Offloading of Tasks with Tight Delay Requirements via Combined Half and Full Duplex UAV Relays

Pavel Mach, *Member, IEEE,* Zdenek Becvar, *Senior Member, IEEE,* Mohammadsaleh Nikooroo, *Member, IEEE*

***Abstract*—In this paper, we focus on offloading of computationally demanding tasks with tight processing delay requirements (hundreds of ms) from user equipments (UEs) to multi-access edge computing servers while exploiting unmanned aerial vehicles (UAVs) as relays. Traditionally addressed problem jointly optimizing an offloading decision and an association of the UEs to the UAVs is, in our work, enriched by optimization of the relaying via UAVs through selection between half-duplex (HD) and full-duplex (FD) under a constraint on the maximum processing delay of individual tasks. To solve this complex problem, we also optimize the length of relaying time slots in HD and the transmission power allocation for the UEs and the UAVs in FD. Then, we transform the problem to one-to-many matching and propose a low-complexity greedy algorithm for the joint offloading decision and UEs association solved together with the duplex selection. We show that our proposal reduces the sum energy consumed by the UEs and UAVs for the tasks offloading by up to 40% compared to related works.**

***Index Terms*—offloading, MEC, UAV, half/full duplex relaying.**

I. Introduction

The multi-access edge computing (MEC) enables computationally demanding tasks to be offloaded from user equipments (UEs) to nearby MEC servers allowing to reduce processing delay of the tasks and/or energy consumption of the UEs [1][2]. The benefits of MEC are often amplified by unmanned aerial vehicles (UAVs), acting as computing servers (see, e.g., [3][4]). However, the sum energy consumption of the energy-constrained UEs and the UAVs *is always increased with respect to the local computing*, as we show later in the paper. The reason is that the computing consumes the same energy disregarding whether it is done at the UE or at the UAV and an extra energy for a delivery of the task to/from the UAV is added on the top of the computing. The UAVs can also act as relays and help the UEs in the offloading towards the BS. When compared to other relaying concepts, such as relaying via the UEs exploiting device-to-device communication [5] or relaying through fixed ground relays [6], the UAVs provide high flexibility and probability of line-of-sight (LoS), thus offer high channel quality necessary for efficient offloading. Also, relaying via the UEs is not always reliable as these may not be willing to relay for others [5]. Thus, the UAVs are convenient to relay the computing tasks to the MEC. Nevertheless, the number of works focusing on the computing task relaying via the UAVs is limited.

The relaying of the computing tasks to MEC servers via UAVs for various scenarios, including IoT or vehicular communications, is addressed in terms of the offloading decision and resource allocation in [7]-[11]. All these works adopting the UAVs as the relays for the task offloading to the MEC assume a simple half-duplex (HD) relaying, where the transmission from the UE to the UAV and from the UAV to the BS is separated in time in non-overlapping time slots allocated for each hop. However, such use of radio resources leads to a low communication efficiency. Moreover, even though the duration of the time slots for each hop directly impacts the energy consumption of both the UEs and the UAVs, none of the related works optimize the duration of these time slots. Even if the optimization of the time slot duration is addressed in works on a traditional HD relaying related without MEC [12], consideration of the computation and offloading to MEC servers completely changes a nature of the investigated problem, as these works do not have to cope with restriction on maximum allowed processing time.

To fully enjoy the benefits of the UAVs relaying for MEC purposes, a simultaneous transmission at both hops by means of full-duplex (FD) should be considered. To the best of our knowledge there are no works that assume FD relaying in UAV-assisted computation offloading. An extension of the works adopting the HD towards the FD is also not straightforward, since the FD is plagued by *self-interference* (SI) [13] and by interference from the offloading UE to the BS due to concurrent transmissions at the same resources. Hence, a transmission power setting at the UEs and the UAVs becomes a key challenge. Although the FD relaying via UAVs is used in works targeting the optimization of communication (e.g., [14]), the problem of tasks offloading to MEC requires completely different solution, as the tasks' maximum allowed processing time encompassing also computing should not be violated. Besides, FD is not always the most suitable choice due to introduced interference and the HD can be more efficient in some cases. Thus, the combination of HD and FD has a great potential to improve the system performance, as demonstrated in [15]. The works combining the HD and the FD, however, target general relaying case without a consideration of the tasks offloading to MEC that calls for completely different solution.

Guided by the above-discussed related works, we shed light on the benefits and performance gains of *combined HD/FD* relaying via the UAVs for purposes of the computation offloading to MEC servers. We target a challenging scenario with the computing tasks having tight time processing requirements (hundreds of ms). Hence, like in [4][7][11],

The authors are with Faculty of Electrical Engineering, Czech Technical University in Prague, Prague, 166 27 Czech Republic (email:{machp2, zdenek.becvar, nikoomoh}@fel.cvut.cz).

