HAPS-Aided Power Grid Connected Green Communication Framework: Architecture and Optimization

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***Abstract*—Realizing energy sustainability is a key theme in sixth generation communications. Along with the emphasis on energy efficiency, operator revenue has emerged as a crucial aspect to make the networks scalable. In this paper, we propose a high altitude platform station (HAPS) aided and power grid connected green communication framework. To design green network, the proposed framework aims to offload excess users with the solar powered terrestrial macro base station (tMBS) to the HAPS mounted MBS (hMBS) in the event of high traffic or low energy harvest. The solar powered tMBS utilizes the power grid connectivity purely for energy selling rather than energy procurement. The inherent communication and energy networks in the proposed system are studied and modeled jointly as a six state discrete time Markov chain. The paper also provides analytical bounds on the solar provisioning required at the hMBS for radio access network functions. The proposed framework is compared with a without offloading and grid energy procurement based competitive state of art, in terms of network quality of service (QoS) and annual operator profit. Our simulation based performance studies demonstrate that the proposed framework under limited hMBS offloading capability offers gains compared to the competitive state of the art, up to 21% enhanced network QoS and 64% increased operator profit.**

***Index Terms*—High altitude platform station (HAPS), offloading, smart grid, green network, Markov model, operator profit**

I. Introduction

Green communication has emerged as a key theme in the upcoming sixth generation (6G) communication technology [1]. Recent research has pertained around integrating the existing terrestrial communication networks with aerial and space networks [2]. High altitude platform stations (HAPS) are emerging as a very attractive technology to integrate with the terrestrial networks as it is averse to energy constraints and latency challenges occurring in drone based unmanned aerial vehicles (UAVs) and satellites, respectively [3], [4].

In addition to integrating aerial and terrestrial networks, achieving energy sustainable terrestrial network design has been a key objective of green communication [5]. With the terrestrial macro base stations (tMBSs) being traditionally powered with carbon emitting power grids, there has been research around powering the tMBSs with purely renewable energy sources (like solar energy) [6]. While such solutions are green, they are not cost effective as well as scalable solutions to the mobile operator due to the high capital investment involved. Through this paper, we propose a operator cost profitable smart grid connected and solar powered communication network which is assisted by an aerial HAPS mounted MBS (hMBS). The communication and energy networks in the considered system are studied and modelled jointly as a discrete time Markov chain (DTMC). In the event of low energy harvest or high traffic density being experienced by the tMBS, with the aim of realizing a green network, the proposed framework aims to offload excess users with the tMBS to the hMBS, rather than procuring energy from the grid. We motivate the problem in the upcoming subsection.

A. *State of art and motivation*

Solar powered and smart grid connected, "dual-powered" tMBSs are becoming very attractive as a cost and energy efficient network solution to mobile operators. Despite being dual-powered, they are not carbon free. It is very challenging to gauge the cellular traffic density in a tMBS cell, as the cellular traffic cannot be controlled. Additionally, solar powered tMBSs are prone to intermittent energy harvest, resulting in sudden energy outages if not connected with power grid. Hence, the user quality of service (QoS) gets affected due to randomness in cellular traffic density and energy harvest.

It may also be noted that the tMBSs are governed by federal communications commission (FCC) guidelines on downlink power radiation [7]. Thus, a tMBS can meet the QoS guarantee of limited cellular users, in the event of high traffic density or low energy harvest. Hence, there is a requirement for additional capacity injection, especially in an urban/dense urban scenario. Heterogeneous networks involving small cells have been a traditional strategy, but they result in extra deployment cost to the operator and are not green. HAPS mounted radio access networks which can provide coverage up to 500 Km, are being studied as an attractive solution. As hMBS provides a wide coverage, the capacity of hMBS per cell is limited [3]. Thus, there is requirement to study the improvement of network QoS under energy and capacity limited hMBS offloading capabilities. In a hMBS aided, solar powered, and smart grid connected communication network, by characterizing the communication and energy networks as a DTMC, this paper aims to study user offloading as an alternative to grid energy procurement in the event of higher user density or low energy harvest, towards realizing operator cost profitable green networks. In the upcoming subsections we discuss the key paper contributions and organization.

