Resource Provisioning for Heterogeneous Services in UAV-Assisted MEC Systems

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***Abstract*—Unmanned aerial vehicle (UAV)-assisted mobile edge computing (MEC) is regarded as an important component in beyond fifth generation (B5G) communication network. However, sharing the UAV resources among heterogeneous services with different requirements would lead to conflicts. This paper considers a UAV-assisted MEC system to meet the low average service delay requirement of enhanced mobile broadband user equipments (eUEs) as well as fulfill the massive machine-type communication user equipments (mUEs) accessing simultaneously. In order to satisfy the differential requirements, we propose the resource provisioning scheme based on resource slicing to isolate the spectrum resource, which can effectively alleviate conflicts caused by heterogeneous services sharing homogeneity resource. Specifically, we formulate an optimization problem to minimize the average service delay of eUEs while maximizing the number of served mUEs by jointly optimizing the user equipments association, spectrum resource slicing, transmit power, and computation resource allocation. By leveraging the unique problem structure, a heterogeneous services-oriented resource provisioning algorithm is designed based on the coalition game and successive convex approximation. Simulation results validate that the proposed algorithm can achieve efficient resource provisioning to concurrently satisfy the requirements of heterogeneous services.**

***Index Terms*—UAV-assisted MEC system, heterogeneous services, resource provisioning.**

I. Introduction

Heterogeneity has become one of the most important characteristics for the beyond fifth generation (B5G) wireless networks, in terms of not only the supported service types but also for dimensions of radio resources. Enhanced mobile broadband (eMBB) and massive machine-type communication (mMTC) are defined as two vital service types [1]. eMBB refers to bandwidth demanding applications that require high data rates and good user quality of experience, and mMTC features the Internet of Things (IoT) aiming at supporting massive connectivity for ubiquitous communications. Furthermore, the edge computing is suggested in current technical standards to extend computation capacity for eMBB [2].

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Unmanned aerial vehicle (UAV)-assisted mobile edge computing (MEC) is expected to play a significant role in providing high-quality delivery of the eMBB and mMTC, due to the attractive characteristics on flexible deployment, line-of-sight (LoS) path and accessible resource provisioning [3]–[5]. Specifically, UAVs equipped with edge computing servers can provide flexible computation offloading with low processing delay for the eMBB. For the mMTC, UAVs are deployed as the assistance of ground base station to enlarge the communication coverage and enhance the connectivity. However, how to meet the diverse requirements of eMBB and mMTC in UAV-assisted MEC system is still worth to be investigated.

Existing works have studied service guarantee of heterogeneous services in UAV-assisted MEC system [6]–[8]. Sabuj *et al.* in [6] proposed a cognitive UAV-assisted MEC scheme to optimize the transmission delay for eMBB and mMTC users. Hellaoui *et al.* in [7] considered a UAV-enabled network for two types of services IoT devices to meet quality of service (QoS) requirements. Xi *et al.* in [8] proposed a multi-UAVs relay network to ensure the differential requirements of users. However, heterogeneous resources allocation is also crucial to meet the differentiated QoS requirements of heterogeneous services in UAV-assisted MEC system. Recently, the service-oriented resource slicing has emerged as an essential component of B5G networks, which can transform a single generic network resource into a set of dedicated networks resource, based on network virtualization technologies [9], [10]. Generally, resource slicing can complete isolation among various services to implement the service-oriented functionalities. Therefore, it is necessary to design the resource provisioning scheme based on resource slicing for meeting the differential service requirements of heterogeneous services in UAV-assisted MEC scenario.

In this paper, we consider a UAV-assisted MEC system to provide resource provisioning for eMBB and mMTC simultaneously. In order to satisfy the differential requirements of heterogeneous services within available resources, resource slicing is leveraged for the spectrum resource provisioning. In particular, aiming at minimizing the average service delay of eMBB user equipments (eUEs) while maximizing the number of served mMTC user equipments (mUEs), we formulate an optimization problem by jointly considering the user equipments (UEs) association, spectrum resource slicing, computation resource allocation, and power control. To tackle this problem, a heterogeneous services-oriented resource provisioning (HSRP) algorithm is proposed based on the coalition game and successive convex approximation (SCA). Extensive simulations demonstrate that the proposed HSRP algorithm can achieve effective resource provisioning in support of eMBB and mMTC services simultaneously.

