A Multidisciplinary Approach to Optimal Communication and Flight Operation of High Altitude Long Endurance Platform

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Abstract—Aerial communication platforms especially stratospheric high altitude pseudo-satellite (HAPS) has the potential to provide/catalyze advanced mobile wireless communication services with its ubiquitous connectivity and ultra-wide coverage radius. Recently, HAPS has gained immense popularity - achieved primarily through self-sufficient energy systems - to render long endurance characteristics. The photo voltaic cells mounted on the aircraft harvest solar energy during the day, which is partially used for communication and station keeping, whereas, the excess is stored in the rechargeable batteries for the night time operation. We carried out an adroit power budgeting to ascertain if the available solar power can simultaneously and efficiently self-sustain the requisite propulsion and communication power expense. We propose an energy optimum trajectory for station-keeping flight and non-orthogonal multiple access (NOMA) for users in multicells served by the directional beams from HAPS communication system. We design optimal power allocation for downlink (DL) NOMA users along with the ideal position and speed of flight with the aim to maximize sum data rate during the day and minimize power expenditure during the night while ensuring quality of service. Our findings reveal the significance of joint design of communication and aerodynamics parameters for optimum energy utilization and resource allocation.

Index Terms—Non-orthogonal multiple access, unmanned aerial vehicles, high-altitude platform systems, internet-of-things, 6G, downlink.

I. INTRODUCTION

Unmanned high altitude long endurance platforms are promising and versatile candidates for the upcoming generations of wireless communication. They can provide universal coverage with dedicated/shared broadband connectivity offering numerous use cases including greenfield coverage, internet of things (IoT), fixed wireless access/catastrophe management, public/private connectivity, and terrestrial backhaul [1]. Recent advances in communications technologies, solar panel efficiency, lightweight composite materials, autonomous avionics and antenna beamforming are the prime enablers behind HAPS [2]. A solar powered HAPS can cruise in specific station keeping trajectory for several months owing to favorable conditions in the lower stratosphere e.g., high solar radiance, minimal weather disturbance, mild turbulence and low wind speed [3].

The perks of aerial communication over satellites to fulfill ever-increasing communication demands and limitations of the existing terrestrial networks are the main motivations behind the HAPS. The key feature of the HAPS include seamless merger with the existing communication infrastructure, no special requirements on the operational spectrum/user equipment (UE), ability to adjust and prioritize capacity or coverage, quick deployment, easy maintenance/up-gradation, and scaling capabilities. HAPS offer ubiquitous connectivity and ultra-wide coverage with low-delay characteristics, higher throughput, and minimal power requirement relative to the satellite communications [3]. Air-based mobile coverage solutions can bridge the digital divide by connecting the unconnected in sparsely populated regions and difficult terrains. We can rely on these floating base station for effective disaster management and rapid relief operation. Moreover, it can assist existing infrastructures as a relay and/or back-haul network to serve dense metropolitan areas [4].

HAPS can be realized as airborne balloons, air-crafts, or airships according to the required power and cargo capabilities [5]. Numerous contributions are presented to tackle different challenges of HAPS communication systems such as trajectory optimization, resource management, performance evaluation, and link/power budgeting [6]–[10]. A recent study suggest optimal flight trajectory of a solar powered high-altitude long endurance aircraft encompassing ascend and descend to maximize sunlight exposure and minimize power expenditure, respectively, according to the time of the day [6]. Other contributions propose non-orthogonal multiple access for effective resource management over millimeter-wave frequency [7]. Another study employs steerable adaptive antenna array to continuously serve same cell users during the repetitive flight pattern over it’s coverage area [9]. Moreover, link budgeting with QPSK for varying code rates is carried out to minimize error rates and power consumption [10]. However, to the best of author’s knowledge, no contribution has jointly addressed the aforementioned aspects in a HAPS communication system.

We present a multidisciplinary approach to mutually tackle the previously mentioned challenges for optimal flight and communication operations with effective resource allocation strategies. The available energy supply, propulsion and payload power consumption and sufficient energy storage are all critical factors in the system design. We propose NOMA based multicell network along with the polygonal beam-steering antenna array [9] for ubiquitous connectivity with efficient spectrum and power management. The link budgeting provides insights like the contrasting channel gains for the users in the boresight direction and the edge users enabling the implementation of DL-NOMA in each cell. The day time allows maximum sun exposure enabling maximum available transmission power to serve numerous cellular/IoT users. On the other side, transmission and flight with minimal energy requirements is the preferred choice during night. Hence, we...
jointly optimize the flight and communication parameters to maximize sum rate and minimize power consumption while guarantying quality-of-service (QoS). We present two different algorithms for day and night time operations based on the closed-form solutions of altitude, airspeed and power factors. The HAPS continues to cruise in the circular trajectory at the derived altitude with optimal speed for a given time and then transitions to the next state while providing the DL-NOMA service link to the users with optimized power allocation. The cycle repeats everyday to ensure net energy balance greater than zero ensuring self-sustenance and long endurance.