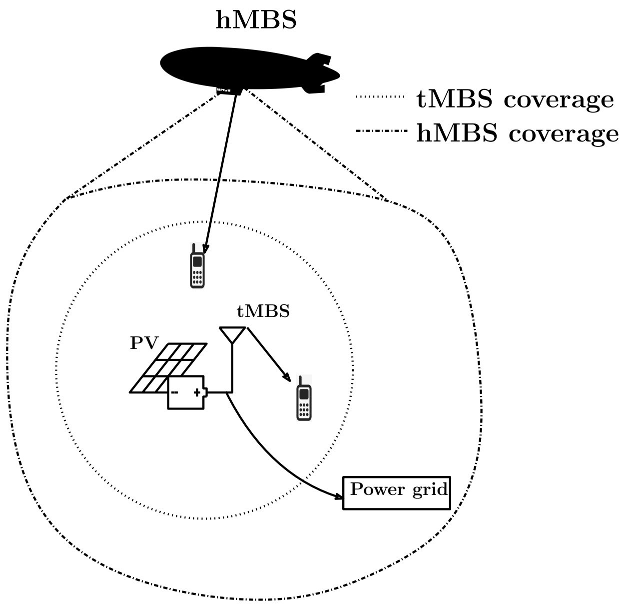


Figure 1: Illustration of HAPS aided, grid connected, and solar powered communication network.

B. Contributions

The key contributions are as follows: (1) The paper proposes a HAPS aided, solar powered, and smart grid connected green communication network. To realize green networks, the paper aims to offload excess users to the hMBS in the event of low energy harvest or high user density rather than relying on grid energy procurement. The power grid infrastructure is utilized only for selling surplus green energy harvested back to the power grid. (2) The inherent communication and energy network in the proposed system are studied and jointly modeled as a six state DTMC. Through the proposed framework, the paper explores the extent of user offloading to an energy and capacity constrained hMBS. (3) The paper provides analytical bounds for solar provisioning at hMBS for radio access network (RAN) functioning. With the current system setting, the operator profit is analytically modeled and studied for an annual time period. (4) Simulation results demonstrate that the framework under limited HAPS aided offloading capability, provides significant gain up to 21.6% and 64.51% in network QoS and operator profit, respectively.

C. Organization

The paper layout is as follows: Section II outlines the system model in detail. Section III presents the proposed joint communication-energy network Markovian model. Section IV presents the operator profit analysis and sustainable system design, while Section V discusses the results and observations. Section VI concludes the paper.

II. System Model

The paper considers a downlink two-tier wireless RAN consisting of solar powered and smart grid connected tMBS and an aerial hMBS as shown in Fig. 1. The tMBS is solar provisioned to harvest green energy with photo-voltaic (PV) panels and storage batteries. The tMBS uses the grid connectivity to sell temporally surplus green energy available with it and is assumed to not procure any energy from power grid. We consider a closed area $\mathcal{A}$, consisting of a set of $\mathcal{U}$ active users denoted as $\mathbf{U} \in \{1, \ldots, \mathcal{U}\}$ modeled as a homogeneous binomial point process. The user set varies temporally as discussed in the later subsections. The users can be served either by the tMBS or the hMBS represented as, $\mathbf{B} \in \{B_1, B_2\}$. It may be noted that while the current work considers a single tMBS framework, the analysis can be generalized to any number of tMBSs. It may also be noted that B_2 represents a hMBS.

