

Energy Efficiency Optimization for HAP-to-UAV FSO Systems with Energy Harvesting

Binh-Minh Vu, Xuan-Toan Dang, Ngoc T. Dang, and Oh-Soon Shin

Abstract—In this paper, we investigate a free-space optics (FSO) system for simultaneous lightwave information and power transfer (SLIPT) from a high-altitude platform (HAP) to an unmanned aerial vehicle (UAV). We develop an optimization framework to maximize energy efficiency by optimizing UAV trajectory planning, HAP power allocation, and power-splitting (PS) ratio under the energy constraint. The formulated optimization problems are highly non-linear and non-convex, posing significant challenges for conventional methods. To address this, we employ inner approximation techniques and propose an iterative algorithm to achieve the locally optimal solution. The simulation results demonstrate substantial performance gains compared to the baseline schemes, highlighting the efficacy of the proposed approach.

Index Terms—Free-space optics, unmanned aerial vehicle (UAV), high-altitude platform (HAP), UAV trajectory planning, simultaneous lightwave information and power transfer (SLIPT).

I. INTRODUCTION

WITH the increasing demand for ubiquitous connectivity, advanced communication systems must ensure seamless coverage, particularly in remote and underserved areas where traditional terrestrial networks are limited by static infrastructure and challenging terrain. To overcome these limitations, non-terrestrial networks (NTNs) have emerged as a transformative solution, offering communication services to hard-to-reach locations and adapting to critical missions such as disaster recovery, aerial surveillance, maritime communication, and national security operations [1], [2]. By leveraging flexible platforms such as unmanned aerial vehicles (UAVs), high-altitude platforms (HAPs), and satellites, NTNs enable the seamless integration of space-based and aerial communication systems with conventional terrestrial networks, enhancing connectivity and operational resilience [3].

UAVs, also known as drones, operate at lower altitudes than HAPs and satellites, providing agile and localized communication solutions ideal for rapid deployment and adaptability in a wide range of applications. Recent studies suggest that developing free-space optics (FSO) communication systems for UAVs enables more flexible and energy-efficient communications in specific scenarios [4], [5]. FSO technology offers

several advantages, including high data rates, low latency, immunity to electromagnetic interference, and a more compact, lightweight design compared to RF antennas. These benefits of FSO communication have drawn significant research interest in UAV-based communications, facilitating easier deployment in dimension-constrained or mobile scenarios [6]. Meanwhile, HAPs, such as stratospheric balloons and airships, enable wide-area coverage with prolonged operation, enhancing connectivity over large regions [1], [6]. Integrating FSO with HAPs and UAVs offers practical benefits across various applications. For instance, the authors in [7] examined the HAP-to-UAV FSO links, considering channel effects and the pointing error caused by the UAV's hovering when evaluating system performance. Additionally, [3] proposed the integrated satellite HAP-UAV downlink communication supported by hybrid FSO/RF systems, analyzing performance metrics under rate adaptation. In another study, [8] examined HAP-UAV downlink communication originating from ground stations.

To the best of our knowledge, existing literature has yet to present a comprehensive optimization framework to maximize the energy efficiency (EE) of a HAP-to-UAV FSO system, supported by the mobile UAV using energy harvesting. This research gap motivates us to propose an optimization framework that enhances the EE of such systems. To ensure the UAV's continuous operation, we integrate a simultaneous lightwave information and power transfer (SLIPT) mechanism along with solar panels for efficient energy harvesting. In the SLIPT system, a power splitter with a power-splitting (PS) ratio divides the received HAP signal for energy harvesting and data transmission. Building on this concept, we formulate the EE maximization problem, optimizing the UAV's trajectory, HAP power allocation, and PS ratio, subject to the practical trajectory and energy constraints. The resulting problem is nonconvex and becomes intricate as accounting for key impairments such as attenuation losses, atmospheric turbulence, and beam misalignment. To address this, we employ inner approximation (IA) techniques, developing an iterative algorithm that converges to local optima. Simulations validate the framework demonstrating UAV trajectories in multi-destination scenarios and significant EE improvement over baseline schemes, such as fixed HAP power allocation and PS ratio.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider an FSO system between an HAP and SLIPT-enabled mobile UAV. Specifically, the mobile UAV operates as a self-sustaining node, simultaneously receives data and energy from HAP, serving a special mission, as illustrated in Fig.

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2023-00208995, RS-2025-02214082).