II. SYSTEM DESCRIPTION

We consider a typical unmanned HAPS which follows a circular trajectory of diameter \(d\) with true airspeed \(V\) at an altitude \(H\) for station keeping over the desired service area as shown in Fig. 1. The stratospheric location (between 18km to 24km) of the HAPS is favorable because of minimum wind speed and suitable air density which is required for minimum propulsion power and stable flight, respectively. In addition, it enables an ultra-wide coverage area with radius from 60 km to 400 km. HAPS provides communication services to various users over the 4G LTE or 5G NR air interface via service link and backhaul to the gateway through the feeder link [9]. Solar HAPS are appealing owing to their long endurance characteristics, which can only be achieved if they collect more energy than they expend. Solar cells are mounted on the wings and stabilizers to harvest the abundant solar energy during the day for its routine operation and onboard fuel cells are utilized to store the excess energy for night time sustenance. Electrical power is consumed by the electric motors and propellers for propulsion, avionics, payload and communication equipment. The objective is to achieve ubiquitous connectivity with minimal power consumption and enhanced system performance.

A. Solar Irradiance Model

Long endurance platform solely depend on the harvested solar power for its flight and communication operations. Thus, it is imperative to adopt an accurate solar irradiance model to quantify the solar flux at the surface of the mounted photovoltaic cells. Solar flux is a measure of light energy that is being radiated at a certain area, given in \(W/m^2\). The amount of solar flux depends on the Julian day index \((j_d)\) and solar elevation \((\epsilon_s)\) angle at a given time and location [11]. The extra-terrestrial radiations undergo attenuation (due to Rayleigh scattering and molecular absorption) while traveling through the atmosphere before falling on the surface. Therefore, solar irradiance is adjusted to account for annual variation due to eccentricity of Earth’s orbit and atmospheric absorption factor \(f(H, \epsilon_s)\) as

\[
I(H, dt) = I_0 \left( 1 + 0.034 \cos \frac{2 \pi j_d(dt)}{365} \right) f(H, \epsilon_s(dt)), \tag{1}
\]

where \(I_0\) is the solar constant, \(j_d\) is the Julian day and \(f(H, \epsilon_s)\) is given as

\[
f(H, \epsilon_s(dt)) = \exp \left( -p_R(H) m_R(90^0 - \epsilon_s(dt))\alpha_{ext}(dt) \right), \tag{2}
\]

where the extinction parameter for clear atmosphere \(\alpha_{ext}(dt)\) and relative air mass \(w_R(\theta)\) are taken from [12]. The solar elevation angle \(\epsilon_s(dt)\) is computed for a given longitude \(\xi\), latitude \(\chi\) and date/time \(dt\) using the solar position algorithm [11]. For this purpose, \(\xi\) and \(\chi\) are computed from north-position, east-position, and altitude of the HAPS using WGS84 Earth model. Moreover, the relative pressure \(p_R(H) = \frac{p_{ext}}{p_0}\) at an altitude \(H\) is calculated according to the international standard atmosphere (ISA) and 1976 U.S. Standard Atmosphere (USSA) [13].

\[
p_h(H) = \begin{cases} 
p_{b1} \exp \left( -\frac{gM(H-H_{b1})}{R_h} \right) & , 11km \leq H \leq 20km \\
p_{b2} \left( \frac{T_h}{T_{b1} + \lambda(H-H_{b2})} \right)^{\frac{gM}{R_h}} & , 20km \leq H \leq 32km \end{cases} \tag{3}
\]

where pressure at mean sea level \(p_0 = 101325\text{Pa}\), base altitudes are \(H_{b1} = 11\text{km}\) and \(H_{b2} = 20\text{km}\) with base static pressures \(p_{b1} = 22632\text{.06}\text{Pa}\) and \(p_{b2} = 5474.889\text{Pa}\), respectively. Base temperature \(T_b = 216.65K\) with base temperature lapse rate \(L_b = 1\text{K/km}\), universal gas constant \(R = 8.31432\text{N.m/mol.K}\), gravitational acceleration \(g\) is 9.8\text{m/s}^2, and molar mass of Earth’s air \(M_a = 0.0289644\text{kg/mol}\). Thus, the available power harvested from direct solar irradiance during the day can be written as

\[
P_a(H, dt) = \eta_p \eta_e I(H, dt), \tag{4}
\]

where \(\eta_p\) is the power conversion efficiency of solar panels and \(A_p = \sum A_s\) is the accumulative solar panel area from \(s\) solar panels on HAPS aircraft which is perpendicular to the solar irradiance. Some part of this available power can be stored in the batteries for night time operation and the rest can be expended for hovering and communications.

