Energy Efficient Resource Allocation for UAV-served Energy Harvesting-supported Cognitive Industrial M2M Networks

Xiao-Ren Xu, Yi-Han Xu, Wen Zhou, *Member, IEEE*, Arumugam Nallanathan, *Fellow, IEEE*

***Abstract*—In this letter, the resource allocation problem for Energy Harvesting-supported Cognitive Industrial Machine-to-Machine (EH-CI-M2M) network underlaying Unmanned Aerial Vehicles (UAVs) communication is investigated with the objective of maximizing the average energy efficiency by jointly considering the EH time slot assignment, transmit power control and bandwidth allocation under the constraints of Quality of Service (QoS) and the available energy status of the EH-CMNet devices. Nevertheless, the optimization problem is difficult to be tackled directly since it is non-convex and NP-hard. We firstly transform the primitive objective problem into a convex form equivalently by non-linear fractional programming and variable relaxation approach. Based on Dinkelbach and Lagrangian theory, an iterative algorithm is proposed to solve optimization problem. Extensive simulation results demonstrate that the proposed scheme outperforms the benchmark schemes in terms of energy efficiency in different network settings.**

***Index Terms*—UAV communications, M2M communications, energy-harvesting, resource allocation, optimization**

I. INTRODUCTION

IN the era of Industry 5.0, automation supported human-to-machine cooperative working in low source depletion is the pioneering feature, which makes the manufactural process more productive and sustainable [1]. To meet the emerging demands from industrial segment, Energy Harvesting-supported Cognitive Industrial Machine-to-Machine (EH-CI-M2M) networks have been regarded as a promising enabler in industry and even academic society. Similar to Device-to-Device (D2D) communications mode, M2M terminals can reuse the resource from cellular networks to enhance the resource utilization for the Machine-Type Devices (MTDs), regarded as a branch field of D2D [2-5]. Distinctively, M2M focuses on the physical and link layers of Open System Interconnection (OSI) in Internet of things (IoT), facing bottom objects such as controlled end terminals that have rigorous restrictions on power consumption and battery changes especially in industry. Thus, Energy Efficiency (EE) optimization has been recognized as a significant issue for the investigation on a range of CI-M2M networks in the long term.

For CI-M2M networks, it is difficult and costly to deploy traditional infrastructures due to the limitations of flexibility and network coverage. Especially in massive MTD scenarios, the Line-of-Sight (LoS) propagation environment is hard to establish. Fortunately, Unmanned Aerial Vehicle (UAV)-assisted communication breaks the bottleneck due to its high mobility and flexible deployment, which has promising research values in different types of scenarios [6-7]. Moreover, trajectory and resource scheduling have been studied in cache-enabled UAV-relaying network with D2D communications to ensure transmission security and minimum secrecy rate in [8].

Hence, the energy efficient industrial MTD communication is regarded as an urgent issue despite that the EE problem has been widely studied in similar area recently [9, 10]. However, associated with UAV-assisted communication, the EH-CI-M2M scenario faces to massive MTD communications in Industry 5.0 is not yet investigated fully. Motivated by the aforementioned, in this letter, an EH-CI-M2M network is proposed intendedly underlaying multiple UAVs-served communications. We aim at maximizing the average EE for EH-CI-M2M devices via resource allocation scheme by EH time slot, bandwidth allocation and transmit power control. In this case, a robust iterative algorithm based on Dinkelbach and Lagrangian dual theory is proposed to optimize the resource allocation strategy due to its low computational overload and resource consumption suitable for industrial MTDs. Numerical results verify the effectiveness of the proposed scheme.

II. SYSTEM MODEL AND PROBLEM FORMULATION

As shown in Fig. 1, a set of UAVs have been deployed as aerial base stations, which are denoted as $U_i (i \in \{1,2,\ldots,I\})$ and a set of Mechanical Arms (MAs) are randomly distributed in an $R \times R$ square area denoted as $M_l (l \in \{1,2,\ldots,L\})$. In order to ensure each of MAs is capable of obtaining the same bandwidth, the total available bandwidth B_{sum} is equally divided into K orthogonal sub-bandwidths as $B_{sub} = \left\{\frac{B_{sum}}{K}, \frac{2B_{sum}}{K}, \ldots, \frac{(K-1)B_{sum}}{K}, B_{sum}\right\}$, which is provided to the

---

This work was supported in part by National Natural Science Foundation of China under Grant of 61601275, and College Student Science and Technology Innovation Foundation of Jiangsu Province in China under Grant of 202210298114Y.

Corresponding author: Yi-Han Xu

Xiao-Ren Xu and Wen Zhou are with the College of Information Science and Technology, Nanjing Forestry University, Nanjing 210037 China (e-mail: xiaorenxu@njfu.edu.cn; wenzhou@ustc.edu).