Binh-Minh Vu, Xuan-Toan Dang, and Oh-Soon Shin are with the School of Electronic Engineering, Soongsil University, Seoul, South Korea (e-mail: binhminhvu@soongsil.ac.kr; osshin@ssu.ac.kr).

Ngoc T. Dang is with the Wireless Systems and Applications Lab., Posts and Telecommunications Institute of Technology, Ha Noi, Viet Nam (e-mail: ngocdt@ptit.edu.vn).

1(a). Geometrically, the HAP is located at a 3D coordinate, $\mathbf{H} = [x_H, y_H, H_{HAP}]$, covering a wide area, and facilitating a reliable LoS link to a mobile UAV.

A. Channel Model for FSO Transmission

The propagation model of HAP-to-UAV FSO system can be presented by three factors: Atmospheric attenuation (h_ℓ^F), HAP-UAV misalignment (h_m^F), and atmospheric turbulence (h_a^F), given by $h_F = h_\ell^F h_m^F h_a^F$ [7].

1) *Atmospheric attenuation*: The atmospheric attenuation coefficient h_ℓ^F is given by $h_\ell^F = \exp(-\alpha_\ell L_{HU})$, where L_{HU} is the propagation distance between HAP and UAV [7]. α_ℓ is the attenuation coefficient, which can be determined by $\alpha_\ell(\lambda) = \frac{3.912}{V} \left(\frac{\lambda}{550}\right)^{-m(V)}$, where $m(V)$ is the specific atmosphere attenuation visibility coefficient, given by $m(V) = 1.6$, if $V > 50$ km; $= 1.3$, if $6 \text{ km} < V < 50 \text{ km}$; $= 0.585V^{1/3}$, if $V < 6 \text{ km}$, where V is the atmospheric visibility.

2) *HAP-UAV misalignment*: The misalignment-induced channel coefficient (h_m^F) is expressed as [9]: $h_m^F \approx A_0 \exp(-2\|\mathbf{u}\|^2/w_z^2)$, where $A_0 = [\text{erf}(v)]^2$ with $v = \frac{\sqrt{\pi}a_p}{\sqrt{2}w_f}$ is the fraction of the collected power at $u = \|\mathbf{u}\| = 0$, $\mathbf{u}$ denotes the misalignment vector in the photodetector (PD) plane and the beam of HAP. Here, a_p presents the detection aperture radius at the UAV and w_f is the beam waist. $w_z = \left(w_f^2 \frac{\sqrt{\pi} \text{erfc}(v)}{2v \exp(-v^2)}\right)^{1/2}$ is the equivalent beam radius at distance Z .

3) *Atmospheric turbulence*: The turbulence-induced fluctuation coefficient h_a^F follows a log-normal distribution as $f_{h_a^F}(h_a^F) = (1/\sqrt{8\pi}h_a^F\sigma_X) \exp\left(-\frac{[\ln(h_a^F/2\mu_X)]^2}{8\sigma_X^2}\right)$, where μ_X and σ_X are the mean and variance of log-amplitude fluctuation, respectively [10].

B. Signal Model

We assume LoS links are guaranteed for the HAP-to-UAV FSO connection. We consider finite time slots T to ensure the efficiency of SLIPT. For simplicity, we have the set of time slots, $t \in \mathcal{T} = \{1, \dots, T\}$. Each time slot is designed to ensure that the UAV operates at the maximum speed V_m . Consequently, the 3D trajectory of the UAV can be denoted by $\mathbf{U}[t] = [x_U[t], y_U[t], h_U[t]]^T, \forall t$. We also assume that UAV implements a task from the initial point ($\mathbf{U}_I$) to the final point ($\mathbf{U}_F$). The UAV trajectory satisfies the following constraints:

$$\mathbf{U}_I = \mathbf{U}[1], \quad (1)$$

$$\mathbf{U}_F = \mathbf{U}[T], \quad (2)$$

$$\|\mathbf{U}[t+1] - \mathbf{U}[t]\|^2 \leq (V_m \tau)^2. \quad (3)$$

In the proposed framework, we consider two UAV trajectory scenarios: Trajectory 1, where the UAV follows a single-destination path; Trajectory 2, where the UAV navigates multiple destinations. The formulation of Trajectory 1 is governed by constraints (1), (2), and (3). For Trajectory 2, we define the trajectory constraints including (1)-(3) and $\mathbf{U}_{D1} = \mathbf{U}[T/3]$ and $\mathbf{U}_{D2} = \mathbf{U}[2T/3]$. At the UAV, a SLIPT system utilizes a power splitter with the PS ratio, $\rho[t] \in (0, 1)$ to separate the received signal into two components in each time slot: one for

