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On the Use of Lightwave Power Transfer in Miniaturized Satellite Communication Systems

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***Abstract*—CubeSats have a significant impact on the satellite communications sector due to their ability to provide rapid, cost-effective, and adaptable improvements to existing satellite networks or to individual missions. The main challenge facing CubeSats is their energy sustainability. Towards this end, we are considering lightwave power transfer (LPT) technology from larger satellites in low earth orbit (LEO) as an alternative power source for CubeSats. We propose a strategy that includes a CubeSat satellite which harvests energy and communicates with a ground base station, utilizing the harvested energy. We formulate an optimization problem for the proposed strategy, aiming to maximize the total harvested energy. Simulation results validate the usefulness of our approach when considering practical assumptions about the satellite orbits.**

***Index Terms*—CubeSats, Lightwave Power Transfer (LPT), Satellite Network**

I. INTRODUCTION

To meet the urgent demands for global coverage and high-data rates with low delay, the integration of space and terrestrial networks (ISTN) was proposed [1]. In an effort to reduce costs, minimize spacecraft's size, and enhance the quality of provided services, generations of small and lightweight satellites, such as CubeSats, have become particularly attractive. CubeSats are compact modular satellites modeled after the standard CubeSat unit (1U), characterized by a cube-shaped structure with each side measuring 10 cm [2], [3]. The flexibility of this modular design enables the creation of spacecraft with consistent shapes and sizes, spanning from 1U to 16U. Prominent use cases for CubeSats include engagements in space science experimentation, monitoring of environmental conditions, and communication activities. Furthermore, the maintenance attributes and utilization of commercially available off-the-shelf (COTS) components [4] facilitate expeditious replacement or restoration in instances of operational anomalies or catastrophic events.

Despite having notable benefits, CubeSats face significant obstacles in their energy efficiency due to specific constraints. The constraints posed by limited space for solar panels result in a hindered ability to efficiently harness solar energy. At the same time, due to their size, they cannot be equipped with large (and heavy) batteries. The sensitivity of commonly used lithium-ion batteries [5] to atmospheric conditions in space further complicates the energy equation. These challenges highlight the need for innovative solutions to enhance power generation and management capabilities, ensuring the sustainability and effectiveness of CubeSat missions. As such, the advancement of solar cells [6], exploration of alternative energy sources, and enhancements in battery characteristics [7] constitute pivotal research areas for CubeSat development. Moreover, the proposition of deploying sophisticated energy management systems and the advancement of materials with resilience to the exigent conditions of space emerge as prospective avenues, poised to undergo further refinement in the future.

In this paper, we examine the alternative of lightwave power transfer (LPT) from larger LEO satellites capable of generating substantial energy quantities to CubeSats, utilizing laser-based technologies. Subsequently, we evaluate the quantity of energy harvested by the CubeSat satellite. To do so effectively, we consider practical orbits for the satellites, since to properly study this system the link distance between the LEO and the CubeSat heavily influences the performance of the LPT system.

II. PROPOSED SYSTEM

We consider an LPT system consisting of one satellite in low earth orbit (LEO) and one CubeSat, which communicates with a ground base station (GBS), as shown in Fig. 1.

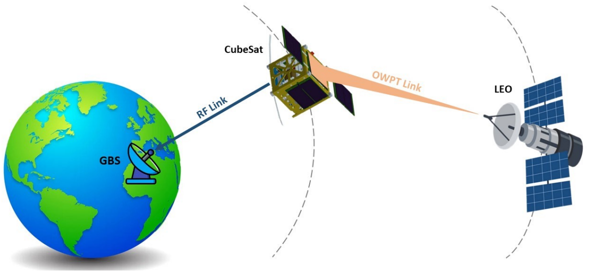

Fig. 1: Illustration of the proposed system.

Without loss of generality, the proposed system's mission is examined at discrete time intervals, during which the positions of both the satellites and the ground base station are regarded as constant. The harvested energy from the LEO is designated to empower the CubeSat functions, e.g., to enable a communication link with the GBS. A directive line-of-sight link is considered for LPT [8].