B. Aerodynamics

In aerodynamics, the steady flight requires a proportional lift force \(L\) against the gravitational pull i.e., weight of aircraft \(W\) and a thrust \(T\) to balance out the drag force \(D\). This requires a certain propulsion power \(P_{pro}\) which depends on the true airspeed of HAPS \(V\) and the required thrust to maintain a steady-level flight at a given altitude \([14]\)

\[
P_{pro} = TV/\eta_p \eta_e, \tag{5}
\]

where \(\eta_p\) and \(\eta_e\) are the propeller and engine efficiencies, respectively. The drag is opposed by an equal and opposite thrust as given by

\[
T = \frac{1}{2} \rho_n V^2 S C_D = \epsilon_{w} \frac{2W^2}{\rho_n SV_T^2}, \tag{6}
\]

where the first part is against the parasitic drag and the second term opposes induced drag \([15]\). Moreover, \(S\) is the total wing area, \(C_D\) is the zero-lift drag coefficient and the coefficient \(\epsilon\) is equal to \((\pi e AR_w)^{-1}\), with Oswald’s efficiency factor \(e\) and wing aspect ratio \(AR_w\). In addition, the air density \(\rho_n\) depends on the air pressure \(p_n\) and temperature \(T_p\) at an altitude \(H\) as

\[
\rho_n = \frac{p_n(H)}{R_{sp} T_p(H)}, \tag{7}
\]
The network comprises of uniformly distributed HAPS with one center cell and $M$ reliable and consistent coverage. We assume a multicell network to be served by a single controller which are responsible to create the desired beam and steer it in real time, as detailed in [9]. This enables the controller to manage the power division within given budget. The presented system undergoes two types of interference:

- Intra-cell interference (IACI)
- Inter-cell interference (IECI) due to frequency reuse

Therefore, using the conventional wireless communication model, the received signal at user $l$ in the $m^{th}$ cell is given by

$$y_l = h_{lm}^{\text{Desired Signal}} + h_{lm}^{\text{IACI}} + h_{lm}^{\text{IECI}}$$

where $h_{lm}^{\text{Desired Signal}}$ is the channel gain coefficient between $j^{th}$ HAPS panel and $l^{th}$ user in $m^{th}$ cell and $w_l$ is the receiver thermal noise modeled as circular symmetric complex Gaussian random variable, i.e., $w_l \sim \mathcal{CN}(0, \sigma^2)$. Moreover, $J_m$ is the set of neighbouring interfering cells around $m^{th}$ cell e.g., $J_1$ is the set of all $M - 1$ cells surrounding the center cell whereas $J_{m\backslash1}$ is the set of 3 immediate neighbors around $m^{th}$ edge cell.

**D. Energy Storage**

The consistent flight operation of HAPS for long-endurance requires the energy storage of the surplus power for night time operation. The electrical energy is stored and drawn from the rechargeable batteries depending on the net power $P_{\text{net}}$, i.e.,

$$P_{\text{net}} = P_h - P_{\text{req}} - P_f,$$

where $P_{\text{net}}$ is the power remainder from the available solar power $P_h$ after meeting all the aerodynamic $P_{\text{req}}$ and communication requirements $P_f = \sum_{m} P_m$. The battery energy moves from state $E_b^{i-1}$ to state $E_b^i$ either by charging or discharging as [6]

$$E_b^i = E_b^{i-1} + \eta_b P_{\text{net}}^{i} \Delta t,$$

1The transmitted/received signals, channel gains and allocated powers are function of time. However, the time notation is omitted for brevity.
where battery efficiency $\eta_b$ is either charging $\eta_c$ or discharging $\eta_d$ efficiency and is given by

$$\eta_b = \begin{cases} \eta_c, & P_{\text{net}} \geq \mu \\ \eta_d, & P_{\text{net}} \leq \mu \end{cases}$$

with $\mu$ as the minimum power required to charge the batteries and $\Delta t$ is the time separation between two battery states.

III. PROPAGATION MODEL AND LINK BUDGET

The radio signal propagation from HAPS to the UE undergoes free space path loss and multipath fading due to the significant distance between them and obstacles around the UE, respectively. Therefore, the propagation loss of the adopted system is modeled as a combination of both large scale propagation model and small scale fading. Hence, the channel coefficient $h_{lm}^j$ is computed as

$$h_{lm}^j = \frac{g_{lm}^j G_m}{\sqrt{L(d_{lm}^j)}}, \quad (14)$$

where $g_{lm}^j$ is the small scale fading coefficient between the $j$th panel and $i$th user in $m$th cell, $G_m$ is the array gain for the link between $j$th panel and $m$th cell, and $L(d_{lm}^j)$ is the path loss as a function of $d_{lm}^j$ i.e., the distance between HAPS and $i$th user in $m$th cell.