Yi-Han Xu is with the College of Information Science and Technology, Nanjing Forestry University, Nanjing 210037 China and School of Electrical Engineering and Telecommunications, The University of New South Wales, Sydney 2052, Australia (e-mail: xuyihan@njfu.edu.cn).

Arumugam Nallanathan is with the School of Electronic Engineering and Computer Science, Queen Mary University of London, London E1 4NS, U.K. (e-mail: a.nallanathan@qmul.ac.uk).

UAV-to-MA (U2M) communications. However, the amount of ground MAs are typically larger than the U2M sub-channels (i.e. $K < L$). To make efficient use of the limited resource, both U2M and M2M transmission modes are permitted to each MA due to the dynamic and uncertain environments. Each M2M pair contains a MA transmitter (MAT) and MA receiver (MAR). Thus, we regulate a binary indicator $o_{mk} \in \{0,1\}$ $(m \in \{1,2,\dots,M\}, k \in \{1,2,\dots,K\})$ to denote whether the m-th EH-CI-M2M reuses the k-th sub-bandwidth of the U2M transmission channels currently. It is considered that each sub-bandwidth of UAVs can be reused by at most X EH-CI-M2M pairs within a time slot n, given by:

$$\sum_{m=1}^{M} o_{mk}^{(n)} \leq X\,, \quad \forall k \in K, n \in N. \tag{1}$$

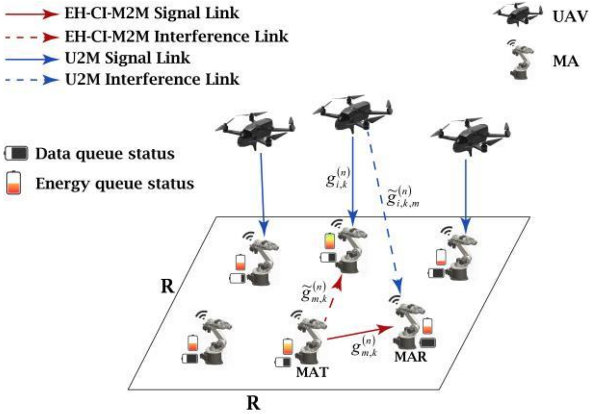

Fig. 1. Multiple UAV-served EH-CI-M2M communication scenario

For U2M transmission mode, we denote a probabilistic path loss model including both LoS and non-LoS (NLoS) propagations. The probability of LoS between UAV i and MA k in time slot n can be expressed by Eq. (2):

$$P_{i,k}^{LoS}(n) = \frac{1}{1 + a\exp\left(-b\sin^{-1}\left(\frac{h_{i,k}^{(n)}}{d_{i,k}^{(n)}}\right) - a\right)}, \tag{2}$$

where a and b are constant values depending on the ambient circumstance. $d_{i,k}^{(n)}$ and $h_{i,k}^{(n)}$ denote the distance and relative height from the UAV i to MA k in time slot n, respectively.

Therefore, the probability of establishing the NLoS link can be deduced as:

$$P_{i,k}^{NLoS}(n) = 1 - P_{i,k}^{LoS}(n). \tag{3}$$

Considering the LoS and NLoS compositions in propagation path loss, we categorized the ergodic U2M channel power gain between UAV i and MA k into $g_{i,k}^{L(n)}$ and $g_{i,k}^{N(n)}$ in time slot n respectively, which can be given by:

$$g_{i,k}^{L(n)} = \beta_0 d_{i,k}^{-\alpha_L}(n)\,, \tag{4a}$$

$$g_{i,k}^{N(n)} = \mu\beta_0 d_{i,k}^{-\alpha_N}(n)\,, \tag{4b}$$

where β_0 denotes the transmission gain between UAV and MA at unit distance and μ denotes the additive signal fading coefficient from NLoS communication. In addition, α_L and α_N are the path loss exponents of LoS and NLoS conditions.

From above discussion, the ergodic power gain in U2M transmission $g_{i,k}^{(n)}$ in time slot n can be calculated by:

$$g_{i,k}^{(n)} = P_{i,k}^{LoS}(n) \cdot g_{i,k}^{L(n)} + P_{i,k}^{NLoS}(n) \cdot g_{i,k}^{N(n)}, \quad \forall k \in K, n \in N. \tag{5}$$

The instantaneous Signal-to-Interference plus Noise Ratio (SINR) of the U2M transmission between UAV i and MA k in time slot n is expressed as Eq. (6):

$$\gamma_{i,k}^{(n)} = \frac{p_{i,k}^{(n)} g_{i,k}^{(n)}}{\sum_{m=1}^{M} o_{mk}^{(n)} p_{m,k}^{(n)} \tilde{g}_{m,k}^{(n)} + \sigma^2} \quad \forall k \in K, n \in N, \tag{6}$$

where $p_{i,k}^{(n)}$ and $p_{m,k}^{(n)}$ represent the transmit powers of UAV i and MAT m on the k-th U2M sub-bandwidth in time slot n, respectively, $\tilde{g}_{m,k}^{(n)}$ denotes the interference gain between m-th MAT and other UAV-served MAs on the same bandwidth and σ^2 denotes the additive white Gaussian noise (AWGN)