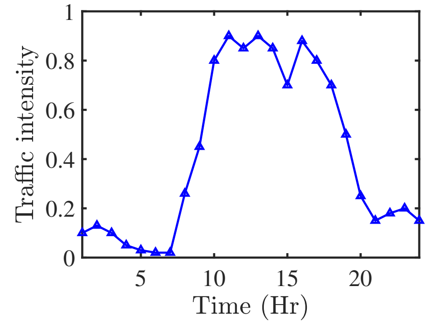


Figure 2: Time varying traffic profile in the considered area [5]

The hMBS is assumed to be self-sustainable, being equipped with sufficient solar panels and storage batteries required to sustain the HAPS in stratosphere [8]. The current paper assumes that the hMBS operates in the sub-6 GHz frequency spectrum with a single beam, and is equipped with an uniform planar array (UPA) antenna structure to mitigate the increased free space path loss. With the total bandwidth resource being W, the tMBS is assumed to operate in full frequency reuse mode, having access to the entire frequency resource. The hMBS is assumed to have limited capacity [3], having access to a fraction $f\%$ of this net frequency resource for the area under consideration. In the upcoming subsections, we discuss the traffic profile, energy profile, and the channel models between the hMBS/tMBS and users.

A. Traffic and energy harvest profile

The tMBS is assumed to be subjected to time varying traffic $\rho(t)$ as shown in Fig. 2. A tMBS $b \in \mathbf{B}$, harvests hourly $H_b(t)$ green energy through N_{PV} PV panels which is stored in N_B storage batteries equipped with it. We obtain annual hourly energy harvest at New Delhi city, India, from National Renewable Energy Laboratory [9]. The battery storage has limited capacity $\beta_{max} = (N_B \times \beta_c)$ and a critical threshold level $\beta_{cr} = (\delta \times N_B \times \beta_c)$, with β_c and δ denoting unit battery capacity and depth of discharge, respectively.

B. Channel models

In this subsection we discuss the analytical modelling of the link between the tMBS–user and hMBS–user.

1) tMBS to user link

The channel state information ψ_{ub} between user u and tMBS b is assumed to be Rayleigh distributed, with the corresponding channel gain $g_{ub} \in \{\mathbf{g}\}$ being exponentially distributed with unit mean. The rate achievable by a user through the associated tMBS is given as $r_{ub} =$

$W_{ub}\log_2(1+SINR_{ub})$, where $SINR_{ub} = P^T_{ub} g_{ub}/(I + (W_{ub}\sigma^2)d^2_{ub})$. Here, $P^T_{ub} \in \{\mathbf{P}\}$ and $d_{ub} \in \{\mathbf{d}\}$ correspond to the transmit power and distance between by tMBS b to user u, σ^2 denotes the power spectral density of additive white Gaussian noise, and I refers to the inter cell interference given as $I = (\sum_{b=1, b\neq b'}^{2} P^T_{u'b'} g_{u'b'} d^{-2}_{u'b'})$. It is assumed that each user has a minimum rate guarantee QoS requirement given as r_{th} such that $r_{ub} \geq r_{th}$.

2) hMBS to user link

The path loss experienced by a user when associated with a hMBS is modeled as per the 3GPP standards [10]. In general, the received power at user is represented as,

$$P_r[dB] = P^T_{uH}[dB] + G^H_t[dB] + G_r[dB] - PL^H[dB]. \quad (1)$$

Here, P^T_{uH} denotes the transmit power of hMBS to user u associated with it, $PL^H = (p_{LoS}PL_{LoS} + p_{NLoS}PL_{NLoS})$ represents the average path loss at user comprising of the line of sight (LoS) and non-LoS components, p_{LoS} and p_{NLoS} denote the probability of LoS and non-LoS components respectively, depending on the elevation angle between hMBS and the user. The LoS and non-LoS path loss components are further modeled through the equations below.

