On the Design and Optimization of SLIPT Systems for Aerial Base Stations

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***Abstract*—In this paper, the application of simultaneous lightwave information and power transfer (SLIPT) for the fronthaul link of an aerial base station (ABS) is studied. SLIPT is a particularly attractive solution for such links, since the directive free-space optical link can provide ultra-high throughput as a fronthaul, while simultaneously transferring considerable amounts of energy to extend the flight duration of the ABS. In general, large receiver areas can be utilized by a SLIPT system to enhance both its data rate and the harvested power, as they balance out the geometric spreading of the beam. However, a larger solar cell area naturally leads to a heavier load for the ABS increasing its power consumption and, in turn, lowering its expected lifetime. Therefore, it is crucial to study the ensuing trade-off between the size of the solar cell and the performance of the ABS. Moreover, SLIPT performance is heavily influenced by the transmission parameters such as direct current (DC) bias. To that end, a joint optimization problem is designed to maximize the energy efficiency on an ABS based on the transmission parameters and the size of the solar cell. Simulation results validate the proposed analysis as they illustrate a great performance gain over benchmark schemes.**

***Index Terms*—Simultaneous lightwave information and power transfer (SLIPT), Aerial base-station (ABS), Energy efficiency**

I. Introduction

The exponential growth of communication networks has triggered the need to integrate aerial base stations (ABSs) as a vital part of the network infrastructure. The operation of such ABSs will provide flexible coverage extension, traffic offloading, and rapid network recovery in case of emergency. Unmanned aerial vehicles (UAVs) have attracted significant attention from the research community and industry alike for their potential use in sensing and communication applications [1], [2]. However, a major limitation of UAVs is the limited battery lifetime, which restricts their ability to act as ABSs for long periods of time. Equipping ABSs with larger batteries is not a viable solution due to the excessive weight of the extra batteries, which would drop the ABS energy efficiency. In this regard, various potential solutions have emerged, such as tethered drones and battery swapping [3]. However, tethered drones are confined into a small coverage area by design, while battery swapping requires additional capital and operational costs, rendering these ideas impractical. On the contrary, a promising, inexpensive and flexible solution is to power the ABSs with a directive lightwave link [4] that not only can transfer high amounts of energy to extend the lifetime of the UAVs, but also simultaneously act as a fronthaul link for communication purposes. An overview on free space optics (FSO) for UAV communications can be found in [5].

The concept of laser-powered drones has long been established with promising results [6]. On that front, laser-based charging has been demonstrated to be superior to respective RF methods, all the while free-space optical communications (FSO) have significantly advanced to closely follow the data rates offered by tethered fiber connections without a costly fiber infrastructure. Lately, the idea of simultaneous lightwave information and power transfer (SLIPT) has been explored and the resulting trade-off between harvested energy and communication data rate has been highlighted for conventional networks. In more detail, in [7], an ABS equipped with a SLIPT receiver is optimized to guarantee quality-of-service (QoS) constraints of its served users by using the time-splitting protocol. Similar systems are presented in [8]–[10]. More specifically, in [8], a laser-powered UAV is considered as a decode-and-forward relay and the energy efficiency of the network is optimized, while in [9], a power-splitting method is proposed to guarantee that the ABS has enough energy to multicast to multiple ground RF users. Next, in [10], a novel method is considered for the UAV's relaying strategy, adding an option to store data on the UAV and transmit at a later time. In [11], a laser-powered ABS is considered and the joint power and bandwidth allocation and placement problem is formulated aiming at the maximization of the rate, while in [12], an ABS that adopts SLIPT is considered with emphasis on studying a modulation that further enhances energy efficiency adjusted to the particularities of such systems.