Therefore, the instantaneous industrial packet achievable rate between UAV i and MA k in time slot n is given by

$$r_{i,k}^{(n)} = B_{sub}\log_2\left(1 + \frac{p_{i,k}^{(n)} \cdot \left(P_{i,k}^{LoS}(n) \cdot \left(g_{i,k}^{L(n)} - g_{i,k}^{N(n)}\right) + g_{i,k}^{N(n)}\right)}{\sum_{m=1}^{M} o_{mk}^{(n)} p_{m,k}^{(n)} \tilde{g}_{m,k}^{(n)} + \sigma^2}\right). \tag{7}$$

For EH-CI-M2M transmission mode, the achievable energy is modeled as a Poisson Process, thus the harvested energy flux $EH_{m,n}$ at achievable time point t_n can be presented as:

$$EH_{m,n} \sim \text{Poisson}(\lambda\tau_n) \quad \forall m \in M, n \in N, \tag{8}$$

where λ denotes the ergodic harvested energy per unit time, τ_n denotes the EH duration time.

Specifically, both large-scale and small-scale fading are considered in this mode. We recognize the path loss and shadowing as the components of large-scale fading, which are respectively denoted as χ_m and ϑ_m while the component of small-scale fading is the Rayleigh fading $\zeta_m^{(n)}$.

In time slot n, the EH-CI-M2M transmission gain between MAT and MAR can be given by:

$$g_{m,k}^{(n)} = \chi_m^{(n)} \cdot \vartheta_m^{(n)} \cdot \left|\zeta_m^{(n)}\right|^2. \tag{9}$$

Then, the SINR of the EH-CI-M2M transmission in time slot n is expressed as:

$$\gamma_m^{(n)} = \frac{p_{m,k}^{(n)} g_{m,k}^{(n)}}{o_{mk}^{(n)} p_{i,k}^{(n)} \tilde{g}_{i,k,m}^{(n)} + \sigma^2} \quad \forall k \in K, m \in M, n \in N, \tag{10}$$

where $\tilde{g}_{i,k,m}^{(n)}$ denotes the interference gain between the UAV i and the m-th MAR occupying the sub-bandwidth k from U2M transmissions in time slot n.

The instantaneous industrial packet achievable rate of the m-th EH-CI-M2M transmission reusing the k-th U2M sub-bandwidth in time slot n is calculated by Eq. (11):

$$r_{m,k}^{(n)} = B_{sub}\log_2\left(1 + \gamma_m^{(n)}\right), \quad \forall k \in K, m \in M, n \in N. \tag{11}$$

Moreover, the ergodic industrial packet achievable rate of EH-CI-M2M m in time slot n can be denoted as $R_{m,n}$, which can be expressed as:

$$R_{m,n} = \sum_{k=1}^{K} o_{mk}^{(n)} r_{m,k}^{(n)} \quad \forall m \in M, n \in N. \tag{12}$$

The ergodic transmit power in the m-th EH-CI-M2M pair in time slot n is denoted as $P_{m,n}$, which can be expressed as:

$$P_{m,n} = \sum_{k=1}^{K} o_{mk}^{(n)} p_{m,k}^{(n)} \quad \forall m \in M, n \in N. \tag{13}$$

Herein, the average EE of all EH-CI-M2M transmissions is denoted as EE_{M2M}, which can be given by:

$$EE_{M2M} = \frac{\sum_{n=1}^{N}\sum_{m=1}^{M} R_{m,n}}{\varepsilon\sum_{n=1}^{N}\sum_{m=1}^{M} P_{m,n} + P_{cir}}, \tag{14}$$

where ε and P_{cir} are the inverse of efficiency for power amplifier and static circuit power, respectively.

The maximization problem can be formulated as Eq. (15):

$$\max_{o_{mk}^{(n)},p_{i,k}^{(n)},p_{m,k}^{(n)},t_{mk}^{(n)}} EE_{M2M}\,, \tag{15}$$

subject to:

$$\sum_{m=1}^{M} o_{mk}^{(n)} \le X \quad \forall k \in K, n \in N \tag{15a}$$

$$\sum_{n=1}^{N}\sum_{k=1}^{K} o_{mk}^{(n)} p_{m,k}^{(n)} t_{mk}^{(n)} \le E_0 + \sum_{n=1}^{N} EH_{m,n} \quad \forall m \in M, n \in N \tag{15b}$$

$$\sum_{k=1}^{K} o_{mk}^{(n)} t_{mk}^{(n)} \le \tau_n \quad \forall m \in M, n \in N \tag{15c}$$