This work was supported by the Ministry of Education, Youth and Sports under the grant no. LTT20004.

we assume the UAVs are static during offloading of one task. This assumption is practical, for example, in case of balloon- or airship-based UAVs, which consume negligible propulsion energy while static and their re-positioning takes place only if the performance of served UEs is below specific requirements, as shown in [16]. Thus, we do not optimize trajectory or positioning of the UAVs as our work is rather complementary to the works targeting the positioning of UAVs (e.g., [4][7][11]) and our proposed optimization can be applied for each fixed positions of UAVs determined by solutions proposed in any related work. The contributions of this paper are summarized as follows:

- We formulate a mixed integer non-linear programming (MINLP) problem minimizing the sum energy consumed by the UEs and the UAVs for the task offloading to MEC under the constraint on the maximum processing time of the tasks. As the problem is NP-hard, we transform it into one-to-many matching problem with a knapsack constraint and we propose a low-complexity greedy algorithm to solve jointly offloading decision, association of the UEs, and selection between HD and FD.
- We optimize the length of the relaying time slots for HD to minimize the energy consumption of the UEs and the UAV relays during the offloading while ensuring the task is processed within a required time.
- We derive a closed-form expression for the transmission power of the UEs and the UAVs in FD considering both the SI and the interference from the UE to the BS imposed by the reuse of radio resources.
- We analyze the impact of SI on the proposed selection of either HD or FD relaying for the offloading and we show the proposal decreases the sum energy consumption of UEs and UAVs by up to 40% in comparison to the related works.

II. System Model

We consider the case with one BS enhanced by the MEC server. Further, we assume M UAVs deployed in the same area. Since we do not optimize trajectory planning/positioning, as justified in Introduction, we adopt k-means to determine the UAVs' positions [4]. The UAVs are opportunistically used by N UEs to offload their computing tasks to the BS. Each task is either computed locally by the UE or offloaded to the MEC server via one of the UAVs using HD or FD. As assumed in closely related works (e.g., [8][10]), we omit direct offloading to the BS as our main objective is to optimize the offloading via UAVs and we also aim to clearly and fairly quantify gains of our proposal with respect to these

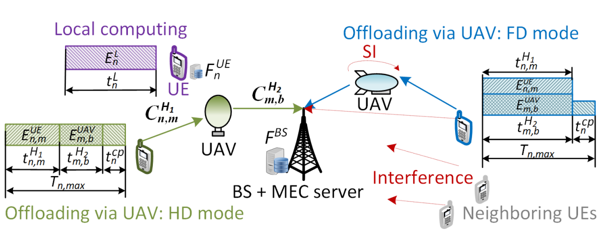


Fig. 1: Illustration of system model and key parameters.

closely related works [8][10]. Note also that the computing at the UAVs is not considered, since this inevitably increases the energy consumption of the energy-constrained devices with respect to the local computing, as shown later in the paper.

The task processing delay for the local computing at the UE encompasses the computing delay at the n-th UE:

$$t_n^L = c_n D_n / F_n^{UE}, \tag{1}$$

where c_n is the average number of CPU cycles to process one bit of the n-th UE's task [2], D_n is the size of the n-th UE's task, and F_n^{UE} is the number of cycles processed by the n-th UE. Further, the energy consumed by the n-th UE for the local computing of the task is:

$$E_n^L = c_n D_n E_n, \tag{2}$$

where E_n is the energy consumed by one processing cycle.

The task offloaded to the BS is sent by the UE to the UAV over the first hop and, then, the UAV relays this task to the BS over the second hop. Like in [14], we assume that both hops are facilitated over the same channel with the bandwidth B_n assigned to the n-th UE by the BS (note that any channel allocation can be applied as this does not affect the proposed solution and math derivations).

The capacity at the first hop between the n-th UE and the m-th UAV is:

$$C_{n,m}^{H_1} = B_n log_2 \left(1 + \frac{p_n^{UE} g_{n,m}^{H_1}}{B_n \left(\sigma + I_m^{UAV}\right) + \delta_n p_{n,m}^{UAV} g_{m,m}^{SI}} \right), \tag{3}$$

where p_n^{UE} is the transmission power of the n-th UE, $g_{n,m}^{H_1}$ is the channel gain between the n-th UE and the m-th UAV at the first hop, σ is the noise spectral density, I_m^{UAV} is the inter-cell interference (ICI) from the UEs in adjacent cells, δ_n indicates whether HD ($\delta_n = 0$) or FD ($\delta_n = 1$) is used, $p_{n,m}^{UAV}$ is the transmission power of the m-th UAV relaying the task for the n-th UE, and $g_{m,m}^{SI}$ is the channel gain between the transmitter and the receiver of the m-th UAV representing the SI in FD [13]. Similarly, the capacity at the second hop is:

$$C_{m,b}^{H_2} = B_n log_2 \left(1 + \frac{p_{n,m}^{UAV} g_{m,b}^{H_2}}{B_n \left(\sigma + I^{BS}\right) + \delta_n p_n^{UE} g_{n,b}^{D}} \right), \tag{4}$$

where $g_{m,b}^{H_2}$ is the channel gain between the m-th UAV and the BS at the second hop, I^{BS} is the ICI at the BS, $g_{n,b}^D$ represents the direct channel gain between the n-th UE and the BS, and $p_n^{UE} g_{n,b}^D$ is interference to the BS in FD due to concurrent transmission of the the n-th UE and the m-th UAV over the same channel (see Fig. 1).