A. Small Scale Multipath Fading

The received signal comprises of both the LOS and NLOS component pertaining to the HAPS boresight position and independent diffuse multipath reflections from the obstacles. The LOS component is generally deterministic whereas the envelope of NLOS component is modelled as a Rayleigh probability distribution. Hence, the aggregate small-scale multipath fading is modelled as a Rician distributed envelope [17], [18].

$$f(x | \nu, \sigma) = \frac{x}{\sigma^2} \exp\left(\frac{-x^2 + \nu^2}{2\sigma^2}\right) I_0\left(\frac{2\nu x}{\sigma^2}\right),$$

where $I_0$ denotes zeroth-order modified Bessel function of the first kind and shape parameter $K = \nu^2/2\sigma^2$ defines the ratio between the average power of LOS component and the average power associated with NLOS multipath components.

B. Directivity Gain

The communication panels are equipped with antenna arrays which are responsible for directional beamforming. The sectorial antenna pattern is favorable for the minimal CCI and yields the following array gain

$$G_m^j (\theta_{lm}^j) = \begin{cases} M_b, & |\theta_{lm}^j| \leq \theta^b \\ \frac{m_b}{m_b}, & \text{otherwise} \end{cases}$$

where $\theta_{lm}^j$ is the angle of departure and $\theta^b$ is the half power beamwidth of the main lobe. Moreover, the directivity gains of main lobe and back lobe are denoted by $M_b$ and $m_b$, respectively. Evidently, the relation $m_b < < M_b$ holds due to the decreasing antenna gain while moving away from the boresight position in a horizontal direction. Hence, the sectorial antenna pattern reaps the maximal directional gain rendering the minimal IECI to the users in neighboring cells.

Note that the HAPS station keeping flight does not contribute to the fast fading since there are no moving scatterers surrounding the aircraft [16].

C. Link Budget

The large scale propagation is characterized as a free space path loss model with path loss exponent $\beta$ and the direct distance $d_{lm}^m$ between HAPS and UE$^m$ as $d_{lm}^m = H/\sin \psi_{lm}^m$, where $\psi_{lm}^m$ is the elevation angle of HAPS from UE$^m$. Evidently, the users in the center cell enjoy a larger elevation angle between $\psi_c \leq \psi_{lm}^m \leq \pi/2$, whereas the edge cell user’s are at relatively smaller elevation angles $\psi_c \leq \psi_{lm}^m \leq \pi/2$, with $0 \leq \psi_c \leq \psi_{lm}^m$, where $\psi_c$ and $\psi_{lm}^m$ depending upon the radius of center cell and entire coverage area, respectively.

We employ space communication model for the aerial HAPS to compute the received signal path loss $L(d_{lm}^m)$ as [20]

$$L(H, \psi_{lm}^m) = \frac{16\pi^2 k_B B T_n H^\beta}{\lambda^2 G_T G_r \sin^2(\psi_{lm}^m)}, \quad (17)$$

where $k_B$ is the Boltzmann’s constant, the system bandwidth $B$ is reused in all $M$ cells, $T_n$ is the equivalent noise temperature of the receiving system, $\lambda$ is the wavelength corresponding to the carrier frequency, $G_T$ is the receiver (UE) antenna gain and $G_r$ is the transmitter (HAPS) antenna gain.

D. Rate Analysis

Consider the uniformly distributed $K_m$ users in $m$th cell ordered as $u_1^m, u_2^m, \ldots, u_{K_m}^m$ depending on their decreasing IECI and increasing channel strengths. Given this ordered arrangement and successive interference cancellation (SIC) technique at user $u_{1}^m$, it is capable of decoding all users from $u_1^m$ to $u_{K_m}^m$ and subtracting these from the received signal. Thus, it can decode it’s own signal from the resultant interference from $u_{K_m+1}^m$ to $u_{K_m}^m$ as noise. Moreover, the IECI in a given cell is also treated as noise at all users. Therefore, the signal-to-interference noise ratio $\gamma$ at user $u_{1}^m$ is given by

$$\gamma_{1}^m = \frac{|h_{1m}^m|^2 P_m \alpha_{1}^m}{|h_{1m}^m|^2 \sum_{k=1}^{K_m} P_k \alpha_k^m + \mathcal{I}_m^m + \sigma^2},$$

where the AWGN noise variance is considered i.i.d for all users i.e., $\sigma^2$ and the inter-cell interference power is given by

$$\mathcal{I}_m^m = \sum_{j \neq m} \sum_{k=1}^{K_j} |h_{jm}^j|^2 P_j \alpha_k^j = \sum_{j \neq m} \sum_{j \neq m} |h_{jm}^j|^2 P_j.$$.