information processing and the other for energy harvesting. Therefore, the received signal for information processing in the t -th time slot can be expressed as

$$y_U[t] = \Re M_a P_T[t](1 - \rho[t])G_{Tx}G_{Rx}h_F[t]x + n_U, \forall t, \quad (4)$$

where $\Re$ is the PD responsivity and M_a is the multiplication factor of the avalanche photodiode (APD). $P_T[t]$, $\forall t \in \mathcal{T}$ denote the transmitted power at the HAP in the t -th time slot. x is the transmitted symbol at the HAP. G_{Tx} and G_{Rx} are the transmitter and receiver telescope gains, respectively, and n_U is additive white Gaussian noise (AWGN) with variance σ_N^2 . Consequently, the signal-to-noise ratio (SNR) for the HAP-UAV FSO link in the t -th time slot can be computed as [7], given by $S[t] = I_p^2[t]/\sigma_N^2, \forall t$, where $I_p[t] = \Re M_a P_T[t](1 - \rho[t])G_{Tx}G_{Rx}h_F[t]$ is the received current at the PD. Assuming thermal noise dominates, the noise variance is given by $\sigma_N^2 = 4k_B T_a F_n \Delta f / R_L$, where k_B is Boltzmann's constant, T_a is the absolute temperature, F_n is the amplifier noise figure, and R_L is the load resistance. $\Delta f = R_{FSO}^S/2$ denotes the effective bandwidth with the FSO link's bit rate, R_{FSO}^S . Given that channel fluctuations occur much faster than the UAV's kinematic changes, we use the ergodic capacity as a performance metric [11]. Therefore, the ergodic capacity at the UAV in t -th time slot can be expressed as

$$C_F[t] = \mathbb{E} \left[\frac{1}{2} \log_2 \left(1 + \frac{I_p^2[t]}{\sigma_N^2} \right) \right], \forall t, \quad (5)$$

where $\mathbb{E}(\cdot)$ is the expected value. The UAV utilizes the remaining portion of the received signal for energy harvesting. The harvested energy at the UAV is given as $P_{EH}[t] = \eta_h M_a P_T[t]\rho[t]G_{Tx}G_{Rx}h_F[t]$, where η_h is energy harvesting efficiency [4].

C. Problem Formulation

The primary objective is to maximize the EE of the HAP-to-UAV FSO communication. This is achieved by jointly optimizing the UAV trajectory planning, the HAP power allocation, and the PS ratio, subject to constraints related to the UAV trajectory and energy availability. Accordingly, the optimization problem for UAV's EE is formulated as

$$\max_{\mathbf{U}[t], \rho[t], P_T[t]} \Xi_{EE} \triangleq \frac{\sum_{t=1}^T C_F[t](\mathbf{U}[t], \rho[t], P_T[t])}{\sum_{t=1}^T P_T[t] + T P_s} \quad (6a)$$

$$\text{s.t.} \quad (1), (2), (3), \quad (6b)$$

$$\sum_{n=1}^N P_T[t] \leq P_s^H, \quad (6c)$$

$$C_F[t](\mathbf{U}[t], \rho[t], P_T[t]) \geq C_F^{min}, \forall t \quad (6d)$$

$$P_{solar} + P_{EH}[t](\mathbf{U}[t], \rho[t], P_T[t]) \geq P_s, \forall t, \quad (6e)$$

$$0 \leq \rho[t] \leq 1, \forall t, \quad (6f)$$

where P_s and P_{solar} are the power required for UAV self-sustainability and power harvested from solar panels in each time slot. Constraint (6b) governs the UAV trajectory, while (6c) limits the total transmitted power at the HAP. Constraint (6d) ensures UAV capacity, (6e) enforces energy constraint for UAV, and (6f) defines PS ratio limits. Solving problem

(6) optimally is challenging due to the non-convexity of the objective (6a) and constraints (6d) and (6e), which stem from the coupling of $\mathbf{U}$, ρ , and P_T into the same expression.

