$$\text{for } k\in\mathcal{K} \text{ and } n=1,\dots,N-2 \tag{13d}$$

bit 收发、计算的限制.

$$\sum_{n=1}^{N-2} L^m_{k,n} = I_k, \text{ for } k\in\mathcal{K} \tag{13e}$$

$$\sum_{n=1}^{N-2} l_{k,n+1} = I_k, \text{ for } k\in\mathcal{K} \tag{13f}$$

$$\sum_{n=1}^{N-2} L^c_{k,n+2} = O_k I_k, \text{ for } k\in\mathcal{K} \tag{13g}$$

Ensure the completion of offloading

$$L^m_{k,n}, l_{k,n}, L^c_{k,n} \ge 0, \text{ for } k\in\mathcal{K} \text{ and } n\in\mathcal{N} \tag{13h}$$

$$\boldsymbol{p}^c_1 = \boldsymbol{p}^c_I, \boldsymbol{p}^c_{N+1} = \boldsymbol{p}^c_F, \tag{13i}$$

$$\|\boldsymbol{v}^c_n\| \le v_{\max}, \text{ for } n\in\mathcal{N} \tag{13j}$$

the cloudlet's position

$$\boldsymbol{v}^c_n = \frac{\boldsymbol{p}^c_{n+1} - \boldsymbol{p}^c_n}{\Delta} \text{ for } n\in\mathcal{N}, \tag{13k}$$

⇒ (Problem 13)

B. Successive Convex Approximation

problem 13 is non-convex due to ① non-convex objective function (13a)
② non-convex constraint (13.b)

$\Downarrow$

* Developed an SCA-based algorithm that build on the inner convex approximation framework proposed in [29] [30]

Algorithm 1: SCA-based algorithm for problem (13) for orthogonal access.

Input: $\boldsymbol{z}(0) = \{\boldsymbol{z}_n(0)\}_{n\in\mathcal{N}} \in \mathcal{X}$ with $\boldsymbol{z}_n(0) \triangleq (\{L^m_{k,n}(0)\}_{k\in\mathcal{K}}, \{l_{k,n}(0)\}_{k\in\mathcal{K}}, \{L^c_{k,n}(0)\}_{k\in\mathcal{K}}, \boldsymbol{p}^c_n(0))$, and $\tau_{L^m_{k,n}}, \tau_{x^c_n}, \tau_{y^c_n} > 0$ for $k \in \mathcal{K}$ and $n \in \mathcal{N}$. Set $v = 0$.

1. If $\boldsymbol{z}(v)$ is a stationary solution of (13), stop;
2. Compute $\hat{\boldsymbol{z}}(\boldsymbol{z}(v))$ using (20);
3. Set $\boldsymbol{z}(v+1) = \boldsymbol{z}(v) + \gamma(v)(\hat{\boldsymbol{z}}(\boldsymbol{z}(v)) - \boldsymbol{z}(v))$ for some $\gamma(v) \in (0, 1]$;
4. $v \leftarrow v + 1$ and go to step 1.

Output: $\{L^m_{k,n}\}$, $\{l_{k,n}\}$, $\{L^c_{k,n}\}$ and $\{\boldsymbol{p}^c_n\}$.

§ IV. Optimal Energy Consumption for Non-Orthogonal Access (Non-orthogonal + mode 1)

A. Problem Formulation

Non-orthogonal

$$\underset{\{L^m_{k,n}\},\{l_{k,n}\},\{L^c_{k,n}\},\{\boldsymbol{p}^c_n\}}{\text{minimize}} \sum_{k=1}^{K}\sum_{n=1}^{N-2} E^m_{N,k,n}(L^m_n, \boldsymbol{p}^c_n) \tag{21a}$$

$$\text{s.t.} \sum_{k=1}^{K}\sum_{n=1}^{N-2} E^c_{k,n+1}(l_{n+1}) + E^c_{N,k,n+2}(L^c_{n+2}, \boldsymbol{p}^c_{n+2}) + \sum_{n=1}^{N} E^c_{F,n}(\boldsymbol{v}^c_n) \leq \mathcal{E} \tag{21b}$$

$$(13c) - (13k). \tag{21c}$$

B. Successive Convex Approximation

Algorithm 2: SCA-based algorithm for problem (22) for non-orthogonal access.