$$B_{sub}\log_2\left(1 + \frac{p_{i,k}^{(n)} g_{i,k}^{(n)}}{\sum_{m=1}^{M} o_{mk}^{(n)} p_{m,k}^{(n)} \tilde{g}_{m,k}^{(n)} + \sigma^2}\right) \ge R_{i,k} \quad \forall k \in K, n \in N \tag{15d}$$

$$o_{mk}^{(n)} \in \{0,1\},\ \ p_{m,k}^{(n)} \ge 0,\ \ 0 \le t_{mk}^{(n)} \le \tau_n,\ \ p_{i,k}^{(n)} \ge 0, \tag{15e}$$

where $t_{mk}^{(n)}$ denotes the transmission time for the k-th U2M sub-bandwidth reused by the m-th EH-CI-M2M pair in time slot n; $(15a)$ ensures each sub-bandwidth of U2M transmissions can be reused by at most X EH-CI-M2Ms per time slot; $(15b)$ presents the energy limitation that the whole energy consumption is no more than the total amount of initial energy E_0 and total harvested energy over N time slots; $(15c)$ depicts the limited transmission duration of the EH-CI-M2M; $(15d)$ states the QoS limitation of the minimum industrial packet transmission rate for each UAV-served MA.

III. SOLUTION APPROACH

The problem (15) is a mixed-integer non-linear programming problem with a non-convex objective function, which is hard to obtain the optimal solution directly. Therefore, the primitive problem should be transformed into a convex form firstly.

EE_{M2M} is a decreasing function of $p_{i,k}^{(n)}$ and $(15d)$ is the QoS constraint from U2M devices. Owing to these, to achieve the optimal EE_{M2M}, the transmit power $p_{i,k}^{(n)}$ must be obtained as:

$$p_{i,k}^{*(n)} = \frac{\alpha\left(\sigma^2 + X p_{m,k}^{(n)} \tilde{g}_{m,k}^{(n)}\right)}{g_{i,k}^{(n)}}, \tag{16}$$

where $p_{i,k}^{*(n)}$ denotes the optimal $p_{i,k}^{(n)}$ and $\alpha = 2^{R_{i,k}/B_{sub}} - 1$, we take $p_{i,k}^{*(n)}$ into (16). Denote $h_{mk}^{(n)} = g_{m,k}^{(n)} g_{i,k}^{(n)}$, $e_{mk}^{(n)} = g_{i,k}^{(n)} + \alpha\tilde{g}_{i,k,m}^{(n)}$ and $f_{mk}^{(n)} = \alpha\tilde{g}_{m,k}^{(n)}\tilde{g}_{i,k,m}^{(n)}$, the primitive function can be rewritten by:

$$\max_{\ell} EE_{M2M} = \frac{\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} o_{mk}^{(n)} \log_2\left(1 + \frac{h_{mk}^{(n)} p_{m,k}^{(n)}}{e_{mk}^{(n)}\sigma^2 + f_{mk}^{(n)} p_{m,k}^{(n)}}\right)}{\varepsilon\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} o_{mk}^{(n)} p_{m,k}^{(n)} + P_{cir}}. \tag{17}$$

It is learned that the optimizing variables are updated to $\ell = \left\{o_{mk}^{(n)}, p_{m,k}^{(n)}, t_{mk}^{(n)}\right\}$. Thus, the maximal average EE of the whole EH-CI-M2M transmissions can be given by:

$$EE_{M2M}^{*} = \max_{\ell^*} EE_{M2M}\,, \tag{18}$$

where EE_{M2M}^{*} denotes the optimal EE_{M2M} while the updated variables reach their optimal value $\ell^* = \left\{o_{mk}^{*(n)}, p_{m,k}^{*(n)}, t_{mk}^{*(n)}\right\}$.

Based on the non-linear fractional programming method similar to [11], Eq. (17) can be transformed into a corresponding subtractive form as:

$$T(\ell^*) = \max_{\ell^*}\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} o_{mk}^{*(n)} \log_2\left(1 + \frac{h_{mk}^{(n)} p_{m,k}^{*(n)}}{e_{mk}^{(n)}\sigma^2 + f_{mk}^{(n)} p_{m,k}^{*(n)}}\right) - EE_{M2M}^{*}\left[\varepsilon\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} o_{mk}^{*(n)} p_{m,k}^{*(n)} + P_{cir}\right]. \tag{19}$$

It is obvious that by the time reaching the point $\left(p_{m,k}^{*(n)}, o_{mk}^{*(n)}\right)$ that is equal to (18) and (19), we can obtain the optimal EE_{M2M}^{*}.