Different from conventional ground base stations (GBSs), the proper utilization of ABSs depends on their flight time, which in turn depends on their design, their battery capacity, as well as their payload [13], [14]. Specifically, the limited power of the ABSs is used primarily for hovering and moving, in addition to the required power for communication purposes. In [15], the battery lifetime of UAVs is addressed in more detail. Also in [16], the hovering and propulsion are taken into account, as well as the energy consumption concerning communication, and an optimization problem is formulated to enhance the energy efficiency of the system. Additionally, the payload of the ABS has to also include the SLIPT receiver. More specifically, to facilitate a SLIPT link between an ABS and a GBS, the UAV is equipped with an adequately sized solar panel, whose area is intrinsic to the amount of energy that can be collected at the ABS side. However, a careless increase in the solar panel size can potentially increase its weight to a degree that the lifetime of the ABS is severely affected, ensuing in a trade-off between the energy collected at the solar panel and the required energy spending of the ABS for the increased payload. On the other hand, the amount of harvested energy reduces as the required data rate of ground-to-air (G2A) link increases. To the best of the authors knowledge, the interdependence among the data rate, the ABS lifetime, and the energy consumption has not been explored in SLIPT-enabled aerial radio access networks.

To that end, our contribution is as follows: First, a practical energy conumption model of the ABS is presented, which highlights the effects of the solar cell size in the operation of the ABS. Following that, the energy efficiency, i.e., the number of delivered bits per joule of consumed energy at the ABS, is optimized based on the solar cell size. On top of that, the SLIPT link parameters are jointly optimized to guarantee optimal performance based on the DC-bias and AC-amplitude of the SLIPT waveform. Finally, the simulation results offer very interesting remarks on the operation of the SLIPT-enabled ABSs and should be carefully taken into account in the design of such systems.

II. System Model

We investigate the link between an ABS and a GBS through SLIPT. The ABS is considered to be a UAV equipped with transmitter (Tx) and receiver (Rx) circuits as well as a solar cell to facilitate the use of SLIPT, as shown in Fig. 1. We take into account the power consumption of the components of the UAV and the weight of the solar cell. The goal is to determine the effect of the solar cell size on the total data transmitted during a single flight. A directive SLIPT link is considered between the GBS and the ABS. Moreover, it is noted that the harvested energy depends on the average optical received power, the DC component, while the information transmission depends on the difference between maximum and average power levels, i.e., the AC component. Safety guidelines require the maximum power to be constrained.

A. Channel Gain

Directive optical wireless links through the atmosphere are hindered by various effects. First of all, the path loss attenuation the beam experiences due to traversing the atmosphere is considered as $h_l = \exp(-vz)$, according to the Beers-Lambert law, where v is the weather dependent attenuation and z is the link distance. Moreover, the geometric loss due to beam spreading and pointing errors can be approximated as

$$h_p = (\mathrm{erf}(\phi))^2 \exp\left(-\frac{2a^2}{w_z}\right), \tag{1}$$

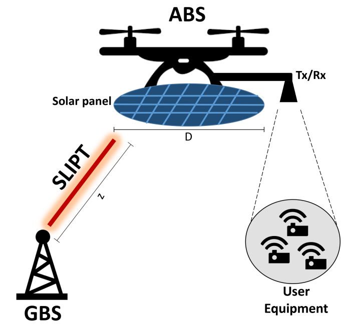

Fig. 1: System Model

where $\mathrm{erf}(\cdot)$ is the error function, $\phi = \frac{\sqrt{\pi}D}{2\sqrt{2}\theta_T z}$, and $w_z = (\theta_T z)^2 \frac{\sqrt{\pi}\mathrm{erf}(\phi)}{2\phi\exp(-\phi^2)}$ with D being the aperture diameter and θ_T being the optical beam's divergence. Without loss of generality, we consider independent identical Gaussian distributed random variables for the random elevation and horizontal displacement of the ABS, therefore a follows a Rayleigh distribution with a scale parameter σ_s. Finally, to account for the atmospheric turbulence or scintillation, h_a is considered as a random variable that follows the Gamma-Gamma ($\Gamma\Gamma$) distribution. The parameters α and β of the $\Gamma\Gamma$ distribution are calculated based on [4], [17] and they are dependent on the atmospheric conditions. Finally, the total channel gain is given by