III. PROPOSED ITERATIVE ALGORITHM

To solve the the above challenges, we first reformulate (6a) into a more tractable form by applying log-arithmetic approximation $\log_2(1 + \Lambda)$ at a given feasible point $\Lambda^{(i)}$ in the i -th iteration [12]. By applying $\Lambda[t] = S[t]$, we have

$$\mathbb{E} \left[\frac{1}{2} \log_2(1 + S[t]) \right] \geq \frac{A^{(i)}[t] \mathbb{E}[\log S[t]] + B^{(i)}[t]}{2 \log 2}, \forall t \quad (7)$$

where $A^{(i)}[t] = \frac{S^{(i)}[t]}{1+S^{(i)}[t]}$, $B^{(i)}[t] = \log(1 + S^{(i)}[t]) - \frac{S^{(i)}[t]}{1+S^{(i)}[t]} \log S^{(i)}[t]$. The term $\log S[t]$ can be expressed as the sum of each of the channel terms:

$$\mathbb{E}[\log S[t]] = 2 \log(C_1 P_T[t](1 - \rho[t])) + 2 \mathbb{E}[\log(h_a^F)] + 2 \log(h_\ell^F[t]) + 2 \log(h_m^F), \quad (8)$$

where $C_1 = \Re M_a G_{Tx} G_{Rx} / \sigma_N$, $\mathbb{E}[\log(h_a^F)] = -\sigma_X^2$, and $\log(h_\ell^F[t]) = -\alpha_\ell L_{HU}[t]$. However, (6a) is non-convex due to $P_T[t](1 - \rho[t])$. We introduce the new variables $P_{T,lb}[t]$, $P_{T,sl}[t]$ for the lower bound (LB) of $P_T[t](1 - \rho[t])$, which satisfies

$$P_T[t](1 - \rho[t]) \geq P_{T,sl}^2[t], \forall t, \quad (9)$$

$$P_{T,sl}^2[t] \geq 2P_{T,sl}[t]P_{T,sl}^{(i)}[t] - (P_{T,sl}^{(i)}[t])^2 \geq P_{T,lb}[t], \forall t, \quad (10)$$

Considering (6e), it remains non-convex due to the product $P_T[t]\rho[t]h_\ell^F[t]$. Firstly, we introduce the new variables $g_{lb}[t]$, $g_{sl,lb}[t]$ for LBs of $P_T[t]\rho[t]$, given by

$$P_T[t]\rho[t] \geq g_{sl,lb}^2[t], \forall t, \quad (11)$$

$$g_{sl,lb}^2[t] \geq 2g_{sl,lb}[t]g_{sl,lb}^{(i)}[t] - (g_{sl,lb}^{(i)}[t])^2 \geq g_{lb}[t], \forall t, \quad (12)$$

We consider the expectation of the FSO channel, given by $\mathbb{E}[h_F] = h_\ell^F h_m^F$ with $\mathbb{E}[h_a^F] = 1$ as [7]. By adding the new variable $h_{\ell,lb}^F[t]$ for the LB of $h_\ell^F[t]$, we rewrite

$$\log(\exp(-\alpha_\ell L_{HU}[t])) \geq \log(h_{\ell,lb}^F[t]), \forall t, \quad (13)$$

Following the upper bound of the function $\log(x)$ at a given feasible point $x^{(i)}$ in the i -iteration [13], we set $x[t] = h_{\ell,lb}^F[t]$, given by

$$0 \geq \alpha_\ell L_{HU}[t] + \log(h_{\ell,lb}^F[t])^{(i)} + \frac{h_{\ell,lb}^F[t]}{(h_{\ell,lb}^F[t])^{(i)}} - 1, \forall t, \quad (14)$$

However, (6e) remains non-convex because of the product $g_{lb}[t]h_{\ell,lb}^F[t]$. We introduce the auxiliary variables $g_{h_\ell^F}[t]$, $g_{h_{\ell,lb}^F}[t]$ for $g_{lb}[t]h_{\ell,lb}^F[t]$, which satisfy

$$g_{lb}[t]h_{\ell,lb}^F[t] \geq g_{h_\ell^F}^2[t], \forall t, \quad (15)$$

$$g_{h_\ell^F}^2[t] \geq 2g_{h_\ell^F}[t]g_{h_\ell^F}^{(i)}[t] - (g_{h_\ell^F}^{(i)}[t])^2 \geq g_{h_{\ell,lb}^F}[t], \quad (16)$$

Based on (11)-(16), we rewrite (6e) in the convex form as

$$g_{h_{\ell,lb}^F}[t]C_2 + P_{solar} - P_s \geq 0, \forall t, \quad (17)$$

where $C_2 = \eta_h M_a G_{Tx} G_{Rx} h_m^F$. Drawing from the preceding discussion, problem (6) can be successfully solved by the

Algorithm 1 Proposed Iterative Algorithm for Solving (6)