The task processing delay for the offloading to the BS via the UAV is composed of the communication delays at the first and second transmission hops ($t_{n,m}^{H_1}$ and $t_{m,b}^{H_2}$) together with the computing delay t_n^{CP} at MEC (see Fig. 1), expressed as:

$$\begin{aligned} t_n^O &= (1-\delta_n)(t_{n,m}^{H_1} + t_{m,b}^{H_2}) + \delta_n \max(t_{n,m}^{H_1}, t_{m,b}^{H_2}) + t_n^{CP} \\ &= (1-\delta_n)\left(D_n/C_{n,m}^{H_1} + D_n/C_{m,b}^{H_2}\right) \\ &\quad + \delta_n \max\left(D_n/C_{n,m}^{H_1}, D_n/C_{m,b}^{H_2}\right) + c_n D_n / F^{BS}, \end{aligned} \tag{5}$$

where F^{BS} represents the number of CPU cycles processed by the BS per second. As, e.g., in [4], we neglect the delivery of the computing results back to the UE, the related delay is negligible with respect to the communication delay for the offloading to the MEC server. Also, we neglect a propagation delay and a delay before the UAVs can start relaying the task to the BS, as these delays are several order of magnitude shorter than the maximum processing delay $T_{n,max}$.

The sum energy consumption E_n^O of the energy constrained devices for the offloading is composed of the consumption at the n-th UE $E_{n,m}^{UE}$ and the m-th UAVs $E_{m,b}^{UAV}$, i.e.,:

$$E_n^O = E_{n,m}^{UE} + E_{m,b}^{UAV} = t_{n,m}^{H_1} p_n^{UE} + t_{m,b}^{H_2} p_{n,m}^{UAV}. \quad (6)$$

Note that we leave out the propulsion energy of the UAVs as we assume the UAVs are fixed during offloading of one task, as explained earlier. This assumption is practical for the UAVs represented by balloons/airships characterized by close-to-zero propulsion energy consumption while hovering [16].

III. Problem formulation

Our objective is to minimize the sum energy consumed by the energy constrained devices, i.e., UEs and the UAVs, for communication and computing while meeting $T_{n,max}$ for each task. The problem is formulated as a joint offloading decision and the UEs' association ($\boldsymbol{\mathcal{X}}$), duplex selection ($\boldsymbol{\mathcal{D}}$), allocation of the relaying time slots length in HD ($\boldsymbol{\mathcal{T}}$), and power allocation in FD ($\boldsymbol{\mathcal{P}}$):

$$\begin{aligned} \boldsymbol{\mathcal{X}}, \boldsymbol{\mathcal{D}}, \boldsymbol{\mathcal{T}}, \boldsymbol{\mathcal{P}} = \; & \underset{x,\delta,t,p}{\text{argmin}} \sum\nolimits_n \Big(E_n^L + \sum\nolimits_m x_{n,m}(E_n^O - E_n^L) \Big) \\ \text{s.t.} \quad & \text{(a) } t_n \leq T_{n,max}, \forall n \\ & \text{(b) } \sum\nolimits_m x_{n,m} \in \{0,1\}, \forall n \\ & \text{(c) } \delta_n \in \{0,1\}, \forall n \\ & \text{(d) } p_n^{UE} \leq P_{max}^{UE}, \forall n \\ & \text{(e) } \sum\nolimits_n x_{n,m} p_{n,m}^{UAV} \leq P_{max}^{UAV}, \forall m \end{aligned} \quad (7)$$

where $x_{n,m}$ is the control variable indicating if the local computing ($\sum_m x_{n,m} = 0$) or the offloading ($\sum_m x_{n,m} = 1$) takes place, (7a) guarantees that the n-th task's processing delay t_n does not exceed $T_{n,max}$, (7b) ensures each task is computed either locally or offloaded, (7c) limits relaying of the n-th task to be either using HD or FD, and (7d) and (7e) guarantee that the maximum transmission power is exceeded by neither the UEs nor the UAVs, respectively.

IV. Proposed framework

The problem in (7) is MINLP, thus NP-hard. Still, as the UEs offload tasks over the orthogonal channels, we can solve optimally the sub-problem $\boldsymbol{\mathcal{T}}$ for HD and we can derive $\boldsymbol{\mathcal{P}}$ in the closed-form for FD. Then, we propose a greedy algorithm managing jointly the sub-problems of determining $\boldsymbol{\mathcal{X}}$ and $\boldsymbol{\mathcal{D}}$ while utilizing the optimal length of the relaying time slots $\boldsymbol{\mathcal{T}}$ for HD and the optimal transmission powers $\boldsymbol{\mathcal{P}}$ for FD. All these steps are described in the next subsections followed by a discussion on complexity and implementation aspects.