$$h = h_l h_p h_a. \tag{2}$$

B. Communication Capacity

The received message at the UAV can be derived from the photocurrent at the solar cell, which is given as

$$i_r = \rho h P_{\mathrm{opt}} + n = \rho h (A_o m(t) + B_o) + n, \tag{3}$$

where ρ is the detector's responsivity, $m(t)$, with $\mathbb{E}[m(t)] = 0$ and $\mathbb{E}[m^2(t)] = 1$, is the message transmitted by the receiver with optical power A_o, B_o is the DC bias, and n is the additive white Gaussian noise (AWGN) at the receiver. The DC part of the received optical power is used for energy harvesting, whereas the AC part is used for the information transmission, according to the principle of SLIPT [18]. Moreover, due to the transceiver structure, which is given as an intensity modulation/direct detection (IM/DD) scheme, the information capacity of the SLIPT link is lower bounded by

$$R = B\log_2\left(1 + \frac{\gamma}{2\pi e}\right), \tag{4}$$

where γ is the signal-to-noise-ratio at the receiver, given by

$$\gamma = \frac{(\rho h A_o)^2}{\sigma^2} \tag{5}$$

with B and σ^2 being the available optical bandwidth and the variance of the background noise, respectively.

C. Energy Harvesting Model

In order to express the harvested energy at the solar cell, the electrical equivalent circuit is utilized. Hence, the I-V characteristic, where I and V denote the output current and is the voltage across the output terminal, respectively, is given by [7], [18]

$$I = I_L - I_0 \left(\exp\left(\frac{V + IR_s}{\eta V_T} \right) - 1 \right) - \frac{V + IR_s}{R_{\text{SH}}}, \quad (6)$$

where V_T is the thermal voltage, I_0 is the dark saturation current of the solar cell, R_s is the series resistance, η is the diode ideality factor of the cell, R_{SH} is the shunt resistance, and I_L is the photocurrent generated at the solar cell due to the DC bias B_o of the received optical power, which is given by

$$I_L = \rho h B_o. \quad (7)$$

Then, to calculate the maximum power point for the energy harvesting, the fill factor (FF) of the solar cell is utilized, which is a measure of the quality of the cell [7]. With this, the harvested power can be expressed as

$$P_H = F I_{\text{sc}} V_{\text{oc}}, \quad (8)$$

where F denotes the FF, I_{sc} denotes the short circuit current, and V_{oc} is the open circuit voltage. For high quality solar cells, the assumption of low R_s and I_0 can be made. Following that, I_{sc} and V_{oc} can be respectively expressed as

$$I_{\text{sc}} = I_L \quad (9)$$

and

$$V_{\text{oc}} = \eta V_T \ln \left(1 + \frac{I_L}{I_0} \right). \quad (10)$$

D. ABS Energy Consumption Model

The lifetime of a SLIPT-powered ABS depends on the available battery energy of the UAV E_b at any given moment, the power consumption P_c and the harvested power P_H. Therefore, it can be calculated as

$$L_t = \frac{E_b}{P_c - P_H}, \quad (11)$$

where the total consumed power P_c is defined as

$$P_c = P_{\text{thr}} + P_{\text{tx/rx}} + P_{\text{circ}}. \quad (12)$$

Regarding $P_{\text{tx/rx}}$, it is assumed as a flat cost for the battery for the communication transmissions as well as the navigational communication of the UAV. The term P_{circ} refers to the consumed power due to the circuitry. Finally, the power for the UAV thrust, P_{thr} is the prevalent factor as far as energy consumption is regarded and it includes the required power for hovering, transiting, counteracting wind drag, etc. To provide a more realistic model, we employ state-of-the-art off-the-self motors for the UAV. Based on the motors' datasheet [19], the behavior of the consumed power for thrusting, given a total weight W, can be reliably characterized by the following equation