II. System Model and Problem Formulation

We consider a UAV-assisted MEC system with heterogeneous services of eMBB and mMTC as shown in Fig. 1, which consists of a set of UAVs $\mathcal{K} = \{1, \ldots, k, \ldots, K\}$, a set of eUEs $\mathcal{U} = \{1, \ldots, u, \ldots, U\}$ and a set of mUEs $\mathcal{V} = \{1, \ldots, v, \ldots, V\}$. Each eUE has a computation-intensive task $N_u^{\mathrm{E}} = (L_u^{\mathrm{E}}, C_u^{\mathrm{E}})$ to complete, where L_u^{E} denotes the input data size of task and C_u^{E} denotes the CPU cycle by computing one bit of data. Each mUE has a latency-sensitive task $N_v^{\mathrm{M}} = (L_v^{\mathrm{M}}, T_v^{\mathrm{M}})$ to transmit, where L_v^{M} denotes the data size of the task and T_v^{M} denotes the maximum tolerable delay in transmission. In order to guarantee the QoS requirements of different services, each UAV is equipped with an edge computing server and acts as an aerial base station to simultaneously provide the computation offloading for eUEs and task transmission for mUEs.

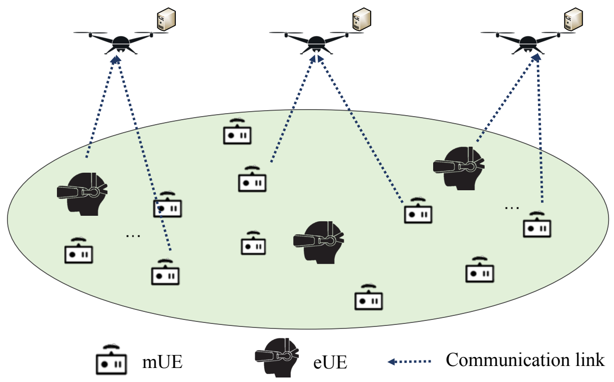


Fig. 1: Multi-UAV-assisted MEC system.

Let $Q_i^{\mathrm{I}} = \{Q_u^{\mathrm{E}}, Q_v^{\mathrm{M}}\}$ as the ground fixed position of UE $i \in \{\mathcal{U}, \mathcal{V}\}$, where $\mathrm{I} \in \{\mathrm{E}, \mathrm{M}\}$. Q_u^{E} and Q_v^{M} denote the locations of eUE u and mUE v, respectively. The position of UAV k is denoted as Q_k^{U} with fixed altitude H. In this paper, we assume the channel quality between UAVs and UEs is dominated by the LoS path. Thus, the channel gain $g_{i,k}^{\mathrm{I}}$ between UE i and UAV k is expressed as

$$g_{i,k}^{\mathrm{I}} = \frac{\beta_0}{H^2 + \left|Q_i^{\mathrm{I}} - Q_k^{\mathrm{U}}\right|^2}, \tag{1}$$

where β_0 is the channel gain at reference distance.

To satisfy differential service requirements of eMBB and mMTC, we use the resource slicing to partition the spectrum resource of UAVs, thereby achieving the isolation of resource usage between two services. Let B_k denote the spectrum resource of UAV k. Further, it can be divided into two parts, B_k^{E} and B_k^{M}, for its associated eUEs and mUEs, respectively.

A. Delay Model of eUE

We apply that FDMA is used to share bandwidth among eUEs during the computing task offloading. Let $\alpha_{u,k}$ denote association index between eUE u and UAV k. The transmission rate from eUE u to the associated UAV k can be expressed as

$$R_{u,k}^{\mathrm{E}} = \alpha_{u,k} B_{u,k}^{\mathrm{E}} \log_2\Big(1 + \frac{p_u^{\mathrm{E}} g_{u,k}^{\mathrm{E}}}{B_{u,k}^{\mathrm{E}} \sigma^2}\Big), \tag{2}$$

where $B_{u,k}^{\mathrm{E}}$ denotes the spectrum resource allocated to eUE u by UAV k, p_u^{E} denotes the transmit power of eUE u. σ^2 indicates noise power. The eUE u will offload its computational task to associated UAV k for computing rather than local processing. Therefore, the transmission delay of eUE u is expressed as

$$T_{u,k}^{\mathrm{Tr}} = \frac{L_u^{\mathrm{E}}}{R_{u,k}^{\mathrm{E}}}. \tag{3}$$

After receiving the task, the UAV will process the computational task of served eUE u. The corresponding processing delay is given by

$$T_{u,k}^{\mathrm{Co}} = \frac{C_u^{\mathrm{E}} L_u^{\mathrm{E}}}{f_{u,k}^{\mathrm{E}}}, \tag{4}$$

where $f_{u,k}^{\mathrm{E}}$ indicates the computing resources allocated to eUE u by UAV k. Therefore, the service delay of eUE u to finish the computation task is expressed as

$$T_{u,k}^{\mathrm{E}} = T_{u,k}^{\mathrm{Tr}} + T_{u,k}^{\mathrm{Co}}. \tag{5}$$