A. Optimization of Half Duplex Offloading via UAVs

In HD, our objective is to minimize the energy consumption of the n-th UE and the m-th UAV ($E_n^{O,HD}$) by finding the optimal $t_{n,m}^{H_1}$ and $t_{m,b}^{H_2}$. We formulate the sub-problem $\boldsymbol{\mathcal{T}}$ as:

$$\begin{aligned} \boldsymbol{\mathcal{T}} = \; & \underset{t_{n,m}^{H_1}, t_{m,b}^{H_2}}{\text{argmin}} E_n^{O,HD} \\ \text{s.t.} \quad & \text{(a) } t_{n,m}^{H_1} + t_{m,b}^{H_2} \leq T_{n,max} - t_n^{CP} \\ & \text{(b) } t_{n,m}^{H_1} > 0, t_{m,b}^{H_2} > 0 \\ & \text{(c) } p_n^{UE} \leq P_{max}^{UE}, p_{n,m}^{UAV} \leq P_{max}^{UAV} \end{aligned} \quad (8)$$

where (8a) ensures the maximum processing delay of the task is not violated while considering the computing time at the MEC server t_n^{CP} proportional to its available resources, (8b) guarantees that the communication delays are not negative, and (8c) assures the maximum transmission powers are not violated for both the UE and the UAV.

Lemma 1. *The optimization problem in (8) and all its constraints are convex.*

Proof. First, we rewrite (6) by expressing p_n^{UE} from (3) and $p_{n,m}^{UAV}$ from (4) while assuming $\delta_n = 0$ (i.e., HD is used), $t_{n,m}^{H_1} = D_n / C_{n,m}^{H_1}$, and $t_{m,b}^{H_2} = D_n / C_{m,b}^{H_2}$:

$$\begin{aligned} E_n^{O,HD} &= t_{n,m}^{H_1} p_n^{UE} + t_{m,b}^{H_2} p_{n,m}^{UAV} = \\ &= t_{n,m}^{H_1} K_{n,m}^{H_1} \big(2^{\frac{D_n}{t_{n,m}^{H_1} B_n}} - 1\big) + t_{m,b}^{H_2} K_{m,b}^{H_2} \big(2^{\frac{D_n}{t_{m,b}^{H_2} B_n}} - 1\big), \end{aligned} \quad (9)$$

where $K_{n,m}^{H_1} = \frac{B_n(\sigma + I_m^{UAV})}{g_{n,m}^{H_1}}$, and $K_{m,b}^{H_2} = \frac{B_n(\sigma + I^{BS})}{g_{m,b}^{H_2}}$.

Then, the Hessian matrix H corresponding to (9) is:

$$H = \begin{bmatrix} \frac{K_{n,m}^{H_1} D_n^2 2^{\frac{D_n}{t_{n,m}^{H_1} B_n}} \ln^2 2}{B_n^2 {t_{n,m}^{H_1}}^3} & 0 \\ 0 & \frac{K_{m,b}^{H_2} D_n^2 2^{\frac{D_n}{t_{m,b}^{H_2} B_n}} \ln^2 2}{B_n^2 {t_{m,b}^{H_2}}^3} \end{bmatrix}. \quad (10)$$

The entries on the main diagonal of H are positive for $t_{n,m}^{H_1} > 0$ and $t_{m,b}^{H_2} > 0$. Therefore, the diagonal matrix H is positive definite and, hence, the objective function in (8) is convex.

Further, the constraints (8a) and (8b) are linear, thus, also convex. Last, using (3) and (4) while considering $t_{n,m}^{H_1} = D_n / C_{n,m}^{H_1}$ and $t_{m,b}^{H_2} = D_n / C_{m,b}^{H_2}$, (8c) can be rewritten as:

$$t_{n,m}^{H_1} \geq \frac{D_n}{B_n \log_2(1 + \frac{P_{max}^{UE}}{K_{n,m}^{H_1}})}, t_{m,b}^{H_2} \geq \frac{D_n}{B_n \log_2(1 + \frac{P_{max}^{UAV}}{K_{m,b}^{H_2}})}, \quad (11)$$

which are convex with respect to $t_{n,m}^{H_1} > 0$ and $t_{m,b}^{H_2} > 0$. ■

Since the optimization problem in (8) and all its constraints are convex, we solve it optimally using CVX in Matlab [17].

B. Optimization of Full Duplex Offloading via UAVs

If the UAV operates in FD, $t_{n,m}^{H_1}$ and $t_{m,b}^{H_2}$ are naturally equal and set according to the following proposition.

Proposition 2. *In FD mode, the overall energy consumption of the n-th UE and the m-th UAV ($E_m^{O,FD}$) is minimized if both $t_{n,m}^{H_1}$ and $t_{m,b}^{H_2}$ are set to $T_{n,max} - t_n^{CP}$.*

Proof. First, we express $E_n^{O,FD}$ in the same way as in (9), but assuming $\delta_n = 1$ for FD:

$$E_n^{O,FD} = t_{n,m}^{H_1} p_n^{UE} + t_{m,b}^{H_2} p_{n,m}^{UAV} = \\ = t_{n,m}^{H_1}(\Gamma_1 + \Gamma_2 p_{n,m}^{UAV}) + t_{m,b}^{H_2}(\Gamma_3 + \Gamma_4 p_n^{UE}), \quad (12)$$

where $\Gamma_1 = K_{n,m}^{H_1}(2^{\frac{D_n}{t_{n,m}^{H_1} B_n}} - 1)$, $\Gamma_2 = \frac{g_{m,m}^{SI}}{g_{n,m}^{H_1}}(2^{\frac{D_n}{t_{n,m}^{H_1} B_n}} - 1)$, $\Gamma_3 = K_{m,b}^{H_2}(2^{\frac{D_n}{t_{m,b}^{H_2} B_n}} - 1)$, and $\Gamma_4 = \frac{g_{n,b}^{D}}{g_{m,b}^{H_2}}(2^{\frac{D_n}{t_{m,b}^{H_2} B_n}} - 1)$.