$$P_{\text{thr}} = 10.5W^2 - 46W + 744, \quad (13)$$

where W is given by

$$W = U_w + B_w + \text{SC}_w + S_w + D_w, \quad (14)$$

that includes the following weights, U_w is the weight of the UAV frame, B_w is the weight of the battery, $\text{SC}_w = A_{\text{sc}} \rho_{\text{sc}}$ is the solar cell weight given as a function of the area of the panel A_{sc} and the area density ρ_{sc}. Moreover, the extra weight added to the motors due to any change in the velocity of the UAV is given by

$$S_w = (T_{\max} - U_w - \text{SC}_w) \frac{S}{S_{\max}}, \quad (15)$$

where $T_{\max}$ is the maximum achievable thrust, S is the average UAV velocity, and $S_{\max}$ is the maximum achievable UAV velocity. Finally, D_w is the extra thrust needed by the motors to counteract the wind drag, given by

$$D_w = \frac{\rho_{\text{air}} v_a^2 C_d A_{\text{sc}}}{2g}, \quad (16)$$

where ρ_{air} is the air density, g is the gravity acceleration, v_a is the average wind velocity, and C_d is the drag shape coefficient.

III. Energy Efficiency Optimization

In general, the proper utilization of an ABS requires energy efficient use of the UAV. To this end, similarly to [1], the energy efficiency of the SLIPT-enabled ABS is considered as the number of bits delivered to the ABS over the energy consumption of the ABS.

A. Problem Formulation

The energy efficiency $\mathcal{E}$ is given by

$$\mathcal{E} = \frac{R}{P_{\text{thr}} + P_{\text{tx/rx}} + P_{\text{circ}} - P_H}. \quad (17)$$

It should be noted that $\mathcal{E}$ can be expressed with the help of the lifetime metric, defined in (11), and as such (17) is expressed as $\mathcal{E} = \frac{RL_t}{E_b}$.

As far as A_o and B_o are concerned, in order to operate in the linear region of the laser diode transmitter, the following constraints need to be met

$$A_o + B_o \leq I_h \quad (18)$$

and

$$B_o - A_o \geq I_l, \quad (19)$$

where I_h and I_l denote the highest and lowest allowed currents to ensure the transmitter's operation in the linear region.

In order to maximize energy efficiency in the system, the optimal size of the solar cell panel is found, assuming its area is given with regards to the diameter D as $A_{\text{sc}} = \pi(D/2)^2$. Moreover, to guarantee the performance of SLIPT in any case, DC bias optimization is required, so in turn the parameters A_o and B_o of the transmission are also taken into account. The joint optimization problem for the design of an energy efficient SLIPT system is formulated as follows:

$$\begin{aligned} \max_{D, A_o, B_o} \quad & \mathcal{E} \\ \text{s.t.} \quad & \text{C}_1 : A_o + B_o \leq I_h, \\ & \text{C}_2 : B_o - A_o \geq I_l. \end{aligned} \quad (20)$$

Problem (20) is non-convex, mainly due to the highly complicated expressions of the rate and the harvested power with regards to the diameter D of the solar cell. On top of that, R also includes the term A_o squared in a logarithm, which also contributes to the non-convexity of problem (20). Due to this condition, problem (20) is difficult to track and solve in polynomial time. As such, we propose the following method to obtain a solution for the problem.

B. Proposed Solution

It should be noted that the energy efficiency depends on all variables A_o, B_o, D, which are subjected to two linear constraints. Despite the small number of optimization variables, there is no obvious way to transform the problem into a convex one, since the expression of $\mathcal{E}$ is highly complicated. First, we employ a searching algorithm over the feasible sets of variables. Following that, and since problem (20) is bounded by two linear constraints, we propose a projection algorithm for the feasible region, defined by those constraints. Finally, combining the search algorithm and the projection algorithm in an alternating fashion, problem (20) is solved.