Assuming perfect decoding with perfect receiver-CSI and user ordering, the achievable rate of user $u_{1}^m$ is

$$R_{1}^m = B \log_2 [1 + \gamma_{1}^m]. \quad (20)$$

The sum rate $R$ of all users in all $M$ cells can be written as $R = \sum_{m=1}^{M} R_{1}^m$ where the sum rate of users in $m$th cell is given as $R_{m} = \sum_{l=1}^{K_m} R_{lm}^m$ yielding

$$R = \sum_{m=1}^{M} R_{m} = \sum_{m=1}^{M} \sum_{l=1}^{K_m} \log_2 [1 + \gamma_{l}^m]. \quad (21)$$

The $\gamma_{l}^m$ in (18) can be elaborated using (14) as

$$\gamma_{l}^m = \frac{|g_{lm}^m|^2 M_b^2 \alpha_{l}^m}{|g_{lm}^m|^2 M_b^2 \sum_{k=1}^{K_m} \alpha_k^m + \sum_{j=1}^{K_m} P_j |g_{lm}^j|^2 + \frac{L(H, \psi_{lm}^m)}{e}}, \quad (22)$$

where $\psi_{lm}^m$ is the elevation angle of HAPS from UE$^m$. Furthermore, we conclude that $\gamma_{1}^m \geq \frac{1}{\sum_{l=1}^{K_m} \gamma_{l}^m}$ for $\alpha_{l}^m = 1$.
where $\eta_m$ is the transmit SNR for $m_{th}$-cell i.e., $\frac{P_m}{\sigma_m^2}$. User experiences high IACI and low IECI owing to high directivity gain $M_b$ and low antenna gain $m_b$ for the users outside the main lobe, respectively. We can now formulate the optimization problem to design optimal power allocation in order to maximize the sum rate of all users within the allocated power budget.

IV. PROBLEM FORMULATION

This work emphasizes the joint optimization of flight and communication parameters given inevitable power limitations. We aim to design the optimal altitude and UAV airspeed (in a circular trajectory of fixed radius) for the station keeping flight along with the optimal power allocation for all the DL-NOMA users in it’s coverage area. We formulate two different design problems for day and night operation based on their different characteristics:

1) The availability of abundant solar power during the day allows optimal flight and maximum transmission power while storing an essential amount for night time operation.

2) The limited stored power should support the dwell flight for entire night by satisfying a minimum rate constraint.

A. Day Time Operation

The objective of day time operation is to maximize the sum rate of all users after storing the adequate power for night time. We divide the daylight period into $n$ equal time intervals (each with almost constant solar flux) and then optimize the power allocation $\alpha[n] = \{\alpha_1, \alpha_2, \ldots, \alpha_m\}$ with $\alpha_m = \{\alpha_{m1}, \alpha_{m2}, \ldots, \alpha_{mM}\}$, altitude $H[n]$ and airspeed $V[n]$ for each interval.

\[
\text{P1 : maximize } \sum_{n=1}^{M} \sum_{l=1}^{K_m} R_l^m (\alpha[n], H[n]) \quad (23a)
\]

subject to

\[
P_l^m \geq \Omega_m, \forall l, m, \quad (23b)
\]

\[
\sum_{k=1}^{K_m} \alpha_k^m [n] = 1, \quad \forall m \quad (23c)
\]

\[
0 \leq \alpha_k^m [n] \leq 1, \quad \forall k, m \quad (23d)
\]

\[
P_{\text{req}}(H[n], V[n]) \geq P_{\text{st}}, \quad (23e)
\]

\[
\sum_{m=1}^{M} P_m[n] \leq \Upsilon P_T, \quad (23f)
\]

\[
H_{\text{min}} \leq H[n] \leq H_{\text{max}}, \quad (23g)
\]

\[
V_{\text{min}} \leq V[n] \leq V_{\text{max}}, \quad (23h)
\]

where the quality of service (QoS) rate constraint (23c) and the sum power constraint (23b) ensure a minimum achievable rate $\Omega_m$ for each user in $m_{th}$ cell and the transmission within power budget, respectively. Moreover, the boundary constraints on power, altitude, and airspeed are given in (23d), (23g) and (23h), respectively. It is important to highlight that $H_{\text{min}}, H_{\text{max}}$ and $V_{\text{max}}$ are constants but the stalling speed $V_s$ is a function of aircraft dimensions and altitude as $V_s = \sqrt{2W/\rho m(H)}SC_{\text{min}}$. It is the minimum speed $V_{\text{min}}$ at $H$ to maintain a steady-level flight. In addition, the constraint (23e) ensures the availability of requisite power stored $P_{\text{st}}$ in batteries for night time operation. Eventually, (23f) restricts the communication power budget for all cells after accounting the feed line losses $\Upsilon$ encountered while drawing effective radiated power from the actual transmission power. The problem P1 is jointly non-convex in the given optimization variables therefore we propose alternate optimization (AO) and solve the sub-problems (24a), (24b) and (24c) iteratively as presented in Algorithm 1. We initialize by selecting a time and date at instance $n$ and choosing the QoS threshold $\Omega_m$. Feasible starting altitude and speed are used to compute the required propulsion power $P_{\text{pro}}[n]$ which is then subtracted from the available power at that instance $P_{a}[n]$ along with the $P_{\text{st}}$ to obtain the transmission power $P_T[n]$. Then, subproblems P1(a), P1(b), and P1(c) are solved iteratively using the results of previously solved problems. Next, we update $P_T[n]$ using the renewed $P_{\text{pro}}[n]$ to find the sum-rate $R[n]$. Alternate optimization works in a loop till it meets the stopping criteria to furnish the optimum values of the $\alpha[n], H[n]$ and $V[n]$.