B. Delay Model of mUE

In order for multiple mUEs can utilize the same spectrum resource to transmit their task to the associated UAV, the NOMA is applied in mUE' task transmission. Without the loss of generality, each UAV can serve as the NOMA receiver to adopt the successive interference cancellation (SIC) decoding technique. The principle of SIC decoding is the descending order of channel gain. Once a signal is successfully decoded, it is removed from the overlaid signals. Let $\theta_{v,k} = 1$ denote the association index between mUE v and UAV k. $\mathcal{V}_k = \{\theta_{v,k} = 1, \forall v \in \mathcal{V}\}$ denotes the set of associated mUEs by UAV k. When the signal of mUE v served by UAV k is decoded, it receives the interference coming from the other mUEs with $g_{i,k}^{\mathrm{M}} < g_{v,k}^{\mathrm{M}}, i \in \mathcal{V}_k$. The received interference of mUE v denotes $I_{v,k}^{\mathrm{M}} = \sum\limits_{i \in \mathcal{S}_v} \theta_{i,k} p_i^{\mathrm{M}} g_{i,k}^{\mathrm{M}}$, where $\mathcal{S}_v = \{i | i \in \mathcal{V}_k, g_{i,k}^{\mathrm{M}} < g_{v,k}^{\mathrm{M}}\}$ is the set of mUEs.

Due to data size of mUE is short enough, the finite blocklength formula is adopted to describe the transmission rate. Hence, the transmission rate of mUE v is expressed by

$$R^{\mathrm{M}}_{v,k} = \theta_{v,k} B^{\mathrm{M}}_{k} \log_2 (1 + \frac{p^{\mathrm{M}}_{v} g^{\mathrm{M}}_{v,k}}{I^{\mathrm{M}}_{v,k} + B^{\mathrm{M}}_{k}\sigma^2}) - \frac{\sqrt{\frac{V^{\mathrm{M}}_{v,k}}{T^{\mathrm{M}}_{v} B^{\mathrm{M}}_{k}}} Q^{-1}(\varepsilon_v)}{\ln 2}, \tag{6}$$

where $V^{\mathrm{M}}_{v,k} = 1 - 1/(1 + \frac{p^{\mathrm{M}}_{v} g^{\mathrm{M}}_{v,k}}{I^{\mathrm{M}}_{v,k} + B^{\mathrm{M}}_{k}\sigma^2})$ is channel dispersion. ε_v is the codeword decoding error probability. $Q^{-1}(\cdot)$ is the inverse of Gaussian Q-function. Let $\kappa_{v,k} = \frac{\sqrt{V^{\mathrm{M}}_{v,k}/(T^{\mathrm{M}}_{v} B^{\mathrm{M}}_{k})} Q^{-1}(\varepsilon_v)}{\ln 2}$ for simplicity of writing. Therefore, the transmission delay for the UAV k to collect the task of mUE v is expressed by

$$t^{\mathrm{M}}_{v} = \frac{L^{\mathrm{M}}_{v}}{R^{\mathrm{M}}_{v,k}}. \tag{7}$$

C. Problem Formulation

We formulate the resource provisioning optimization problem for satisfying QoS requirements of the eMBB and mMTC in the considered UAV-assisted MEC system. The optimization problem aims at minimizing the network utility to simultaneously reduce the average service delay of eUEs and increase the number of served mUEs by jointly optimizing the UEs association index $\mathcal{A} = \{\alpha_{u,k}, \forall k \in \mathcal{K}, \forall u \in \mathcal{U}\}$ and $\Theta = \{\theta_{v,k}, \forall k \in \mathcal{K}, \forall v \in \mathcal{V}\}$, spectrum resource slicing $\mathcal{B} = \{B^{\mathrm{E}}_{u,k}, B^{\mathrm{M}}_{k}, \forall k \in \mathcal{K}, \forall u \in \mathcal{U}\}$, the transmit power of mUEs $\mathcal{P}^{\mathrm{M}} = \{p^{\mathrm{M}}_{v}, \forall v \in \mathcal{V}\}$ and the computation resource $\mathcal{F} = \{f^{\mathrm{E}}_{u,k}, \forall k \in \mathcal{K}, \forall u \in \mathcal{U}\}$. The formulated problem is expressed as

$$\mathbf{P1}: \min_{\substack{\mathcal{A},\mathcal{B},\Theta\\ \mathcal{F},P^{\mathrm{M}}}} \quad Fun = \bar{T}^{\mathrm{E}} - \lambda \sum_{v\in\mathcal{V}} \theta_{v,k} \tag{8}$$

$$\text{s.t.} \quad \sum_{u\in\mathcal{U}} B^{\mathrm{E}}_{u,k} + B^{\mathrm{M}}_{k} \le B_k, \forall k \in \mathcal{K}, \tag{8a}$$

$$\sum_{k\in\mathcal{K}} \alpha_{u,k} \le 1, \forall u \in \mathcal{U}, \tag{8b}$$

$$\sum_{k\in\mathcal{K}} \theta_{v,k} \le 1, \forall v \in \mathcal{V}, \tag{8c}$$

$$\theta_{v,k} t^{\mathrm{M}}_{v} \le T^{\mathrm{M}}_{v}, \forall v \in \mathcal{V}, \tag{8d}$$