The amount of energy required by a LEO for its operations can vary depending on factors such as the satellite's size, the type of the mission it performs and the efficiency of its systems. As stated in [9], depending on their size, LEOs have the capability to generate significant power levels. The capability to support LPT to the CubeSat is made possible by the fact that generated energy frequently surpasses the requisite energy. The excess energy for a given observation time can be approximated by

$$E_{\mathrm{T}} = P_{\mathrm{g}} T_{\mathrm{T}} a k, \tag{1}$$

where P_{g} represents the average power generated by the LEO's solar panels, T_{T} is the observation time during which the LPT process takes place, a is the percentage of the LEO's excess energy and k is the percentage of time within the sun and the satellite are in line of sight.

As previously mentioned, we assume that satellites' and GBS' positions change at steady intervals t. Within each time interval, in conjunction with the stabilized state of the satellites and the GBS, we make the assumption of a consistent transmission power, and consequently, a constant received power. First, we must take into consideration that the energy allocated for transmission is limited, in accordance with the following constraint

$$t \sum_{n=1}^{N} P_{\mathrm{tl},n} \leq E_{\mathrm{T}}, \tag{2}$$

where $P_{\mathrm{tl},n}$ is LEO's transmission power, constrained also by a maximum value $P_{\mathrm{tl,max}}$, which varies based on the satellite's equipment and the specific mission requirements [9] and N denotes the count of time intervals t within the observation time T_{T} and is calculated as

$$N = \frac{T_{\mathrm{T}}}{t}. \tag{3}$$

The received power at the CubeSat is then given by [9], [10]

$$P_{\mathrm{rc},n} = \frac{4 P_{\mathrm{tl},n} A_{\mathrm{R}} \tau_{\alpha} \tau_{\tau} \tau_{\mathrm{R}}}{\pi d_{\mathrm{n}}^2 \phi^2}, \ \forall n \in \{1, 2, \ldots, N\} \tag{4}$$

where A_R is the effective receiver aperture area, τ_α is atmosphere transmissivity, τ_T is transmitter transmissivity, τ_R is receiver transmissivity and d_n is the distance between the LEO and the CubeSat. It is imperative to accentuate that during intervals devoid of optical line of sight, the transmission power $P_{\mathrm{tl},n}$ and, by extension, the received power $P_{\mathrm{rc},n}$ are equal to zero. Regarding the divergence angle $\phi = \mathrm{SpotSize}/\mathrm{Range}$, the term $\mathrm{SpotSize}$ represents the diameter, approximately matching the length of the CubeSat's edge, and the term Range is the path length between the transmitter and the receiver.

The CubeSat can leverage the proposed LPT without requiring modifications to their electrical or electronic systems, utilizing their existing panels [9]. Finally, the harvested energy for each t is calculated as

$$E_{\mathrm{H},n} = \eta t P_{\mathrm{rc},n}, \tag{5}$$

where η is the efficiency of the CubeSat's panels.

III. MISSION ANALYSIS AND PROPOSED STRATEGY

In this subsection, we present the proposed strategy which examines the process of LPT, given the orbits of the satellites. Before delving into the analysis, we go through our assumptions. Initially, we assume that the CubeSat utilizes its solar panels to collect additional energy from the sun. This energy is stored in the primary battery, presumed to sufficiently meet the remaining energy needs of its subsystems. Moreover, a dedicated secondary battery is assumed for the LPT process, with E_{b} representing its energy storage capacity.