For a given flight at altitude $H$ with airspeed $V$ at an instant $n$, the power allocation problem is given by (24). The transmit power budget is calculated from (11) after deducting $P_{\text{req}}[n]$ from the available solar power $P_{a}[n]$ for a fixed $P_{\text{st}}$.

\[
\text{P1(a) : maximize } \sum_{m=1}^{M} \sum_{l=1}^{K_m} R_l^m (\alpha[n], H[n]) \quad (24a)
\]

subject to

\[
(23c), (23d), (23g), (23h). \quad (24b)
\]

Interestingly, the optimization problem P1(a) can be solved independently in $\alpha_1, \alpha_2, \ldots, \alpha_m$ as it is a disjoint problem for all cells, given a fixed altitude and equal power budget i.e., $P_{a}[n] = TP_T/M$. The elaborate closed-form solution to this problem is presented in [21] as:

\[
\text{Theorem 1. In power allocation problem, the sum rate and minimum power coefficients of users in } m_{th}-\text{cell, respectively, are given by}
\]

\[
R_m = K_m \Omega_m + \log_2 \left[ 1 + \frac{1 - \sum_{k=1}^{K_m} \alpha_k^m}{\frac{P_m}{\sigma_m^2}} \right], \quad (25)
\]
\[ \hat{\alpha}^m_i = (2\Omega - 1) \left( \sum_{k=1}^{K_m} \hat{\alpha}^m_k + A^m_i \right), \]  
where 
\[ A^m_i = \frac{m^2}{M^2} \sum_{j=1}^{J_m} \frac{P_j |g_{lm}|^2 + L(H, \psi_{ij}^m)}{\varrho_m M^2 |g_{lm}|^2}. \]  
if the following condition holds 
\[ (2\Omega - 1) \left( \sum_{k=1}^{K_m} 2^{i-1} A^m_k \right) \leq 1. \]  
The first term of \( R_m \) is the QoS thresholds of all users in \( m\text{-th} \) cell whereas the second term is the additional rate of \( K_m \) user after allocating the remaining power \( 1 - \sum_{k=1}^{K_m} \hat{\alpha}^m_k \) to it, which maximizes the sum rate.

**Theorem 2.** For \( \sum_{k=1}^{K_m} \hat{\alpha}^m_k \geq 1 \), there exists a user \( u \) in \( 1 \leq u \leq K_m \) which satisfies the following condition:
\[ \begin{cases} (2\Omega - 1) \left( \sum_{k=1}^{K_m} 2^{i-1} A^m_k \right) \leq 1, \\ (2\Omega - 1) \left( \sum_{k=1}^{K_m} 2^{i-1} A^m_k \right) \geq 1. \end{cases} \]
Hence, the maximum achievable sum rate is given by
\[ R_m = (K_m - u) \Omega_m + \log_2 \left[ 1 + \frac{\Delta \alpha}{1 - \Delta \alpha + A^m_u} \right], \]  
where 
\[ \Delta \alpha = 1 - (2\Omega - 1) \left( \sum_{k=1}^{K_m} 2^{i-1} A^m_k \right). \]

The problem \( P_{2} \) is jointly non-convex in optimization variables \( H \) and \( V \) pertaining to the indefinite Hessian matrix. Nonetheless, it is convex in both \( H \) and \( V \), individually. Hence, we break down \( P_2 \) to \( P_2(a) \) and \( P_2(b) \) in order to minimize the propulsion power requirement with respect to \( H \) and \( V \), respectively.