The first partial derivative of $E_n^{O,FD}$ is negative with respect to $t_{n,m}^{H_1}$ and $t_{m,b}^{H_2}$ for $t_{n,m}^{H_1} > 0$ and $t_{m,b}^{H_2} > 0$, respectively. Hence, $E_n^{O,FD}$ is decreasing with increasing $t_{n,m}^{H_1}$ and $t_{m,b}^{H_2}$, respectively. Thus, setting $t_{n,m}^{H_1} = t_{m,b}^{H_2} = T_{n,max} - t_n^{CP}$ minimizes $E_n^{O,FD}$. ■

Furthermore, we observe that $C_{n,m}^{H_1}$ is negatively affected by $p_{n,m}^{UAV}$ due to SI inherent to FD transmissions (see (3)) and $C_{m,b}^{H_2}$ is affected by p_n^{UE} due to interference of the UE to the BS (see (4)). Then, the goal is to ensure that $C_{n,m}^{H_1} = C_{m,b}^{H_2}$ so that $t_{n,m}^{H_1} = t_{m,b}^{H_2}$. Therefore, we formulate the sub-problem $\boldsymbol{\mathcal{P}}$ to minimize the energy consumption of the n-th UE and the m-th UAV via an allocation of $p_{n,m}^{H_1}$ and $p_{m,b}^{H_2}$ as:

$$\begin{aligned} \boldsymbol{\mathcal{P}} = \quad & \underset{p_{n,m}^{H_1}, p_{m,b}^{H_2}}{\text{argmin}} \; E_n^{O,FD} \\ \text{s.t.} \quad & \text{(a) } t_{n,m}^{H_1} = t_{m,b}^{H_2} = T_{n,max} - t_n^{CP}, \text{ (8c)} \end{aligned} \quad (13)$$

where (13a) and (8c) again limit the time for overall offloading by a consideration of the time required for the computing and the transmission power of the energy-constrained devices, respectively.

Lemma 3. *If the n-th UE offloads the task via the m-th UAV employing FD mode, p_n^{UE} and $p_{n,m}^{UAV}$ are derived as:*

$$p_n^{UE} = (\Gamma_1 + \Gamma_2\Gamma_3)/(1 - \Gamma_2\Gamma_4), \quad (14)$$

$$p_{n,m}^{UAV} = \Gamma_3 + \Gamma_4(\Gamma_1 + \Gamma_2\Gamma_3)/(1 - \Gamma_2\Gamma_4). \quad (15)$$

Proof. First, we derive p_n^{UE} and $p_{n,m}^{UAV}$ from (12) as:

$$p_n^{UE} = \Gamma_1 + \Gamma_2 p_{n,m}^{UAV}, \quad (16)$$

$$p_{n,m}^{UAV} = \Gamma_3 + \Gamma_4 p_n^{UE}. \quad (17)$$

From (16) and (17), we observe that p_n^{UE} and $p_{n,m}^{UAV}$ can be obtained by solving a system of linear equations. Since each line is of a different slope (the slope of p_n^{UE} in (16) and (17) is Γ_2 and $1/\Gamma_4$, respectively), there is just one solution. Hence, we get p_n^{UE} by substituting $p_{n,m}^{UAV}$ from (17) to (16) and, after several math operations, we obtain p_n^{UE} as in (14). Then, $p_{n,m}^{UAV}$ is determined by substitution of (14) to (17). ■

Remark: The solution in Lemma 3 is valid only if (8c) is met. Otherwise, FD is not feasible and HD is employed.

C. Proposed greedy algorithm

This section describes the proposed greedy algorithm for the selection of the UAV for relaying of the tasks to MEC. The selection of the relaying UAV is of a critical importance, as the energy consumption for relaying via individual UAVs varies significantly due to: *i)* various channel quality between the UE and the UAV and the channel quality between the UAV and the BS, *ii)* different ICI at individual UAVs (i.e., I_m^{UAV}) resulting in a different energy consumption at each, and *iii)* a knapsack constraint (7e) limiting the overall transmission power of each UAV.

To manage the offloading decision and the UEs association to the UAVs ($\boldsymbol{\mathcal{X}}$) jointly with the duplex selection ($\boldsymbol{\mathcal{D}}$), we express the energy consumption savings (denoted as $G_{n,m} \in \boldsymbol{G}$) if the n-th UE offloads the task to the BS via the m-th UAV instead of the local computing, as:

$$G_{n,m} = \max(E_n^L - E_n^{O*}, 0), \quad (18)$$

where $E_n^{O*} = \min(E_n^{O,HD}, E_n^{O,FD})$. Calculation of $G_{n,m}$ in (18) solves the problem of duplex selection and, hence, (7) can be rewritten as:

$$\begin{aligned} \boldsymbol{\mathcal{X}} = \quad & \underset{x}{\text{argmax}} \sum\nolimits_n \sum\nolimits_m x_{n,m} G_{n,m} \\ \text{s.t.} \quad & \text{(7b), (7e)} \end{aligned} \quad (19)$$