Therefore, the equivalent converted optimization function (17) has the following re-expression as:

$$\max_{\ell}\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} o_{mk}^{(n)} \log_2\left(1 + \frac{h_{mk}^{(n)} p_{m,k}^{(n)}}{e_{mk}^{(n)}\sigma^2 + f_{mk}^{(n)} p_{m,k}^{(n)}}\right) - EE_{M2M}\left[\varepsilon\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} o_{mk}^{(n)} p_{m,k}^{(n)} + P_{cir}\right], \tag{20}$$

subject to: (15a), (15b) and (15c).

Due to the integer variable $o_{mk}^{(n)}$, the problem (21) is not yet in a convex form. To deal with the problem, we relax $o_{mk}^{(n)}$ to interval $[0, 1]$ and denote a variable $z_{mk}^{(n)} = o_{mk}^{(n)} p_{m,k}^{(n)}$. Replacing $p_{m,k}^{(n)}$ by $\frac{z_{mk}^{(n)}}{o_{mk}^{(n)}}$, problem (20) can be rewritten as:

$$\max_{\ell}\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} o_{mk}^{(n)} \log_2\left(1 + \frac{h_{mk}^{(n)}\cdot\frac{z_{mk}^{(n)}}{o_{mk}^{(n)}}}{e_{mk}^{(n)}\sigma^2 + f_{mk}^{(n)}\cdot\frac{z_{mk}^{(n)}}{o_{mk}^{(n)}}}\right) - EE_{M2M}\left[\varepsilon\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} z_{mk}^{(n)} + P_{cir}\right], \tag{21}$$

subject to (15a), (15c),

$$\sum_{n=1}^{N}\sum_{k=1}^{K} z_{mk}^{(n)} t_{mk}^{(n)} \le E_0 + \sum_{n=1}^{N} EH_{m,n} \quad \forall m \in M, n \in N. \tag{21b}$$

All the limitations in the latest optimization objective function (21) are jointly convex in $o_{mk}^{(n)}$ and $z_{mk}^{(n)}$. Moreover, the problem (21) can be optimally and effectively tackled under the Karush-Kuhn-Tucker (KKT) conditions. We relax the constraints in (15a), (15b) and (15c) to propose the Lagrangianas in (22), where $\lambda_{1,k,n} \ge 0, \lambda_{2,m,n} \ge 0, \lambda_{3,m,n} \ge 0$ denote the Lagrangian multipliers regarding to the constraints (15a), (15b) and (15c). Denote $\ell = \left\{o_{mk}^{(n)}, p_{m,k}^{(n)}, t_{mk}^{(n)}\right\}$ and $\Psi = \left(\lambda_{1,k,n}, \lambda_{2,m,n}, \lambda_{3,m,n}\right)$, we define the dual function in a further way as Eq. (23).

$$L(\ell, \Psi) = -\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} o_{mk}^{(n)} \log_2\left(1 + \frac{h_{mk}^{(n)} p_{m,k}^{(n)}}{e_{mk}^{(n)}\sigma^2 + f_{mk}^{(n)} p_{m,k}^{(n)}}\right) - EE_{M2M}\left[\varepsilon\sum_{n=1}^{N}\sum_{m=1}^{M}\sum_{k=1}^{K} o_{mk}^{(n)} p_{m,k}^{(n)} + P_{cir}\right] + \sum_{n=1}^{N}\sum_{k=1}^{K} \lambda_{1,k,n}\left(\sum_{m=1}^{M} o_{mk}^{(n)} - X\right)$$

$$+\sum_{n=1}^{N}\sum_{m=1}^{M}\lambda_{2,m,n}\left(\sum_{n=1}^{N}\sum_{k=1}^{K}o_{mk}^{(n)}p_{m,k}^{(n)}t_{mk}^{(n)}-E_0-\sum_{n=0}^{N-1}EH_{m,n}\right)$$
$$+\sum_{n=1}^{N}\sum_{m=1}^{M}\lambda_{3,m,n}\left(\sum_{k=1}^{K}o_{mk}^{(n)}t_{mk}^{(n)}-\tau_n\right) \qquad (22)$$
$$g(\Psi)=\max_{\ell}L(\ell,\Psi) \qquad (23)$$

It is considered that the bandwidth of k-th U2M is assigned to the m-th M2M link. Thus, the optimal transmit power and transmission time $p_{m,k}^{*(n)}$ and $t_{mk}^{*(n)}$ can be given as (24) and (25):

$$p_{m,k}^{*(n)}=\max\left\{0,\frac{\lambda_{3,m,n}}{\lambda_{2,m,n}}\right\}, \qquad (24)$$

$$t_{mk}^{*(n)}=-\frac{e_{mk}^{(n)}h_{mk}^{(n)}\sigma^2}{\lambda_{2,m,n}\ln 2\left(e_{mk}^{(n)}\sigma^2+p_{m,k}^{(n)}\cdot\left(f_{mk}^{(n)}+h_{mk}^{(n)}\right)\right)\cdot\left(e_{mk}^{(n)}\sigma^2+f_{mk}^{(n)}p_{m,k}^{(n)}\right)}+\frac{\varepsilon EE_{m,n}}{\lambda_{2,m,n}}. \qquad (25)$$