$$p^{\mathrm{M}}_{v} \le \theta_{v,k} p^{\mathrm{M}}_{\max}, \forall v \in \mathcal{V}, \tag{8e}$$

$$\frac{p^{\mathrm{M}}_{v} g^{\mathrm{M}}_{v,k}}{I^{\mathrm{M}}_{v,k} + B^{\mathrm{M}}_{k}\sigma^2} \ge \eta, \forall v \in \mathcal{V}, \tag{8f}$$

$$\sum_{u\in\mathcal{U}} \alpha_{u,k} f^{\mathrm{E}}_{u,k} \le f_k, \forall u \in \mathcal{U}, \tag{8g}$$

where $\bar{T}^{\mathrm{E}} = \frac{\sum_{k\in\mathcal{K}} \sum_{u\in\mathcal{U}} T^{\mathrm{E}}_{u,k}}{U}$ denotes the average service delay of eUE, $\lambda \ge 0$ is the weight parameter between eMBB and mMTC services. (8a) represents the maximum constraint of available spectrum bandwidth. (8b) and (8c) constraint that each user is associated with at most one UAV. (8d) gives the maximum tolerant delay for mUE's transmission. (8e) restricts the maximum transmit power of mUE. (8f) is the SIC decoding condition successfully, where η denotes SIC threshold. (8g) guarantees the total computation resource allocated to eUEs cannot exceed the UAV capacity f_k.

III. PROBLEM OPTIMIZATION

Since $\mathbf{P1}$ is a mixed-integer non-convex problem and difficult to solve directly, we decompose $\mathbf{P1}$ into four subproblem, including eUE association optimization, spectrum resource slicing design, eUE computation resource optimization and mUE power optimization and access control. The HSRP algorithm is proposed to alternately iterate the subproblems and obtain suboptimal solutions.

A. eUE Association Optimization

In this section, the sub-problem about the binary eUEs association is structured as a coalitional game formulation to solve.

Definition 1 (Coalition Game Formulation): Let $\pi_k \in \Pi = \{1, \ldots, \pi_K\}$ represent the coalition k formed by UAV k, i.e., the set of eUEs is served by UAV k. Each eUE selects at most one coalition, i.e. one UAV, and joins in the preferred coalition by utility function $\phi_{u,k} = T^{\mathrm{E}}_{u,k}$. The utility function of UAV k is given by

$$\Phi_k(\pi_k) = \frac{\sum_{u\in\pi_k} \phi_{u,k}}{\|\pi_k\|},$$

where $\|\pi_k\|$ denotes the number of served eUEs by UAV k.

UAV may spare a large amount of resources due to serving less eUEs. Hence, the overloaded UAVs could offload eUEs' task to the underload UAV making the effect of system improving. Therefore, the transfer and exchange rule is introduced as follow.

Definition 2 (Transfer Rule): $\exists u \in \pi_k$, if eUE u chooses to leave the current coalition k and join in the coalition j by the utility function to determine, the following criteria must be satisfy:

$$\phi_{u,k} \ge \phi_{u,j}, \tag{9}$$

$$\Phi_k(\pi_k) + \Phi_j(\pi_j) > \Phi_k(\pi'_k) + \Phi_j(\pi'_j), \tag{10}$$

where π'_k and π'_j represent the coalition after the transfer. (9) means the eUE u would rather stay in coalition j and (10) ensures that the overall utility of system network is improved after the eUE u transfers to coalition j.

Definition 3 (Exchange Rule): $\exists m \in \pi_p$ and $n \in \pi_q$, if eUE m and n would like leave the current and exchange their coalition. The condition is that at least one eUE utility value can be improved and the total utility of the coalition will not deteriorate.

B. Spectrum Resource Slicing Design

The eUE association is determined in Section III-A. As for mUE association, we primarily stipulate that each mUE is associated with the nearest UAV. With the given UEs association variables, the spectrum resource slicing problem is formulated as

$$\mathbf{P2}:\min_{\mathcal{B}} \quad \bar{T}^{\mathrm{E}}-\lambda\sum_{v\in\mathcal{V}}\theta_{v,k} \tag{11}$$
$$\text{s.t.} \quad \text{(8a)},\text{(8d)},\text{(8f)}.$$

The problem is the non-convex and difficult to solve directly. In order to solve the problem, we propose spectrum resource slicing (SRS) algorithm based on bisection search method to find the optimal $\mathcal{B}$. In each iteration, the spectrum resource division problem $\mathbf{P21}$ of eUEs is solved under the correspond eMBB spectrum slicing,

$$\mathbf{P21}:\min_{\{B_{u,k}^{\mathrm{E}}\}} \quad O_1=\bar{T}^{\mathrm{E}} \tag{12}$$
$$\text{s.t.} \quad \sum_{u\in\theta_k} B_{u,k}^{\mathrm{E}}=B_k^{\mathrm{E}},\forall k\in\mathcal{K}, \tag{12a}$$