The problem in (19) is a knapsack problem, which is NP-complete. Thus, we propose a low-complexity greedy approach summarized in Algorithm 1. Initially, $G_{n,m}$ is calculated according to (18) and $x_{n,m} = 0$ is set for each n and m indicating that all UEs are initially assumed to compute the tasks locally (see line 1 in Algorithm 1). Then, as long as at least one entry in $\boldsymbol{G}$ is positive, the following steps are repeated to decide if the offloading via UAVs would decrease the energy consumption. First, the maximum value in $\boldsymbol{G}$ is found (line 3). The n-th UE offloads the task via the m-th UAV if the constraint on P_{max}^{UAV} is not violated for this particular UAV (indicated by setting $x_{n,m} = 1$, see line 5). Then, all positive entries in the n-th row $\boldsymbol{G}$ are set to 0 (line 7) and the offloading for the n-th UE is resolved. In case that the constraint on P_{max}^{UAV} cannot be met, $G_{n,m}$ is set to zero, as this matching option is not feasible (see line 8).

The proposed greedy algorithm is optimal if (7e) is not violated for any offloaded task. Still, even if the greedy approach is not optimal and (7e) is violated, the UEs are associated with those UAVs yielding the highest $G_{n,m}$. Hence, these UEs would be associated with the same UAVs also by the optimal association, as these UE-UAV pairs contribute the most to

Algorithm 1 Proposed greedy algorithm

```
1: Derive G_{n,m} acc. (18) and set x_{n,m} = 0 ∀n, m
2: while max(G_{n,m}) > 0 do
3:     {n, m} ← max(G_{n,m})
4:     if (7e) is met then
5:         x_{n,m} = 1 (n-th UE offloads task via m-th UAV)
6:         Set n-th row in G to 0
7:     else
8:         Set G_{n,m} = 0
9:     end if
10: end while
```

the maximization of the objective function in (19). Thus, any difference between the greedy and optimal associations occurs only for a small $G_{n,m}$. Since the small $G_{n,m}$ contributes only marginally to the objective function, the gap between the optimal and greedy associations is supposed to be small. As the association problem is NP-hard, the optimal solution can not be found. Still, in the next section, we investigate the gap to a theoretical and practically infeasible upper bound in case the constraint on the transmission power of the UAVs (the constraint (7e)) would be neglected.

D. Complexity and implementation aspects

The complexity of convex optimization problem is $\mathcal{O}(K^2L^{2.5} + L^{3.5})$ [18], where K and L are the numbers of variables and constraints, respectively. Hence, the complexity of CVX is negligible. The complexity of Algorithm 1 is equal to $\mathcal{O}(M(N^2 + N))/2)$. Assuming only few UAVs are deployed per BS (i.e., $M << N$), the complexity of Algorithm 1 is low and equal to $\mathcal{O}(N^2 + N) = \mathcal{O}(N^2)$.

As assumed in many recent papers (see, e.g., [14]), Algorithm 1 is executed centrally by the BS to avoid computation/processing burden of the energy-constrained UAVs. To this end, the BS should be aware of E_n^L and of the task-related information on D_n, c_n, $T_{n,max}$ to decide if the offloading via the UAV is beneficial or not. All these information can be reported by the UEs to the BS with the offloading requests and generated additional signaling overhead is negligible.

V. Performance Evaluation

In this section, we first outline simulation scenario and settings. Then, we evaluate and discuss performance of the proposal and compare it with state-of-the-art-works.

For simulations in Matlab, we adopt an urban scenario with buildings whose height is randomly generated between 25 and 29 m. The BS is located at the building closest to the middle of the simulated area at coordinates [275, 300, 30]m in line with [14] (see Fig. 2). As explained in Section II, the positions of UAVs are determined by k-means [4]. The UEs having a task to compute are uniformly deployed in the outdoor area. Without loss of generality, the BS splits available bandwidth to the users equally. The channel between any two nodes (i.e., UEs, UAVs, and BS) is based on well-established model for the UAV communication in an urban environment introduced in [19]. Since we perform evaluations in a realistic and in-detail modeled environment, instead of a probabilistic determination whether LoS or non-LoS is utilized, we directly determine if there are any buildings (and

TABLE I: Parameters and settings for simulations

Parameter	Value	Parameter	Value
Area size	500x500 m	σ	-174 dBm/Hz
BS coord.	[275,300,30]	I^{BS},I_m^{UAV}	N(-150,10) dBm/Hz [20]
Carrier freq.	2 GHz	D_n	[0.5 2] Mbits [2]
B	100 MHz	c_n	[1.5 2]x10^3 cyc./bit [2]
N; M	50; 4	F_n^{UE}	[0.5 2]x10^9 cycles/s [2]
P_{max}^{UE};P_{max}^{UAV}	15; 27 dBm	F^{BS}	40x10^9 cycles/s [2]
Building atten.	20 dB	E_n	[0 20]x10^{-11} J/cyc. [1]

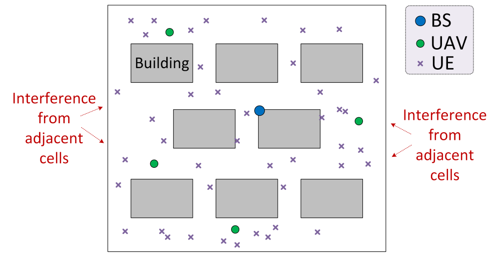


Fig. 2: Illustrative example of simulation scenario.

how many) in the communication path between a transmitter and a receiver according to the exact positions of both (see Fig. 2 illustrating the building distribution). Then, each building interrupting the LoS communication path attenuates the signal by additional 20 dB. Note that the UAVs are assumed to be flying at the altitudes above the buildings and, thus, the UAVs communicate with the BS via LoS. All important simulation parameters, including those related to the task computing and offloading, are listed in Table I.