Pursuing the reliability and repeatability of the results, it is necessary to ensure the periodicity of the mission. One of the factors that characterizes the periodicity of the mission is the phenomenon period T_{P}. This refers to the time required for both satellites and the GBS in order to return to their original positions simultaneously for the first time and it's calculated by exploiting the periodicity of their orbits. As regards the satellites, assuming that they perform circular orbits, their orbital period is calculated as [11]

$$T = 2\pi \sqrt{\frac{r^3}{\mu}}, \tag{6}$$

where μ represents the Kepler constant and r the distance of each satellite from the center of the earth. Conversely, with respect to the GBS, its period coincides with that of the Earth. With regard to the satellites' positions, periodicity is ensured by selecting the time period for the execution of the proposed strategy, to be equal to integer multiple of the phenomenon period. Regarding the CubeSat's battery, periodicity is ensured by setting the level at both the beginning and the end of the mission time equal to E_0. It is also worth noting that, at the start of the mission, the LEO's surplus energy must be at least equal to the energy that will be in excess during each phenomenon period.

In this strategy, the mission duration spans two phenomenon periods. The CubeSat harvests LEO's excess energy during the first phenomenon period and during the second period, it communicates with the GBS. While the mission commences with the battery initialized to zero level, it is crucial to ensure that the battery level at each time interval t, does not exceed the value of E_{b}. Also, without loss of generality, we assume that during the second period, the whole harvested energy has been used up. We examine the LPT system only and the received power $P_{\mathrm{rg},n}$ is calculated using (4), $\forall n \in \{1, 2, \ldots, N\}$, considering the constraint (2). Then, the optimization procedure is expressed as follows

$$\begin{aligned} \max_{\mathbf{P}_{\mathrm{tl}}} \quad & \textstyle\sum_{n=1}^{N} E_{\mathrm{H},n} \\ \text{s.t.} \quad & \mathrm{C}_1 : 0 \leq P_{\mathrm{tl},n} \leq P_{\mathrm{tl,max}}, \ \forall n \in \{1, N\}, \\ & \mathrm{C}_2 : t \textstyle\sum_{n=1}^{N} P_{\mathrm{tl},n} \leq E_{\mathrm{T}}, \\ & \mathrm{C}_3 : \textstyle\sum_{n=1}^{N} E_{\mathrm{H},n} \leq E_b. \end{aligned} \tag{7}$$

In order to simulate and analyze the orbits of the two satellites and the position of the ground station during the mission, we employ the general mission analysis tool (GMAT) software. The GMAT is an open-source software used for the design, optimization and navigation of space missions. It enable us to initially define the behavior of the two satellites and the ground station, as well as extract data throughout the mission.

Initially, we define the Keplerian parameters of the satellites and the ground station's geographic coordinates. Through the program, we extract the Cartesian coordinates of these at discrete equidistant time intervals t, considering the center of the Earth as the origin of the coordinate system. Using these coordinates and utilizing the Matlab software, we examine the existence of visual contact and calculate the distance between the LEO satellite and the CubeSat.

Following that, we solve the optimization problem in (7), which is convex, and as such, it can be solved through efficient methods such as the interior-point algorithm. The methodology for simulating the trajectories and conducting the optimization is succinctly depicted in Fig. 2.

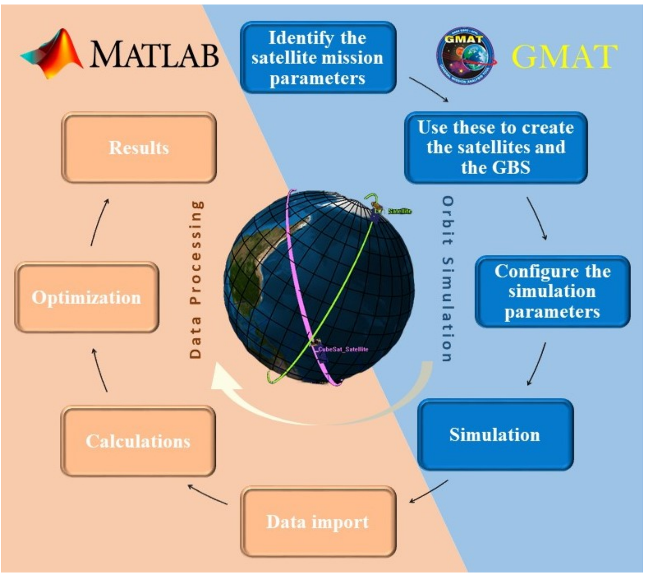

Fig. 2: The methodology of conducting the simulation of the proposed system.