where $\mathbf{P21}$ is the subproblem of $\mathbf{P2}$ to obtain the spectrum resource division among eUEs associated with the same UAV. Due to the problem is non-convex, by introducing the auxiliary variable $\{\gamma_{u,k}^{\mathrm{E}}\}$ to slave the non-convex item, the problem $\mathbf{P21}$ is further transformed as

$$\mathbf{P22}:\min_{\{B_{u,k}^{\mathrm{E}}\},\{\gamma_{u,k}^{\mathrm{E}}\}} \quad O_1=\frac{1}{U}\sum_{u\in\theta_k}\frac{L_u^{\mathrm{E}}}{\gamma_{u,k}^{\mathrm{E}}}+T_{u,k}^{\mathrm{Co}} \tag{13}$$
$$\text{s.t.} \quad \sum_{u\in\theta_k} B_{u,k}^{\mathrm{E}}=B_k^{\mathrm{E}},\forall k\in\mathcal{K}, \tag{13a}$$
$$\gamma_{u,k}^{\mathrm{E}}\le R_{u,k}^{\mathrm{E}}. \tag{13b}$$

Besides,the conditions (8d), (8f) of mUEs in problem $\mathbf{P2}$ should be satisfied under the corresponding mMTC spectrum slicing. The feasibility of problem $\mathbf{P22}$ and constraints (8d), (8f) are verified for all UEs. According to the problem and constraints feasibility or not, the corresponding spectrum slicing is updated and the the identical process is repeated in the next iteration. The SRS algorithm is summarized in Algorithm 1.

C. eUE Computation Resource Optimization

For given $\mathcal{A}$ and $\mathcal{B}$, the problem optimizing the computation resource allocated to eUEs is formulated as

$$\mathbf{P3}:\min_{\mathcal{F}} \quad O_2=\bar{T}^{\mathrm{E}} \tag{14}$$
$$\text{s.t.} \quad \sum_{u\in\mathcal{U}}\alpha_{u,k}f_{u,k}^{\mathrm{E}}\le f_k. \tag{14a}$$

$\mathbf{P3}$ is a linear programming problem and can be efficiently solved with the standard convex optimization methods.

D. mUE Power Optimization and Access Control

With the spectrum resource slicing $\mathcal{B}$ obtained and given the mUE access, the problem (8) in terms of power optimization of mUEs is simplified as

$$\mathbf{P4}:\min_{\mathcal{P}^{\mathrm{M}}} \quad -\lambda\sum_{v\in\mathcal{V}}\theta_{v,k} \tag{15}$$
$$\text{s.t.} \quad \text{(8d)},\text{(8e)},\text{(8f)}.$$

Algorithm 1 Spectrum resource slicing algorithm (SRS)

Initialization
Set spectrum range of eMBB service is $[B_l, B_u]$.
Set the iteration $t=0$, the tolerance error $\varepsilon_o=10^{-6}$ and initial valve of objective function $O[0]=+inf$.
repeat
  Compute eMBB service allocated spectrum $B^{\mathrm{E}}=\frac{B_l+B_u}{2}$ and the remaining spectrum $B^{\mathrm{M}}=B_t-B^{\mathrm{E}}$ belongs to mMTC service.
  Solve $\mathbf{P22}$ to obtain the optimal solution and $O[t+1]=O_1^*$.
  if the problem $\mathbf{P22}$ is feasible **then**
    Check whether the constraints (8d), (8f) are satisfied under the mMTC bandwidth B^{M}.
    if the (8d) is not satisfied **then**
      $B_u=B^{\mathrm{E}}$
    end if
    if the (8f) is not satisfied **then**
      $B_l=B^{\mathrm{E}}$
    end if
  else
    $B_l=B^{\mathrm{E}}$
  end if
  $B^{\mathrm{E}}=\frac{B_l+B_u}{2}$, $B^{\mathrm{M}}=B_t-B^{\mathrm{E}}$
until $|O[t+1]-O[t]|\leqslant\varepsilon_o$ **or** $t\ge t_{max}$

Obviously, the problem $\mathbf{P4}$ is a non-convex problem due to the term $\frac{1}{R_{v,k}^{\mathrm{M}}}$ in (8d), thus we introduce the slack variable $\{\gamma_{v,k}^{\mathrm{M}}\}$ to approximate the non-convex transmission rate function as $0\le\frac{1}{R_{v,k}^{\mathrm{M}}}\le\gamma_{v,k}^{\mathrm{M}}$ and could further transformed into

$$\gamma_{v,k}^{\mathrm{M}}-B_{k,1}^{\mathrm{M}}\log_2\Big(\sum_{i\in\mathcal{S}_v}\theta_{i,k}p_i^{\mathrm{M}}g_{i,k}^{\mathrm{M}}+B_k^{\mathrm{M}}\sigma^2+p_v^{\mathrm{M}}g_{v,k}^{\mathrm{M}}\Big)+ \tag{16}$$
$$B_{k,1}^{\mathrm{M}}\log_2\Big(\sum_{i\in\mathcal{S}_v}\theta_{i,k}p_i^{\mathrm{M}}g_{i,k}^{\mathrm{M}}+B_k^{\mathrm{M}}\sigma^2\Big)+\kappa_{v,k}\leqslant 0.$$