In Fig. 3, we analyze the energy consumption (EC) of the proposed approach influenced by different SI attenuation. Moreover, we assume that $T_{n,max}$ is generated randomly for each task according to uniform distribution either between 0.1 and 0.5 s or between 0.1 and 1 s, representing more tight and more relaxed requirements on $T_{n,max}$, respectively. If the SI att. = 90 dB, FD is exploited rarely, as HD usually yields a lower energy consumption. If $T_{n,max}$ varies between 0.1 and 0.5 s, the proposed approach converges to HD and outperforming FD by up to 21%. If SI at the UAVs is well mitigated (SI attenuation of 140 dB), FD becomes more efficient than HD. Hence, the proposed approach employs FD more frequently resulting in a gain with respect to HD by up to 12%. Besides, we observe that if $T_{n,max}$ is generally longer and generated randomly between 0.1 and 1 s, the energy consumption is decreased roughly by 40% compared to the shorter $T_{n,max}$ generated randomly between 0.1 and 0.5 s.

Fig. 4 compares the performance of the proposal with the following schemes: *i)* local computing (*LC*), *ii)* offloading to the computing UAVs as in [3][4] (*LC+CU*), and *iii)* offloading via HD UAVs without optimization of relaying time slots [7]-[11] (*LC+OU*). If $T_{n,max}$ increases, the sum energy consumption of all schemes supporting offloading to the BS decreases, since generally a lower transmission power can be used while still meeting $T_{n,max}$. In contrast, if the computing is performed at the UAVs, the sum energy consumption for

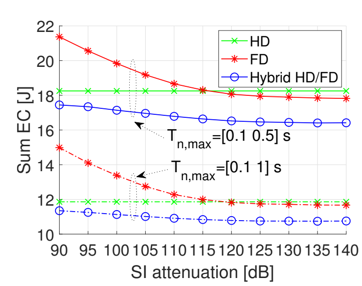
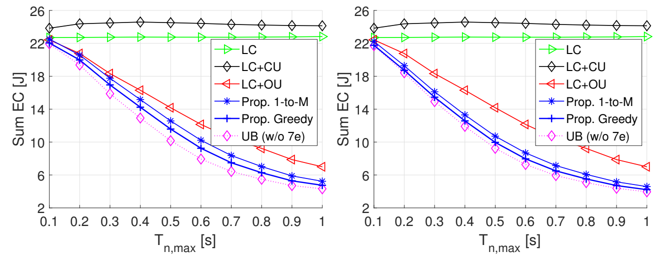


Fig. 3: Performance analyses of proposed hybrid HD/FD.



(a) SI attenuation = 90 dB. (b) SI attenuation = 140 dB.

Fig. 4: Comparison of proposal with competitive schemes.

the offloading and computing is even higher than in case of the local computing due the energy consumption of the UAVs. Fig. 4 also illustrates that even if SI is strong (i.e., SI attenuation is only 90 dB), the proposal with greedy association of UEs outperforms the best performing competitive scheme *LC+OU* by up to 33.5% (see Fig. 4a). If the SI is adequately attenuated (SI att.=140 dB), the performance gap between the proposal and *LC+OU* rises even up to 40% (see Fig. 4b).

Now, let us analyze the performance of the proposed greedy algorithm and compare it to the conventional one-to-many matching. The one-to-many matching is not tailored to handle the problems with a knapsack constraint and cannot guarantee a fulfillment of the constraint (7e). Hence, after the matching is done, we assume each UAV relays only the tasks that do not exceed the UAV's transmission power budget. All tasks violating the constraint (7e) are processed locally at the UE. Fig. 4 shows that the proposed greedy algorithm outperforms the conventional one-to-many matching by up to 10.6% and 9.1% if the SI attenuation is 90 dB and 140 dB, respectively. The reason is that the proposed greedy algorithm continuously checks if the individual UAVs are able to relay the tasks and selects potentially the next most beneficial UAV (if any is available) in terms of the energy consumption, if the first one cannot relay the task.

Last, we discuss performance of the proposed greedy approach compared to a theoretical optimum. Since the defined problem is NP-hard, the optimal solution cannot be found for a higher number of UEs (we assume 50 UEs). Thus, we introduce a theoretical "upper bound", where all UEs always exploit the UAV offering the highest energy savings while neglecting the constraint (7e)) (denoted as UB (w/o 7e)). Even if this scheme is unrealistic, it represents a "best-case" performance that can be theoretically achieved by the proposed greedy algorithm. Fig. 4 demonstrates that, depending on $T_{n,max}$, the gap between the proposed greedy algorithm and the theoretical upper bound varies between 0.5%-16% and between 0.3% and 9.6% for SI attenuation 90 dB and 140 dB, respectively. Of course, the gap between the optimal solution and the greedy algorithm is always lower in the real-world, since the UAVs exceed their transmission power on average by 50% roughly in 37% of cases in the case of the theoretical upper bound.