Furthermore, we find that the dual function (23) enables to be decoupled into K separate sub-problems. Among these the sub-problem corresponding to k-th sub-bandwidth is

$$\max_{\ell_k}L_k(\ell_k,\Psi), \qquad (26)$$

where $\ell_k=\left\{\boldsymbol{o}_k^{(n)},\boldsymbol{p}_k^{(n)},\boldsymbol{t}_k^{(n)}\right\}$. We denote $\boldsymbol{o}_k^{(n)}$, $\boldsymbol{p}_k^{(n)}$ and $\boldsymbol{t}_k^{(n)}$ as the k-th column of $\boldsymbol{o}$, $\boldsymbol{p}$, $\boldsymbol{t}$ matrices, which are on the k-th sub-bandwidth in time slot n.

Owning to the constraint (15a), one sub-bandwidth resource in single U2M transmission can be assigned to X EH-CI-M2M pairs, and the indicator $\mathbf{o}_k^{(n)}$of bandwidth resource is an all-zero matrix except for one binary non-zero entry. Herein, the optimal indicator $o_{mk}^{*(n)}$ can be deduced in

$$o_{mk}^{*(n)}=\begin{cases}1, & k=\underset{1\le k\le K}{\operatorname{argmax}}\,\eta_{m,k}^{(n)}\\ 0, & \text{otherwise}\end{cases}, \qquad (27)$$

in which we can obtain:

$$\eta_{m,k}^{(n)}=-\log_2\left(1+\frac{h_{mk}^{(n)}g_{m,k}^{(n)}}{e_{mk}^{(n)}\sigma^2+f_{mk}^{(n)}p_{m,k}^{(n)}}\right). \qquad (28)$$

From (27), it is obvious that the value $\eta_{m,k}^{(n)}$ is optimal when the k-th sub-bandwidth can be assigned to the m-th EH-CI-M2M in time slot n. From (28), it is also clear that different transmission gains have decisive impacts on $\eta_{m,k}^{(n)}$. Thus, we get an integer solution from the temporary relaxation of $o_{mk}^{(n)}$ within $[0,1]$ and propose an iterative algorithm to optimize the average EE of EH-CI-M2M transmissions in Algorithm 1.

Algorithm 1:

```
1. Input: $R_{i,k}, g_{i,k}, \forall k$; $g_{m,k}, \tilde{g}_{i,k,m}, \forall k,m$; $EH_{m,n}, \forall m,n$;
   $\tau_n, \forall n, T_{opm}, N, M, K, \sigma^2, \alpha$
2. Output: $p_{m,k}^{*(n)}, t_{m,k}^{*(n)}, o_{mk}^{*(n)}, p_{i,k}^{*(n)}, \forall k,m,n; \eta_{ee}^*$
3. Initialize $\eta_{ee}$ point and maximal tolerance $\varepsilon$
4. Initialize $\lambda_{2,m,n}^{(0)}=1$ and $\lambda_{3,m,n}^{(0)}=1$
5. Calculate $p_{m,k}^{*(n)}, t_{mk}^{*(n)}$ and $\eta_{m,k}^{(n)}, \forall m,k,n$ from (24), (25) and (28) respectively
6. Match the $m$-th EH-CI-M2M transmission with $k$-th sub-bandwidth from (27)
7. while $T(\ell) > \varepsilon$, do
8.   $\lambda_{2,m,n}^{(\theta+1)}=\left(\lambda_{2,m,n}^{(\theta)}-\alpha\left(\sum_{n=0}^{N-1}EH_{m,n}-\sum_{n=1}^{N}\sum_{k=1}^{K}o_{mk}^{(n)}p_{m,k}^{(n)}t_{mk}^{(n)}\right)\right)^+$
9.   $\lambda_{3,m,n}^{(\theta+1)}=\left(\lambda_{3,m,n}^{(\theta)}-\beta\left(\tau_n-\sum_{m=1}^{M}o_{mk}^{(n)}t_{mk}^{(n)}\right)\right)^+$
10.  Calculate $p_{m,k}^{(n)}, t_{mk}^{(n)}, o_{mk}^{(n)}, \eta_{ee}$
11. end while
12. Obtain $p_{i,k}^{*(n)}=\frac{\alpha\left(\sigma^2+p_{m,k}^{*(n)}\tilde{g}_{m,k}^{*(n)}\right)}{g_{i,k}^{(n)}}$, for $o_{mk}^{*(n)}=1$
```