**Algorithm 2 Alternate Optimization: Night Time Operation**

1: Initialize \( P_{2}^{(i-1)} \leftarrow 0, i \leftarrow 1 \), and \( \epsilon \leftarrow \infty \)
2: Set tolerance \( \delta \) and Select a time instance \( n \)
3: Choose feasible starting point \( H[n]^{(i-1)} \)
4: while \( \epsilon \geq \delta \) do
5: Evaluate \( V[n]^{(i)} \) using \( H[n]^{(i-1)} \) in (36)
6: Compute \( H[n]^{(i)} \) using \( V[n]^{(i)} \) in (38)
7: Calculate \( P_{2}^{(i)} \) using \( H[n]^{(i)} \) and \( V[n]^{(i)} \)
8: Update \( \epsilon \leftarrow \| P_{2}^{(i)} - P_{2}^{(i-1)} \| \) and \( i \leftarrow i + 1 \)
9: end while
10: \( P_{2}^{*} \leftarrow P_{2}^{(i)} \), \( H^{*}[n] \leftarrow H[n]^{(i)}, V^{*}[n] \leftarrow V[n]^{(i)} \)

Alternate Optimization: Night Time Operation

The night time function of HAPS is largely limited by the stored power in rechargeable batteries. Therefore, we propose a flight which minimizes the power consumption during night time and transmission with a fixed power budget. We formulate \( P_2 \) to minimize the propulsion power requirement with respect to \( H \) and \( V \).

\[ \text{P2 : minimize}_{H[n],V[n]} P_{2}(V[n],H[n]) \]  
s.t. (23g), (23h). \hspace{1cm} (34a)

The propulsion power in (3) is convex and strictly increasing in \( V \). Therefore, we can find the closed-form optimal solution of \( P_2(a) \) as
\[ V^{*}[n] = \begin{cases} V_m[n], & V_s[n] \leq V_m[n] \leq V_{\max} \\ V_s[n], & V_m[n] \leq V_s[n] \end{cases} \]  
where, \( V_m[n] \) is derived using the second order sufficient optimality condition.
\[ V_m[n] = \sqrt{\frac{2W \rho [n] S}{3C_{D_{0}}}}. \]  

\( P_2(a) \) is the local minimum below which steady level flight is not possible.

\( P_2(b) \) is the local minimum below which steady level flight is not possible.

\( \epsilon \)The proof of indefinite \( \nabla^2 P_{2} \) and non-negative second-order gradients \( \partial^2 P_{2}/\partial H^2 \) and \( \partial^2 P_{2}/\partial V^2 \) is straightforward but omitted for brevity.
Similarly, $P_{pro}$ is convex and strictly decreasing function of altitude $H$, enabling us to compute the optimal solution of $P2(b)$ as

$$H^*[n] = \begin{cases} 
H_m[n], & H_{min} \leq H_m[n] \leq H_{max} \\
H_{max}, & \text{otherwise} 
\end{cases}$$

(38)

where $H_m[n]$ is the stationary point and obtained using the second order sufficient condition

$$H_m[n] = \begin{cases} 
H_{b1} - \frac{RT}{S} \ln \left( \frac{\sigma[n]}{\rho_s} \right), & \text{Stratosphere-I} \\
H_{b2} - \frac{\chi}{L_b} + \frac{1}{L_b} \left( \frac{p_{kT}^{\frac{\gamma M}{\gamma M + RL_b}}}{\sigma[n]} \right)^\theta, & \text{Stratosphere-II} 
\end{cases}$$

(39)

where $\sigma[n] = \frac{2W}{SV[n]^2} \sqrt{\frac{e}{C_{D_0}}}$. We either choose the feasible case or Stratosphere-II if both are feasible. $H_m[n]$ is the global solution to $P2(b)$ if it satisfies (39) otherwise $H_{max}$ is the local optimal owing to the strictly decreasing nature of $P_{pro}$.

The closed-form optimal solutions of $P2(a)$ and $P2(b)$ are iteratively updated using the alternate optimization technique to solve the original problem $P2$ as detailed in Algorithm 2. It begins by setting tolerance $\delta$ and a feasible $H$ at the chosen instance $n$. Then, we solve $P2(a)$ for a given $H[n]$ to obtain the optimal $V[n]$, which is then used to solve $P2(b)$ to update $H[n]$. This process repeats iteratively until the convergence criteria is met. The minimized $P_{res}$ is deducted from the stored energy yielding a fixed transmission power $P_T$ for the night time communication. Given a requisite $P_T$, we can again use the optimal power allocation strategy to maximize the sum rate within power budget as detailed in the solution of $P1(a)$.

V. NUMERICAL RESULTS

The numerical results are evaluated for each hour of summer solstice (SS) and winter solstice (WS) of the current year at a location indicated by $\xi$ and $\chi$. Using this information, parameters $\eta_d$ and $\epsilon_s$ are computed using the Python’s module Pysolar [22]. The relative air pressure and air density in (3) and (6), respectively, are approximated with second degree polynomials for the desired altitude range as $\rho_h(h) = 60h^2 - 3276.7h + 47022.8$ (Pa) and $\rho_h = 0.95162h^2 - 52.29356h + 753.39927(g/m^3)$. We assume a station keeping flight radius in range $2.5km \leq r \leq 4km$ which guarantees 99.00% to 99.95% availability over a certain coverage area. Moreover, we assume A-300 Mono Crystalline Silicon Solar Cells for rechargeable batteries mounted on the aircraft [23]. We consider one center cell and 6 edge cells [9] with uniformly distributed users at elevation angles defined by the boundaries $\psi_c = \pi/13.33$ and $\psi_c = \pi/6$ in the 100km coverage radius. The values of numerous simulation parameters are presented in Table I unless specified otherwise.