Initialization: Set $i := 0$ and generate an initial feasible point $(P_T^{(0)}[t], \mathbf{U}^{(0)}[t], \rho^{(0)}[t], F^{(0)}[t])$ and a random τ , $F = 0$;
1: **while** $F = 0$ **do**
2: Solve (18) to obtain the optimal solution $(P_T^*[t], \mathbf{U}^*[t], \rho^*[t], F^*[t])$ with maximum EE under the current τ .
3: Update $P_T^{(i+1)}[t] := P_T^*[t]$, $\mathbf{U}^{(i+1)}[t] := \mathbf{U}^*[t]$, $\rho^{(i+1)}[t] := \rho^*[t]$, $F^{(i+1)}[t] := F^*[t]$.
4: **if** $\Xi_{EE,D}^* \leq \epsilon$ **then**
5: $F = 1$;
6: **else**
7: Update $\tau = \frac{\sum_{t=1}^T C_F[t](\mathbf{U}^{(i+1)}[t], \rho^{(i+1)}[t], P_T^{(i+1)}[t])}{\sum_{t=1}^T P_T^{(i+1)}[t] + TP_s}$;
8: Set $i := i + 1$; $F = 0$;
9: **end while** Convergence

following optimization problem at the i -th iteration using Dinkelbach method [14]:

$$\max_{\substack{\mathbf{U}[t], \rho[t] \\ P_T[t], F[t]}} \Xi_{EE,D} \triangleq \sum_{t=1}^T \lambda[t] - \tau \left(\sum_{t=1}^T P_T[t] + TP_s \right) \quad (18a)$$

$$\text{s.t.} \quad (6b), (6f), (9)-(12), (14)-(17), \quad (18b)$$

$$\frac{A^{(i)}[t]S_{lb}[t] + B^{(i)}[t]}{2 \log 2} \geq \lambda[t], \forall t, \quad (18c)$$

$$\lambda[t] \geq 2^{2C_F^{min}} - 1, \forall t, \quad (18d)$$

where $F[t] = \{P_{T,lb}[t], P_{T,sl}[t], g_{lb}[t], g_{sl,lb}[t], g_{h_\ell^F}[t], g_{h_{\ell,lb}^F}[t], \lambda[t]\}_{\forall t}$ and $S_{lb}[t] = 2 \log(C_1 P_{T,lb}[t]) - 2\sigma_X^2 + 2 \log(h_m^F) - \alpha_\ell L_{HU}[t]$. By solving (6) following the steps of Algorithm 1 and the solution from (18), we obtain the next feasible point $(P_T^{(i+1)}, \mathbf{U}^{(i+1)}, \rho^{(i+1)}, F^{(i+1)})$ along with the current τ . This algorithm generates a non-decreasing sequence of objective values, i.e., $\Xi_{EE,D}^{(i+1)} \geq \Xi_{EE,D}^{(i)}$, converging to the maximum value τ^* . This guarantees convergence to at least a local optimum, as the convex approximations satisfy the properties outlined in [15]. Consequently, the optimization problem can be efficiently solved using the MOSEK solver and the YALMIP toolbox.

IV. NUMERICAL RESULTS

In this section, the numerical results are presented to demonstrate the EE of the proposed system. HAP and UAV are located at $\mathbf{H} = [0, 0, 18,000]$ m and $\mathbf{U} = [x_U, y_U, 100]$ m, respectively. Additionally, we set the starting point, endpoint, and destination as in Fig. 1(a). Other parameters are used as given in [4] and [7]: $a_p = 10$ m, $w_f = 50$ m, $u = 1$ m, $\Re = 0.8$ A/W, $M_a = 10$, $R_L = 10$ Ω , $T_a = 298$ K, $\Delta f = 0.5$ GHz, $G_{Tx} = 25$ dB, $G_{Rx} = 10$ dB, $\eta_H = 0.6$, $P_s = 1010$ W, $P_{solar} = 1015$ W, $\lambda = 1550$ nm, $V = 30$ km, $V_m = 50$ m/s, $\tau = 0.1$ s, and $C_F^{min} = 2$ bps/Hz. Based on the parameters, we develop the iterative algorithm (i.e., Alg. 1) with an optimization framework, where the convergence threshold is set to $\epsilon = 10^{-3}$. To evaluate the effectiveness of the proposed algorithm, we compare it with the following benchmarking schemes: ‘‘FPS’’, the PS ratio is fixed with $\rho = 0.25, 0.45, 0.65$; ‘‘FTP’’, the HAP power allocation is fixed with $P_T[t] = (0.85 \times P_S^H)/T$, $P_T[t] = (0.65 \times P_S^H)/T$,