It is obvious that (16) is still non-convex function. We utilize the SCA technique by first order Taylor expansion at any point to overcome the non-convexity [11]. Therefore, we obtain the upper bound of p_v^{M} at $p_v^{\mathrm{M}}[m]$ for the m-th iteration as follow:

$$\gamma_{v,k}^{\mathrm{M}}-B_{k,1}^{\mathrm{M}}\log_2\Big(\sum_{i\in\mathcal{S}_v}\theta_{i,k}p_i^{\mathrm{M}}g_{i,k}^{\mathrm{M}}+B_k^{\mathrm{M}}\sigma^2+p_v^{\mathrm{M}}g_{v,k}^{\mathrm{M}}\Big)+ \tag{17}$$
$$B_{k,1}^{\mathrm{M}}\log_2\Big(\sum_{i\in\mathcal{S}_v}\theta_{i,k}p_i^{\mathrm{M}}[m]g_{i,k}^{\mathrm{M}}+B_k^{\mathrm{M}}\sigma^2\Big)+\kappa_{v,k}(p_v^{\mathrm{M}}[m])+$$
$$\nabla F(p_v^{\mathrm{M}}[m])(p_v^{\mathrm{M}}-p_v^{\mathrm{M}}[m])\leqslant 0,$$

where $\kappa_{v,k}(p_v^{\mathrm{M}}[m]) = \sqrt{\frac{1-1/(1+\frac{(p_v^{\mathrm{M}}[m])g_{v,k}^{\mathrm{M}}}{I_{v,k}^{\mathrm{M}}+B_k^{\mathrm{M}}\sigma^2})}{T_v^{\mathrm{M}}B_k^{\mathrm{M}}}}Q^{-1}(\varepsilon_v)/\ln 2$ and $\nabla F(p_v^{\mathrm{M}}[m])$ is the partial derivatives value of the last two terms in (16) at point $p_v^{\mathrm{M}}[m]$. The problem $\mathbf{P4}$ is reformulated as

$$\mathbf{P5}: \min_{\mathcal{P}^{\rm M}} \quad -\lambda \sum_{v\in\mathcal{V}} \theta_{v,k} \tag{18}$$
$$\text{s.t.} \quad (8e), (8f), (17).$$

$\mathbf{P5}$ is an approximate convex problem with respect to power optimization and could be solved by CVX. If $\mathbf{P5}$ has optimal solution, the result of power optimization and access control problem is obtained. But if not, the mUE with the worst channel gain will be removed from the associated UAV until the optimal solution is emerged. Then, we conclude the power optimization and access control algorithm in Algorithm 2.

Algorithm 2 Power optimization and access control algorithm.

Initialization
Obtain the initial mUE association Θ^*.
repeat
  Solve the problem $\mathbf{P5}$ by SCA.
  if the solution state has optimal solution **then**
    break
  else
    Remove the worst channel gain mUE in the currently associated UAV.
    $\Theta^* \longleftarrow \Theta^* - 1$
  end if
until the problem could be solved **or** the served mUE number $|\Theta^*| = 1$.

E. Heterogeneous Services Resource Provisioning Algorithm

We proposed an efficient HSRP algorithm to solve problem $\mathbf{P1}$, as shown in Algorithm 3. Firstly, the eUE association can be determined in Section III-A. The mUE association index is stipulated by distance. Then, the detailed procedure in solving the remaining variables is designed to iterate. At each iteration, the spectrum resource slicing problem is solved by SRS algorithm. Then, the results of eMBB spectrum division are incorporated into the problem $\mathbf{P3}$ to solve the computation resource allocation problem. Meanwhile, the results of mMTC spectrum slicing are incorporated into the problem $\mathbf{P5}$ to get the conclusion of power optimization and access control. The above steps are executed alternately until the convergence condition is satisfied. The convergence condition is that the gap of network utility between two adjacent iterations is small sufficiently.

Considering that the objective value is non-increasing and has a finite lower bound in each iteration, the proposed HSRP algorithm can be ensured to converge. Else, the complexity of solving UEs association is $\mathcal{O}(U(U-1)K)$, where $U(U-1)$ represents the number of potential combinations among eUEs. Then, the complexity of Algorithm 1 is $\mathcal{O}(log(1/\varepsilon_o))$. The complexity of computation resource optimization is $\mathcal{O}(UK)^{3.5}$. The complexity of power and access control is $\mathcal{O}(\epsilon(VK)^{3.5})$, where ϵ is the iteration number. The total complexity is $\mathcal{O}(U(U-1)K + V) + \mu((log(1/\varepsilon_o)) + (UK)^{3.5} + \epsilon(VK)^{3.5})$ under the HSRP algorithm, where μ represents the iteration number required to update variables.