For two values $A_{o,d}$ and $B_{o,d}$ the projection problem onto the feasible set is formulated as:

$$\begin{aligned} \min_{A_o,B_o} \quad & (A_o - A_{o,d})^2 + (B_o - B_{o,d})^2 \\ \text{s.t.} \quad & \mathrm{C}_1 : A_o + B_o \leq I_h, \\ & \mathrm{C}_2 : B_o - A_o \geq I_l. \end{aligned} \tag{21}$$

The problem is convex and thus can be solved easily by any standard convex optimization method. Nonetheless, in this case, a closed form solution can be derived. The Lagrangian of the problem is given as

$$\begin{aligned} \mathcal{L} = & (A_o - A_{o,d})^2 + (B_o - B_{o,d})^2 \\ & + \lambda_1 (A_o + B_o - I_h) + \lambda_2 (A_o - B_o + I_l). \end{aligned} \tag{22}$$

Since the projection problem is convex, the Karush-Kuhn-Tacker conditions are necessary and sufficient condition for the optimal point of (21) to exist. Then, we have

$$\frac{\partial \mathcal{L}}{\partial A_o} = 0 \Leftrightarrow A_o = \frac{2A_{o,d} - \lambda_1 - \lambda_2}{2}, \tag{23}$$

$$\frac{\partial \mathcal{L}}{\partial B_o} = 0 \Leftrightarrow B_o = \frac{2B_{o,d} - \lambda_1 + \lambda_2}{2}. \tag{24}$$

In this problem, constraint C_1 will hold with equality, since the maximum allowed values of both A_o and B_o are needed to maximize the energy efficiency, as it is defined in (17). In more detail, a higher value of A_o leads to the maximization of the data rate, while a higher value of B_o leads to the maximum harvested energy, which in turn lowers the denominator in (17), thus increasing the total energy efficiency of the system. Therefore, due to the complementary slackness condition [20], it holds that $\lambda_1^* > 0$. Consequently, two cases related to constraint C_2 are studied.

Case 1: If constraint C_2 holds with equality, i.e., $B - A = I_l$, the projection algorithm is trivial, due to being a system of two equations and two variables. As such, the optimal values of A_o, B_o are

$$A_o = \frac{I_h - I_l}{2}, \tag{25}$$

$$B_o = \frac{I_h + I_l}{2}. \tag{26}$$

Case 2: If constraint C_2 holds with inequality, from the complementary slackness it follows that $\lambda_2 = 0$. As such, A_o and B_o are given as

$$A_o = \frac{2A_{o,d} - \lambda_1}{2}, \tag{27}$$

$$B_o = \frac{2B_{o,d} - \lambda_1}{2}. \tag{28}$$

It should be highlighted that for given values of $A_{o,d}$, $B_{o,d}$ and for $\lambda_2 = 0$, C_2 holds strictly with inequality, when $B_{o,d} - A_{o,d} > I_l$. Also, due to constraint C_1, the following needs to hold:

$$A_o + B_o = I_h \Rightarrow \lambda_1 = A_{o,d} + B_{o,d} - I_h. \tag{29}$$

Finally, the optimal projected values of $A_{o,d}$ and $B_{o,d}$ are given as

$$A = \frac{I_h + A_{o,d} - B_{o,d}}{2}, \tag{30}$$

$$B = \frac{I_h + B_{o,d} - A_{o,d}}{2}. \tag{31}$$

The projection algorithm is summarized in Algorithm 1.

Algorithm 1 Proposed Projection Algorithm

input $A_{o,d}, B_{o,d}, I_h, I_l$
$A_{o,d} = [A_{o,d}]^+$, $B_{o,d} = [B_{o,d}]^+$
if $B_{o,d} - A_{o,d} > I_l$ **then**
  $A \leftarrow \left[\frac{I_h + A_{o,d} - B_{o,d}}{2}\right]^+$
  $B \leftarrow \left[\frac{I_h + B_{o,d} - A_{o,d}}{2}\right]^+$
else
  $A \leftarrow \frac{I_h - I_l}{2}$
  $B \leftarrow \frac{I_h + I_l}{2}$
end if

The original non-convex problem (20) can now be solved by searching the feasible set of variables B_o and D and using Algorithm 1. The algorithm for solving problem (20) is described in Algorithm 2.