VI. Conclusions

In this paper, we have introduced an optimization framework for offloading computing tasks to the MEC with the assistance of the UAVs. We first optimize the setting of relaying time slots duration for HD and derive transmission powers in closed-form for FD. Then, we propose a greedy approach with a low complexity to manage the offloading and the association of UEs to UAVs. We have shown that the proposed framework significantly outperforms most related competitive schemes up to 42% in terms of energy consumption.

References

[1] C. You, K. Huang, H. Chae, and B.-H. Kim, "Energy-Efficient Resource Allocation for Mobile-Edge Computation Offloading," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3., pp. 1397-1411, 2017.

[2] T. Fang, *et al.*, "Joint Task Offloading, D2D Pairing, and Resource Allocation in Device-Enhanced MEC: A Potential Game Approach," *IEEE Internet Things J.*, vol. 9, no. 5, pp. 3226-3237, 2022.

[3] Y. Liu, at al., "Joint Communication and Computation Resource Scheduling of a UAV-Assisted Mobile Edge Computing System for Platooning Vehicles," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 7, 2022.

[4] T. Ren, at al. "Enabling Efficient Scheduling in Large-Scale UAV-Assisted Mobile-Edge Computing via Hierarchical Reinforcement Learning," *IEEE Internet Things J.*, vol. 9, no. 10, pp. 7095-7109, 2022.

[5] M. Li, *et al.*, "Multi-Relay Assisted Computation Offloading for Multi-Access Edge Computing Systems With Energy Harvesting," *IEEE Trans. Veh. Technol.*, vol. 70, no. 10, 2021.

[6] J. Hajipour, "Fairness and Efficiency in Stochastic Buffer-Aided Relay-Assisted MEC,", *IEEE Wireless Commun. Letters*, vol. 11, no. 7, 2022.

[7] T. Zhang, *at al.* "Joint Computation and Communication Design for UAV-Assisted Mobile Edge Computing in IoT," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 8, 2020

[8] S. Zheng, Z. Ren, X. Hou, and H. Zhang, "Optimal Communication-Computing-Caching for Maximizing Revenue in UAV-Aided Mobile Edge Computing," In Proc. *GLOBECOM*, Taipei, Taiwan, 2020.

[9] L. Zhao, at al. "A Novel Cost Optimization Strategy for SDN-Enabled UAV-Assisted Vehicular Computation Offloading," *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 6, 2021.

[10] X. Diao, *et al.*, "UAV-Relaying-Assisted Multi-Access Edge Computing With Multi-Antenna Base Station: Offloading and Scheduling Optimization," *IEEE Trans. Veh. Technol.*, vol. 70, no. 9, pp. 9495-9509, 2021.

[11] L. Wang, at al. "Computation Efficiency Maximization for UAV-Assisted Relaying and MEC Networks in Urban Environment," *IEEE Trans. Green Commun. Netw.*, vol. 7, no 2, 2023.

[12] S. Jain, M. Cardone, and S. Mohajer, "Optimality of Energy-Efficient Scheduling and Relaying for Half-Duplex Relay Networks," *IEEE Journal on Selected Areas in Information Theory*, no. 3, vol. 1, 2022.

[13] H. Wang, *et al.*, "Spectrum sharing planning for full-duplex UAV relaying systems with underlaid D2D communications," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 9, pp. 1986–1999, Sep. 2018.

[14] P. Mach, Z. Becvar, and M. Najla, "Power Allocation, Channel Reuse, and Positioning of Flying Base Stations with Realistic Backhaul," *IEEE Internet Things J.*, vol. 9, no. 3, pp. 1790-1805, 2022.

[15] J. Gong, X. Chen, and M. Xia, "Transmission Optimization for Hybrid Half/Full-Duplex Relay With Energy Harvesting," *IEEE Trans. Wireless Commun.*, vol. 17, no. 5, 2018.

[16] Z. Becvar, M. Nikooroo and P. Mach, "On Energy Consumption of Airship-based Flying Base Stations Serving Mobile Users," *IEEE Trans. Commun.*, vol. 70, no. 10, 2022.

[17] M. Grant and S. Boyd. "CVX: MATLAB Software for Disciplined Convex Programming, Version 2.2." Jan. 2020.

[18] Q.-V. Pham, *et al.*, "UAV Communications for Sustainable Federated Learning," *IEEE Trans. Vehicular Tech.*, 70(4), pp. 3945-49, 2021.

[19] A. Al-Hourani, S. Kandeepan and S. Lardner, "Optimal LAP Altitude for Maximum Coverage," IEEE Wireless Commun. Lett., vol. 3, no. 6, pp. 569-572, Dec. 2014.

[20] M. Najla, Z. Becvar, P. Mach, and D. Gesbert, "Positioning and Association Rules for Transparent Flying Relay Stations," *IEEE Wireless Commun. Lett.*, vol. 10., no. 6, pp. 1276-1280, 2021.