Algorithm 3 HSRP algorithm.

Initialization
Set $z = 0$ and objective function $\Lambda[0] = +inf$.
Solve UEs association problem to obtain eUE association $\mathcal{A}^*$ and the initial mUE access $\Theta[0]$.
repeat
  Obtain $\mathcal{B}^*$ by Algorithm 1 under the determined $\mathcal{A}^*$ and $\Theta[0]$.
  Solve $\mathbf{P2}$ to obtain $\mathcal{F}^*$ and the optiaml value O_2^*.
  Performing Algorithm 2 to obtain $\mathcal{P}^{\rm M*}$, the current served mUEs association Θ^* and served number $|\Theta^*|$.
  Calculate the network utility $\Lambda^* = O_2^* - |\Theta^*|$.
  Set $z = z + 1$.
  Update $\mathcal{B}[z] = \mathcal{B}^*$, $\mathcal{F}[z] = \mathcal{F}^*$, $\mathcal{P}^{\rm M}[z] = \mathcal{P}^{\rm M^*}$, $\Theta[z] = \Theta^*$ and objective function $\Lambda[z] = \Lambda^*$.
until $\Lambda[z] \geq \Lambda[z-1]$

IV. Simulation Results

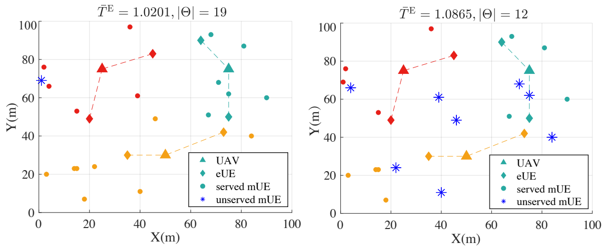
In this section, we show simulation results to evaluate the performance of the proposed HSRP algorithm. All UEs and UAVs are uniformly distributed in an area of 100 m $\times$ 100 m. The simulation parameters are summarized in Table I. In addition, the comparison algorithm is designed to N-RP, which makes spectrum resource slicing is fixed and spectrum bandwidth is equally allocated between eMBB and mMTC.

TABLE I: Default Simulation Parameters

Parameters	Values
The number of UAVs, K	3
The fixed altitude of the UAV, H	100 m
The number of eUEs, U	6
The number of mUEs, V	20
The noise power, σ^2	-114 dBm
The size of computation data of eUE, $L_u^{\rm E}$	$[1, 2]$ Mbits
The size of offloading data of mUE, $L_v^{\rm M}$	$[100, 200]$ Kbits
Transmit power of of eUE, $p_{u,k}^{\rm E}$	27 dBm
Maximum transmit power of mUE, $p_{v,k}^{\rm M}$	20 dBm
The channel power gain at a reference distance of $d_0 = 1$ m, h_0	-30 dB
The computation capacity of UAV, f_k	4 GHz
The weight between average service delay of eUEs and number of served mUEs, λ	0.1

Fig. 2 shows a result of the UEs association obtained by HSRP and comparison algorithm, where $\bar{T}^{\rm E}$ denotes the average service delay of eUEs. $|\Theta|$ denotes the number of served mUEs. We can observe that the number of served mUEs in proposed algorithm is significantly higher than the comparison algorithm. Moreover, the proposed HSRP algorithm achieves the lower average service delay of eUEs than N-RP algorithm.

Fig. 3 shows the network utility versus SIC threshold under two case, i.e., $U = 6, V = 20$ and $U = 8, V = 30$. It can be seen that with the growth of η, the decoding condition becomes more strictly, resulting in massive mUEs cannot satisfy this condition. Ultimately, mUEs that is not decoded



(a) HSRP (b) N-RP

Fig. 2: UEs-UAVs association relation under different algorithms.

successfully cannot access UAV. However, the proposed HSRP algorithm can achieve access massive mUEs, due to alleviate the interference in NOMA and obtain the balance between the eMBB and mMTC by effectively resources provisioning scheme.

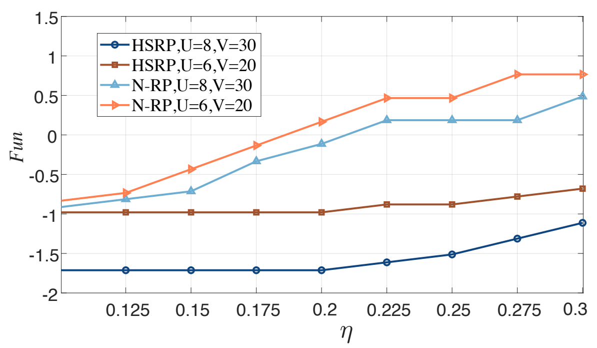


Fig. 3: The impact of SIC threshold on heterogeneous services.