IV. Numerical Results and Discussion

In this section, numerical results for the considered SLIPT-enabled ABS are provided, which highlight the importance of the considered parameters in the system performance and validate the effectiveness of our proposed scheme. More specifically, for the ABS, we have considered a UAV with four motors (quadcopter) with a power consumption that is characterized by (13). The size of the UAV frame, that affects the rest of the UAV parameters, is carefully selected to be

Algorithm 2 Solution of (20)

input I_h, I_l, channel parameters, harvesting parameters
for $D = 0 : D_{\max}$ **do**
  for $B_{o,d} = I_l : I_h$ **do**
    $A_{0,d} \leftarrow 0$
    $(A_o, B_o) \leftarrow$ Algorithm $1(A_{o,d}, B_{o,d})$
    if $\mathcal{E}(A_o, B_o, D) > \mathcal{E}^*$ **then**
      $\mathcal{E}^* \leftarrow \mathcal{E}(A_o, B_o, D)$
      $A_o^* \leftarrow A_o, B_o^* \leftarrow B_o, D^* \leftarrow D$
    end if
  end for
end for
optimal values are given by A_o^*, B_o^*, D^*

TABLE I: ABS parameters.

Parameter	Value	Parameter	Value
E_b	276 Wh	B_w	2.46 kg
U_w	8 kg	P_{circ}	0.2 W
P_{txrx}	1 W	$T_{\max}$	22 kg
$S_{\max}$	45 km/h	S	0 km/h
ρ_{air}	1.225 kg/m^3	v_a	2.5 m/s
C_d	0.005	UAV radius	3 m

able to lift all the different sized solar panels employed in our simulations, both in terms of weight and area. Unless otherwise stated, the UAV parameters are found in the Table I.

TABLE II: Simulation parameters.

Parameter	Value	Parameter	Value
I_l	0	I_h	10^4
ρ_{SC}	0.5 kg/m^2	SC_w	$\rho_{\text{SC}} A_{\text{sc}}$
B	10^9 Hz	θ_T	2.5 mrad
z	0.5 km	λ	1550 nm
σ^2	10^{-11} A^2	η	1
V_T	25 mV	I_0	10^{-9} A
ρ	0.2 A/W	F	0.7
a_F^{clear}	0.43 dB/km	C_n^{clear}	5×10^{-14}
a_F^{haze}	4.3 dB/km	C_n^{haze}	1.7×10^{-14}

Next, we present the results obtained from Monte Carlo simulation over random values of h. The results aim at validating, at first, the relationship between the energy efficiency and the size of the solar panel. Then, the proposed scheme is evaluated for different kinds of weather. For clarity, the system's parameters are summarized in Table II. To illustrate in greater detail the perks of the proposed scheme, it is compared with an identical system that omits the DC bias optimization and aims at maximizing its capacity and an identical system, but the ABS is not equipped with an energy harvesting receiver. The latter is effectively an FSO system. The results prove the effectiveness of our analysis as the increase in energy efficiency is significant.

More specifically, in Fig. 2, the energy efficiency is plotted with regards to the diameter of the solar panel. As it can clearly be seen, the diameter plays a very important role in the resulting energy efficiency, with the proposed scheme boasting an increase of around 17% over the rest of the schemes. It seems that, while in all schemes there is a point at which the solar panel becomes too heavy for its use, the optimized scheme is able to withstand a larger panel and enjoy its perks thanks to its efficient use of SLIPT.