IV. Simulations Results and Discussion

In this section, we present results from simulations of the proposed system for different CubeSat trajectories. The satellites' Keplerian parameters are summarized in Table I. Alongside the proposed strategy, a benchmark is also shown that instead of the optimal solution, allocates the same equal power at each interval.

TABLE I: Keplerian parameters

Parameters	CubeSat values	LEO values
Semi-Major Axis [km]	6932, 7258, 7626	8044
Eccentricity	0	0
Inclination [deg]	52	98
RAAN [deg]	0	0
Argument of Perigee [deg]	0	0
True Anomaly [deg]	0	0

The path that the satellites follow on the Earth's surface as they orbit for a phenomenon period, is depicted in Fig. 3. The time step is t = 200 sec. At these times, the line-of-sight distance between the LEO and the CubeSat is given in Fig. 4 for different values of the CubeSat's semimajor axis (SMA), a common way to describe the orbits size. Table III details the count of temporal intervals of line of sight for the LPT link.

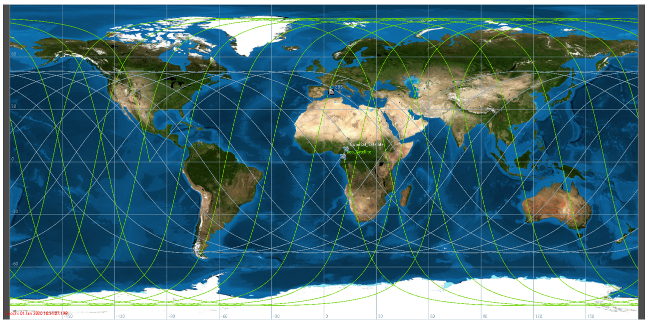

Fig. 3: Ground track of both satellites for a phenomenon period.

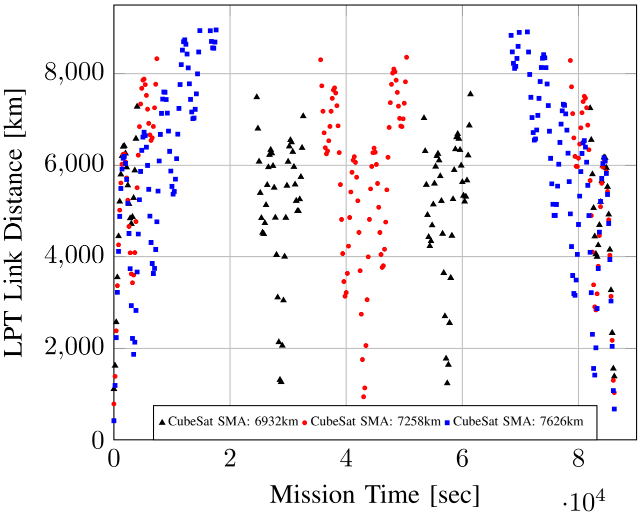

Fig. 4: Line-of-sight distance at LPT link during the mission time.

The results aim at investigating the amount of CubeSat's harvested energy, through the optimal utilization of the proposed strategy. For clarity, the considered system's parameters are summarized in Table II.