IV. NUMERICAL RESULTS AND PERFORMANCE ANALYSIS

In this simulation, there are 4 UAVs flying along the diagonal of an 800 × 800 m^2 manufacturing area, acting as industrial servers. To emulate the real industrial site such as automatic production, intelligent detection and so on, all MAs are randomly distributed in this field to receive the industrial instructions. With the aim of green-reliable IIoT in future Industry 5.0, we generate 100 independent runs and average the performance of EE for each configuration by using PC Intel® Core (TM) i7–8700 CPU @ 3.2 GHz with MATLAB R2018a. Some other simulation parameters are listed in Tab. 1. Four benchmark schemes are used for comparison: (1) The scheme maximizes EE without EH considered (non-EH); (2) The scheme maximizes EE with equally separating each time slot into EH time and transmission time (EH-T); (3) The scheme maximizes the transmission rate (max-TR); (4) The scheme maximizes the spectrum efficiency (max-SE).

Tab. 1. Simulation Parameters

Parameters	Values	Parameters	Values
V_{UAV}, H_{UAV}	40 m/s, 20 m	MA distance	[20, 50] m
EH limit	[0, 100] J	B_{sum}/K	75 KHz
X	3	N	50
α_L, α_N	2, 5	σ^2	-80 dBm
E_0	2000 J	P_{cir}	23 dBm

Fig. 2 presents the optimization process for average EE. It is observed that the proposed scheme converged after 130 iterative times. Though the proposed scheme did not converge the fastest among the five schemes, it obtains the highest average EE of 194.32 bit/J after reaching convergence since the proposed scheme considers EH time in each time slot, resulting in a lower speed. Nevertheless, the proposed scheme acquires the best EE as compared to the other four schemes.

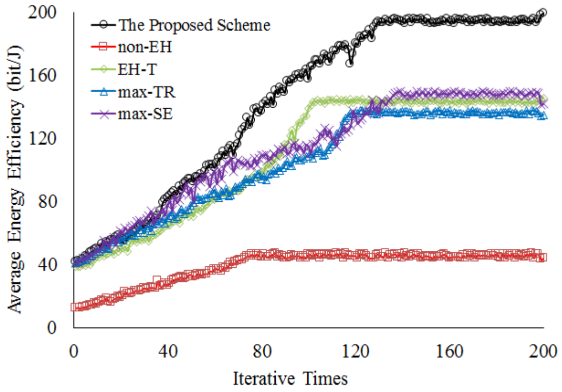

Fig. 2. The optimization process for average EE

Fig. 3 gives the demonstration on average EE versus the different quantities of deployed MAs with QoS constraints of minimum required SE (12 bps/Hz). The proposed scheme is capable of obtaining the highest EE. As the number of MA increases, the average EE follows up initially since more MAs cause the growing of the network throughput. However, while the quantity of MAs goes up to 34, the average EE of all schemes tend to be stable until the number further increases to 46. After that, the EE goes down due to the reason that more mutual interference will be involved, which consumes more power. Nevertheless, it is worth noting that while the number of MA further increases to 64, the EE will not decrease continuously. This is because more deployed MAs result in the shorter distance between transmitter and receiver in MA pair, which may improve energy efficiency inversely.

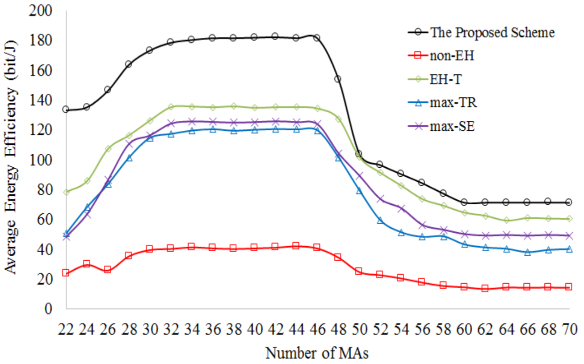

Fig. 3. Average EE versus different numbers of MAs with $SE = 12\ bps/Hz$

Fig. 4 depicts the EE with the varying EH rates λ. We found that the proposed scheme enables to achieve the highest EE among the five schemes. As it is able to gain the optimal correlation between EH time and transmission time, making a significant contribution to the EE. With the rise of λ, the average EE is enhanced for all schemes except non-EH since more energy can be harvested in each time slot.