The average available transmission power at every hour of the day on SS and WS is presented in Fig. 2. We proposed a fixed transmission power for night time operation, computed after deducting the propulsion and accessory expenses from the total stored energy. However, the day time operation benefits from the abundant solar power and utilizes all the surplus power for transmission. Intuitively, the $P_m$ increases with the increasing $\epsilon_s$ reaching it’s maximum value at noon and then decreases with the decreasing $\epsilon_s$. Evidently, the large and wide $P_m$ during summers is the result of lower extinction factor and increased daylight hours, respectively. The extended daylight hours are also responsible for a slightly higher $P_m$ at night as they allow extra energy storage before saturating the batteries.

The average sum rate of all users in the coverage area is obtained using the optimized parameters in Algorithm 1 and 2 for the day and night hours, respectively. The sum
rates are optimized for three different QoS thresholds i.e., \( \Omega_m = 1, 2, \) and 4 Mbps on both SS and WS as illustrated in Fig. 3. Evidently, users can achieve a higher sum rate at both day and night during the summers as compared to the one during winters pertaining to the higher \( P_{m} \). Interestingly, the optimized system renders 11.45%, 10.68% and 7.45% relative gain in the sum-rates over the unoptimized system with 1, 2, and 4 Mbps QoS thresholds, respectively.

Eventually, the optimal average speed and altitude are demonstrated for the entire duration of the day in Fig. 4. The station keeping flight operates at 18km in the day time and at 24km in the night to maximize sum rate and minimize propulsion power, respectively. These results are in contrast to the general concept where HAPS are expected to fly high during the night to harvest more solar energy and cruise at lower altitude during the night to reduce potential energy. This contradiction is pertaining to the different flight objectives. We proposed a low altitude flight to maximize sum rate given adequate power harvesting for the sustenance. The presented average speed minimizes the propulsion power for the station keeping flight at a given altitude rendering more power for transmission from the available power budget.

VI. Conclusion

We propose self sustaining long endurance HAPS to serve a large coverage area while cruising in a stratospheric station keeping flight. We present an interdisciplinary approach to tackle the challenges in solar energy harvesting, aerodynamics and communications for efficient power budgeting. We further proposed downlink NOMA strategy to serve a multicell network from the array panels (mounted underneath the flying base station in HAPS) for efficient resource management. The propagation model and link budgeting involves both the small and large scale fading for accurate performance analysis. We formulated different optimization problems for the day and night operations with the objectives to maximize sum-rate and minimize power requirements, respectively. We furnished Algorithm I and II to describe the optimization procedure based on the closed form solutions of the sub-problems. Our findings of the numerical result emphasize the joint design of flight and transmission parameters for optimal power allocation. The optimized parameters render relative sum-rates gains upto 11.5% while satisfying QoS thresholds of the users. Thus, stratospheric aerial communication platforms emerge as a promising candidate for global coverage without requiring any special UE.

APPENDIX A
DERIVATION OF \( H_m \) AND \( V_m \)

The gradient of propulsion power \( P_{prop} (5) \) with respect to altitude \( H \) is given by

\[
\frac{\partial P_{\text{req}}}{\partial H} = \frac{1}{\eta_p \rho_c} \left( \frac{1}{2} \frac{\partial \rho_h}{\partial H} V^3 S C_{D_h} - \epsilon \frac{2W^2}{\rho_h^2 S V^2} \frac{\partial \rho_h}{\partial H} \right) \tag{40}
\]

Equating (40) to zero yields the following

\[
\rho_h (H^*) = \frac{2W}{S V^2} \sqrt{\frac{\epsilon}{C_{D_h}}} \tag{41}
\]

We can then obtain the optimum \( H_m \) (39) using the piecewise function \( \rho_h \) for Stratosphere-I and Stratosphere-II. Similarly, the gradient of propulsion power with respect to airspeed is given as

\[
\frac{\partial P_{\text{req}}}{\partial V} = \frac{1}{\eta_p \rho_c} \left( 3 \frac{\rho_h V^2 S C_{D_h}}{2} - \epsilon \frac{2W^2}{\rho_h S V^2} \right) \tag{42}
\]

The stationary point obtained by setting (42) to zero renders the optimal \( V_m \) in (37).

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