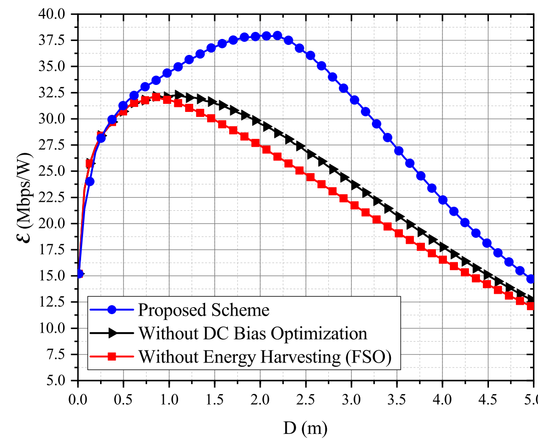

Fig. 2: Energy efficiency with regards to the size of the receiver for clear weather and $z = 0.5$km.

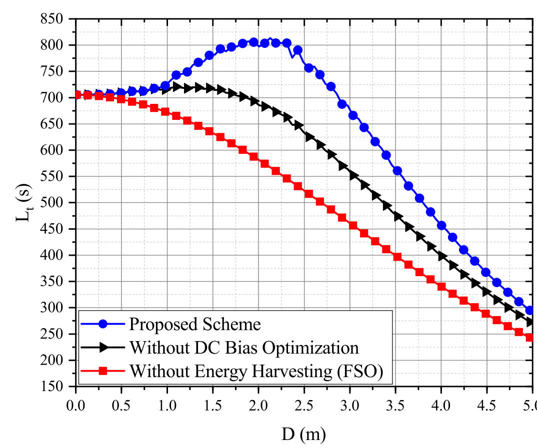

Fig. 3: Lifetime with regards to the size of the receiver for clear weather and $z = 0.5$km.

Similarly, the lifetime of the ABS is plotted with regards to the diameter of the receiver in Fig. 3. As it is expected, the proposed scheme is able to increase the lifetime of the ABS by over 10% of the rest of the schemes.

Finally, in Fig. 4, the energy efficiency of the proposed scheme is illustrated with regards to the link distance. The superiority of the proposed method is clearly observed, especially in shorter distances, where it offers more than a 20% increase over the next best scheme at 250 m link distance. To quantify the performance gain in a different way, the performance of the proposed scheme at $z = 750$ m is the

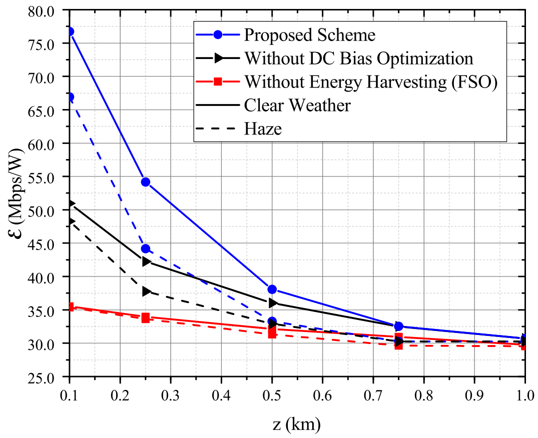

Fig. 4: Energy efficiency with regards to the link distance.

same as the benchmark at $z = 500$ m, showing that the design and transmission optimization of the SLIPT system can greatly increase the coverage of a single ABS.

V. Conclusions

In this paper, we have investigated and optimized a SLIPT-enabled ABS system. Specifically, utilizing a practical energy consumption model, we have defined the energy efficiency of the considered ABS system taking into account the harvested power through SLIPT. Following that, we have formulated an optimization problem aiming at the maximization of the energy efficiency, by jointly optimizing the solar cell size and the SLIPT link parameters, i.e., the DC-bias and the AC-amplitude of the SLIPT waveform. Because of the non-convex nature of the problem, we have employed a search and a projection algorithm to solve it in an alternating fashion, while providing a closed-form solution for the projection problem. Simulations have illustrated the value of such design optimization, as the size of the panel greatly influences the energy efficiency of the ABS. Finally, the obtained optimal values for the size can be used to choose a practical value of diameter to cover for a range of link distances that the ABS can operate.

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