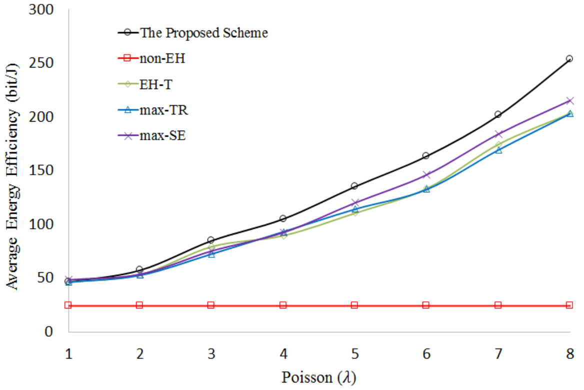

Fig. 4. Average EE versus different energy harvesting rates λ

Fig. 5 shows the standard deviation of energy consumption against different number of MAs. The proposed scheme obtains a standard deviation of 29.56 since it stabilizes the energy balance for each MA via selecting the optimal EH duration, transmit power and available bandwidth. The standard deviation increases initially when the quantity of MAs is small. With an ulterior growth in scale, the standard deviation declines and stabilizes until the number of deployed MAs increases to 46. The standard deviation grows again since more interference will be involved as the scale of MAs rises. Moreover, the standard deviation for the non-EH scheme has gone up drastically as the scheme manages transmit power without considering the available energy residual in each MA.

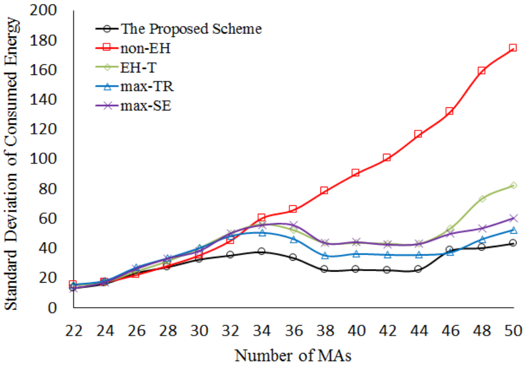

Fig. 5. Standard deviation of consumed energy with different numbers of MAs.

V. CONCLUSIONS

In this letter, we aim at maximizing the EE for all the EH-CI-M2M devices in a multi-UAVs-served network by jointly considering the EH duration time, bandwidth allocation, transmit power control, available energy status and the QoS. A novel scheme on the basis of Dinkelbach and Lagrangian theory is proposed to acquire the optimal resource allocation strategy. Numerical results verify the feasibility of the proposed scheme in various network settings.

REFERENCES

[1] H. R. Chi, C. K. Wu, N. -F. Huang, K. -F. Tsang and A. Radwan, "A Survey of Network Automation for Industrial Internet-of-Things Toward Industry 5.0," in IEEE Transactions on Industrial Informatics, vol. 19, no. 2, pp. 2065-2077, 2023.

[2] Y. Jiang, Q. Liu, F. Zheng, X. Gao and X. You, "Energy-Efficient Joint Resource Allocation and Power Control for D2D Communications," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6119-6127, 2016.

[3] P. Mach, Z. Becvar and M. Najla, "Resource Allocation for D2D Communication With Multiple D2D Pairs Reusing Multiple Channels," IEEE Wireless Communications Letters, vol. 8, no. 4, pp. 1008-1011, 2019.

[4] L. Xu, C. Jiang, Y. Shen, T. Q. S. Quek, Z. Han and Y. Ren, "Energy Efficient D2D Communications: A Perspective of Mechanism Design," IEEE Transactions on Wireless Communications, vol. 15, no. 11, pp. 7272-7285, 2016.

[5] T. D. Hoang *et al.*, "Energy-Efficient Resource Allocation for D2D Communications in Cellular Networks," IEEE Transactions on Vehicular Technology, vol. 65, no. 9, pp. 6972-6986, 2016.

[6] F. Zhou, Y. Wu, R. Q. Hu and Y. Qian, "Computation Rate Maximization in UAV-Enabled Wireless-Powered Mobile-Edge Computing Systems," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 9, pp. 1927-1941, 2018.

[7] F. Zhou, R. Q. Hu, Z. Li and Y. Wang, "Mobile Edge Computing in Unmanned Aerial Vehicle Networks," IEEE Wireless Communications, vol. 27, no. 1, pp. 140-146, 2020.

[8] J. Ji, K. Zhu, D. Niyato and R. Wang, "Joint Trajectory Design and Resource Allocation for Secure Transmission in Cache-Enabled UAV-Relaying Networks With D2D Communications," in IEEE Internet of Things Journal, vol. 8, no. 3, pp. 1557-1571, 2021.

[9] Z. Becvar, M. Nikooroo and P. Mach, "On Energy Consumption of Airship-Based Flying Base Stations Serving Mobile Users," in IEEE Transactions on Communications, vol. 70, no. 10, pp. 7006-7022, 2022.

[10] W. Wu, F. Zhou, R. Q. Hu and B. Wang, "Energy-Efficient Resource Allocation for Secure NOMA-Enabled Mobile Edge Computing Networks," IEEE Transactions on Communications, vol. 68, no. 1, pp. 493-505, 2020.

[11] S. He, Y. Huang, L. Yang and B. Ottersten, "Coordinated Multicell Multiuser Precoding for Maximizing Weighted Sum Energy Efficiency," IEEE Transactions on Signal Processing, vol. 62, no. 3, pp. 741-751, 2014.