Input: $\boldsymbol{z}(0) = \{\boldsymbol{z}_n(0)\}_{n\in\mathcal{N}} \in \mathcal{X}$ with $\boldsymbol{z}_n(0) \triangleq (\{L^m_{k,n}(0)\}_{k\in\mathcal{K}}, \{l_{k,n}(0)\}_{k\in\mathcal{K}}, \{L^c_{k,n}(0)\}_{k\in\mathcal{K}}, \boldsymbol{p}^c_n(0), \{\alpha_{k,n}(0)\}_{k\in\mathcal{K}}, \{\beta_{k,n}(0)\}_{k\in\mathcal{K}})$, and $\tau_{\alpha_{k,n}}, \tau_{x^c_n}, \tau_{y^c_n} > 0$ for $k \in \mathcal{K}$ and $n \in \mathcal{N}$. Set $v = 0$.

1. If $\boldsymbol{z}(v)$ is a stationary solution of (22), stop;
2. Compute $\hat{\boldsymbol{z}}(\boldsymbol{z}(v))$ using (27);
3. Set $\boldsymbol{z}(v+1) = \boldsymbol{z}(v) + \gamma(v)(\hat{\boldsymbol{z}}(\boldsymbol{z}(v)) - \boldsymbol{z}(v))$ for some $\gamma(v) \in (0, 1]$;
4. $v \leftarrow v + 1$ and go to step 1.

Output: $\{L^m_{k,n}\}$, $\{l_{k,n}\}$, $\{L^c_{k,n}\}$, $\{\boldsymbol{p}^c_n\}$, $\{\alpha_{k,n}\}$ and $\{\beta_{k,n}\}$.

§ V. UAV's Propulsion Energy Consumption (Model 2: velocity + acceleration)

previous model: flying energy depends on velocity

$$\text{(Model 1)} E_{F,n}^{c}(\boldsymbol{v}_n^c) = \kappa \left\| \boldsymbol{v}_n^c \right\|^2, \tag{8}$$

refined model: . . . . depends on velocity + acceleration vectors

(Model 2)

$$E_{F,n}^{c}(\boldsymbol{v}_n^c, \boldsymbol{a}_n^c) = \kappa_1 \left\| \boldsymbol{v}_n^c \right\|^3 + \frac{\kappa_2}{\left\| \boldsymbol{v}_n^c \right\|} \left(1 + \frac{\left\| \boldsymbol{a}_n^c \right\|^2}{g^2} \right), \tag{29}$$

§ VI. Numerical Results

Evaluate the performance via numerical experiments

Fig. 3. Position of the MUs and optimized UAV's trajectory for orthogonal access with Algorithm 1 ($K = 3$, $T = 2.25$ s, $(I_1, I_2, I_3) = (4, 6, 2)$ Mbits, $\boldsymbol{p}_1^m = (0, 10, 0)$ m, $\boldsymbol{p}_2^m = (10, 10, 0)$ m, $\boldsymbol{p}_3^m = (10, 0, 0)$ m, $\boldsymbol{p}_I^r = (0, 0)$ m, $\boldsymbol{p}_F^r = (5, 0)$ m and the reference SNR $g_0/(N_0 B) = -5$ dB).

Fig. 4. Optimized bit allocation for the UAV trajectory under Model 2 in Fig. 3 ($K = 3$, $T = 2.25$ s, $(I_1, I_2, I_3) = (4, 6, 2)$ Mbits, $\boldsymbol{p}_1^m = (0, 10, 0)$ m, $\boldsymbol{p}_2^m = (10, 10, 0)$ m, $\boldsymbol{p}_3^m = (10, 0, 0)$ m, $\boldsymbol{p}_I^r = (0, 0)$ m, $\boldsymbol{p}_F^r = (5, 0)$ m and the reference SNR $g_0/(N_0 B) = -5$ dB).

§ VII. Conclusion Remarks

A mobile cloud computing architecture based on a UAV-mounted cloudlet which provides the opportunities to multiple static mobile devices.

Two types of access frames $\begin{cases} \text{Orthogonal Access} \\ \text{Non-orthogonal Access} \end{cases}$

Minimization of the mobile energy and UAV's trajectory $\Rightarrow$ By means of successive convex approximation methods (SCA)