Fig. 4 presents the system performance when the total available spectrum resource is varying from 10 to 15 MHz. The result shows that the proposed HSRP algorithm outperforms the comparison algorithm on system performance. This is because that HSRP algorithm facilitates dynamic spectrum slicing between eMBB and mMTC to further reduce the average service delay of eUEs and meanwhile access more mUEs. However, due to the inability for achieving the optimal spectrum slicing, N-RP algorithm cannot simultaneously meet the demands of eMBB and mMTC, resulting in a negative trend in network utility.

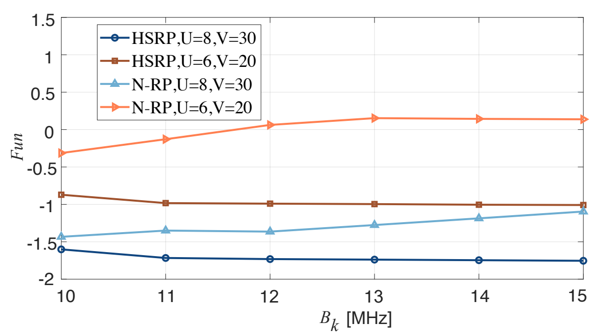


Fig. 4: The impact of bandwidth on heterogeneous service.

V. CONCLUSIONS

In this paper, we have studied the heterogeneous services of eMBB and mMTC to meet the differential QoS requirements in UAV-assisted MEC system. In order to minimize the network utility between the average service delay of eUEs and number of served mUEs, we have proposed HSRP algorithm, which includes the UEs association relationship, spectrum resource slicing, computation resource allocation, and power control. Simulation results have present that our proposed HSRP algorithm can efficiently ensure the differential requirements of heterogeneous services.

REFERENCES

[1] M. Almekhlafi, M. A. Arfaoui, C. Assi, and A. Ghrayeb, "Superposition-based URLLC traffic scheduling in 5G and beyond wireless networks," *IEEE Trans Commun.*, vol. 70, no. 9, pp. 6295–6309, 2022.

[2] J. Janković, Z. Ilić, A. Oračević, S. M. Ahsan Kazmi, and R. Hussain, "Effects of differentiated 5G services on computational and radio resource allocation performance," *IEEE Trans. Netw. Service Manag.*, vol. 18, no. 2, pp. 2226–2241, 2021.

[3] X. Luo, J. Xie, L. Xiong, Z. Wang, and C. Tian, "3-D deployment of multiple UAV-mounted mobile base stations for full coverage of iot ground users with different QoS requirements," *IEEE Commun. Lett.*, vol. 26, no. 12, pp. 3009–3013, 2022.

[4] C. Zhao, J. Liu, M. Sheng, W. Teng, Y. Zheng, and J. Li, "Multi-UAV trajectory planning for energy-efficient content coverage: A decentralized learning-based approach," *IEEE J. Sel. Areas Commun.*, vol. 39, no. 10, pp. 3193–3207, 2021.

[5] G. Zheng, C. Xu, M. Wen, and X. Zhao, "Service caching based aerial cooperative computing and resource allocation in multi-UAV enabled MEC systems," *IEEE Trans. Veh. Technol.*, vol. 71, no. 10, pp. 10 934–10 947, 2022.

[6] S. R. Sabuj, D. K. P. Asiedu, K.-J. Lee, and H.-S. Jo, "Delay optimization in mobile edge computing: Cognitive UAV-assisted eMBB and mMTC services," *IEEE Trans. Cogn. Commun. Netw.*, vol. 8, no. 2, pp. 1019–1033, 2022.

[7] H. Hellaoui, M. Bagaa, A. Chelli, T. Taleb, and B. Yang, "On supporting multi-services in UAV-enabled aerial communication for the internet of things," *IEEE Internet Things.*, pp. 1–1, 2023.

[8] X. Xi, X. Cao, P. Yang, J. Chen, T. Q. S. Quek, and D. Wu, "Network resource allocation for eMBB payload and URLLC control information communication multiplexing in a multi-UAV relay network," *IEEE Trans Commun.*, vol. 69, no. 3, pp. 1802–1817, 2021.

[9] H. Hellaoui, M. Bagaa, A. Chelli, T. Taleb, and B. Yang, "On supporting multi-services in uav-enabled aerial communication for the internet of things," *IEEE Internet Things.*, pp. 1–1, 2023.

[10] Q. Ye, W. Shi, K. Qu, H. He, W. Zhuang, and X. Shen, "Joint RAN slicing and computation offloading for autonomous vehicular networks: A learning-assisted hierarchical approach," *IEEE Open J. Veh. Technol.*, vol. 2, pp. 272–288, 2021.

[11] X. Hu, K.-K. Wong, and Y. Zhang, "Wireless-powered edge computing with cooperative UAV: Task, time scheduling and trajectory design," *IEEE Trans. Wireless Commun.*, vol. 19, no. 12, pp. 8083–8098, 2020.