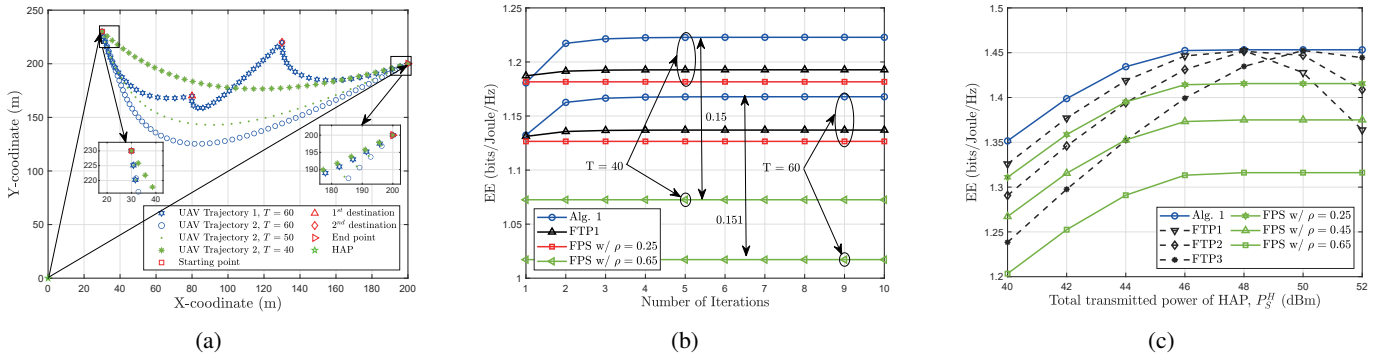


Fig. 1. (a) UAV trajectory. (b) Convergence behavior of EE with $P_S^H = 35$ dBm. (c) EE versus P_S^H in $T = 45$.

and $P_T[t] = (0.45 \times P_S^H)/T$ for FTP1, FTP2, and FTP3, respectively.

Fig. 1(a) illustrates the UAV trajectory over multiple time slots in two missions. In the first mission, the UAV follows Trajectory 1, traveling from the starting point to the endpoint. The second mission, represented by Trajectory 2, passes through intermediate stops before reaching the endpoint. The evaluation for multi-destination is necessary for real-world applications such as aerial surveillance and environmental monitoring. Considering the number of time slots from $T = 40$ to $T = 60$, the UAV gains greater flexibility in optimizing its trajectory, allowing it to move closer to the HAP, improving communication quality, and enhancing the UAV's EE.

Fig. 1(b) describes the convergence behavior of various schemes, with most reaching convergence by the 3-rd iteration. This rapid convergence highlights the efficiency of the proposed algorithm with low computational complexity. Among the schemes, Alg. 1 consistently outperforms the highest gains at both $T = 40$ and 60 . The FPS schemes with $w/\rho = 0.65$ show lower gains of EE (0.15 and 0.151 for $T = 40$ and $T = 60$, respectively), due to the lack of optimization in HAP power allocation or PS ratio. As anticipated, the gains of EE decrease as the number of time slots increases, mainly due to higher UAV power consumption during extended operation.

Fig. 1(c) depicts the variation of EE as P_S^H changes. Alg. 1 consistently outperforms all other schemes, highlighting the benefits of optimized HAP power allocation, PS ratio, and UAV trajectory planning. As P_S^H in $T = 45$ increases from 46 to 52 dBm, the EE gain of Alg. 1 and the FPS schemes reach saturation, enabling the optimal HAP power allocation. In contrast, the FTP1, FTP2, and FTP3 schemes fail to reach saturation, instead showing an initial increase followed by a decline. This is due to the lack of effective HAP power allocation, where non-optimal power allocation reduces the gains of EE as P_S^H increases, only enabling the optimal HAP power allocation at the highest EE for the FTP schemes.

V. CONCLUSION

The paper comprehensively investigated an FSO system between a HAP and a mobile UAV using SLIPT. We developed a robust optimization framework to maximize UAV's EE by optimizing UAV trajectory planning, HAP power allocation, and PS ratio under the constraints of energy and trajectory.

IA techniques were applied to tackle non-linearity and non-convexity in the problem formulation. The simulation results demonstrated the best performance of Alg. 1 compared to the baseline schemes and its adaptability to multi-destination trajectory scenarios.

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