TABLE II: System parameters

Variable	Value	Variable	Value
k	100%	η	20%
a	5%	T_{Cb}	5743.8, 6154.57, 6628 sec
$P_{\mathrm{tl,max}}$	10 W	T_{l}	7180.34 sec
A_R	0.01	T_{P}	86164.09 sec
τ_α	1	ϕ	0.1 μrad
τ_T	0.85	E_0	0 Wh
τ_R	0.85	E_{b}	1.66 Wh

TABLE III: System's details

CubeSat SMA [km]	6932	7258	7626
Optical Contact Intervals	125	152	165

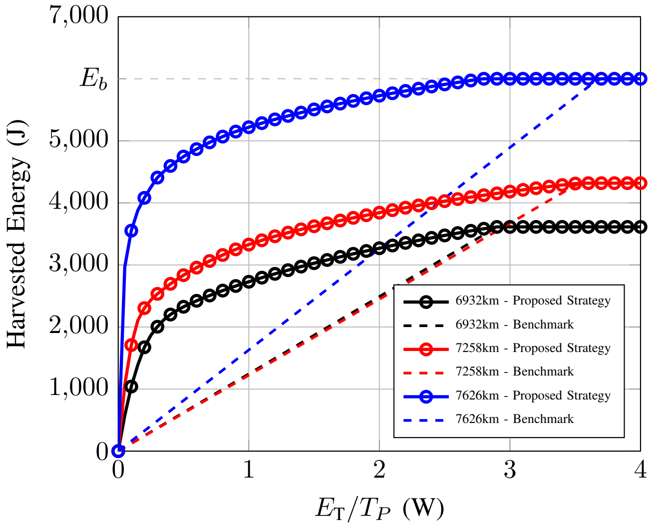

Fig. 5: Harvested energy in a mission time for different values of the average available power of LEO E_{T}/T_P.

In Fig. 5, the CubeSat's total harvested energy at the end of the first phenomenon period is depicted. The analysis is conducted for different values of the LEO's average available power and for three CubeSat SMA values. It can be observed that, by increasing the LEO's average available power, the total harvested energy increases for each SMA value until the curves reach a ceiling. In reference to the two lowest SMAs, this bottleneck depends on the number of time intervals of optical contact. Beyond a certain point, the available energy permits maximum power transmission during all optical contact intervals. Regarding the highest SMA, pictured with the blue curve, the attainment of the ceiling is caused by the battery's limited capacity. The superiority of the proposed strategy is evident for the three different values of CubeSat SMA due to the optimal power allocation. To emphasize this, Fig. 6 illustrates the percentage improvement between the proposed strategy and the benchmark in the performance of the system. Furthermore, it is noted that the curves corresponding to different SMA values follow a specific order in terms of the quantity of harvested energy. By also observing Fig. 4, slight differences in distances between the three SMA values are noted. Thus, the variance in the collected energy is primarily attributed to the number of time intervals of optical contact, depicted in Table III.

V. CONCLUSION

In this paper, an LPT system between a LEO satellite and a CubeSat was proposed and optimized based on the orbits of both satellites. In this way, the CubeSat can obtain sufficient energy to utilize for communicating with a GBS. Through the proposed strategy, the transmitted power from the LEO was optimized given the orbits to efficiently transfer the maximum amount of power to the CubeSat. Simulation results validated the effectiveness of the strategy, which clearly outperforms a benchmark that does not take into consideration how the satellite orbits affect the LPT.

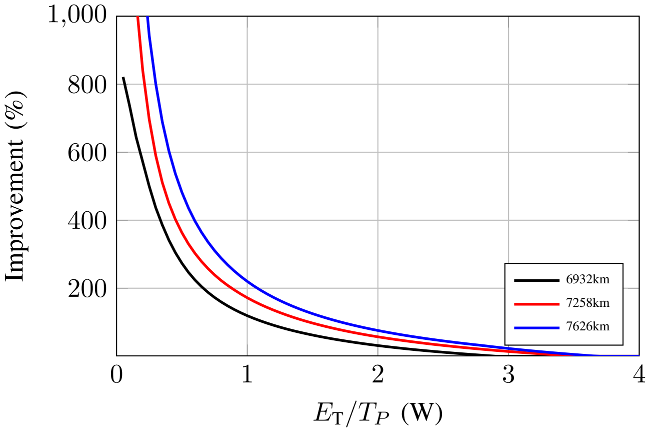

Fig. 6: Percentage improvement between proposed strategy and benchmark for three CubeSat SMA values.

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