$$PL_{LoS} = PL^b_{LoS} + PL_{ag} + PL_s + PL_e, \quad (2)$$
$$PL_{NLoS} = PL^b_{NLoS} + PL_{ag} + PL_s + PL_e, \quad (3)$$
$$\text{where, } PL^b_{LoS} = FSPL + CL_{LoS} + X_{LoS}, \quad (4)$$
$$PL^b_{NLoS} = FSPL + CL_{NLoS} + X_{NLoS}, \quad (5)$$
$$PL_s = PF/\sqrt{2} = \frac{1.1(f_c/4)^{1.5}}{\sqrt{2}}, \quad (6)$$
$$FSPL = 32.45 + 20\log_{10}(f_c) + 20\log_{10}(d), \quad (7)$$
$$\text{and } d = \sqrt{R_e^2 sin^2(\theta) + H^2_{hap} + 2H_{hap}R_e} - R_e sin(\theta). \quad (8)$$

Here, PL^b_x (for $x \in \{LoS, NLoS\}$) denotes the basic path loss, PL_{ag} represents the loss due to atmospheric gases. It is neglected as the system operates in sub-6GHz. PL_s denotes the scintillation loss at the ionosphere, while PL_e is termed as building entry loss (neglected for outdoor scenario). CL_x and X_x represent the clutter loss and shadow fading loss respectively, $FSPL$ in (4), (5) stands for free space path loss, f_c denotes the carrier frequency of operation, R_e radius of earth, θ the elevation angle, and H_{hap} denotes the height of hMBS. Depending on P_r, $r_{uh} = f\log_2(1 + SINR_{uh})$, where f is the fraction of frequency resource with the hMBS for the current area under study.

III. Proposed Integrated Communication-Energy Network Markovian Model

A HAPS aided, grid connected, and solar powered tMBS framework consists of a communication network and an energy network. In this section, we first explain these two systems separately and then integrate them as a Markovian model.

A. Communication network modelling

The communication network is formed by the downlink communication between tMBS/ hMBS and the users. For the set of $\mathbf{U}$ temporally active users, each having a minimum rate gurantee r_{th}, the minimum power required to be allocated per user by a tMBS is calculated as given below.

$$\begin{aligned}
&\mathbb{P}(r_{ub}(t) \geq r_{th}) \geq p_o \\
&\mathbb{P}\left(g_{ub}(t) \geq \frac{\exp(r_{th}\ln 2/W_{ub} - 1)\left(d^2_{ub}(W_{ub}\sigma^2) + I\right)}{P^T_{ub}(t)}\right) \geq p_o \\
\text{or, } &\exp\left(-\frac{\exp(r_{th}\ln 2/W_{ub} - 1)\left(d^2_{ub}(W_{ub}\sigma^2) + I\right)}{P^T_{ub}(t)}\right) \geq p_o \\
&P^T_{ub}(t) \geq \frac{\exp(r_{th}\ln 2/W_{ub} - 1)\left(d^2_{ub}(W_{ub}\sigma^2) + I\right)}{\ln(1/p_o)}.
\end{aligned} \quad (9)$$

The net power consumption of the tMBS for RAN, as a function of number of users, channel gain, and distance of each user, is calculated as

$$\sum_u \pi_{ub}P^T_{ub}(t) = P^T_b(t) = f(\mathbf{U}, \mathbf{g}, \mathbf{d}) \leq P_{max}. \quad (10)$$

Here, P_{max} refers to the maximum transmit power level of the tMBS in accordance with the FCC guidelines. $\pi_{ub} \in \{0, 1\}$ refers to a variable indicating association of user u to BS b and is defined as

$$\pi_{ub} = \begin{cases} 1, & \text{if user } u \text{ associated with } b \\ 0, & \text{else.} \end{cases} \quad (11)$$

A communication system can be modeled as a two state Markov model as described below.

1) *QoS satisfied (QS)* state: The system will be in QS state at time t if the QoS rate requirement of all the active users are met by the tMBS and the net power consumption of the tMBS does not violate the FCC guidelines (10), i.e.,
$$r_{ub}(t) \geq r_{th} \ \forall\ u \in \mathbf{U} \text{ such that, (10).} \quad (12)$$
2) *QoS violation (QV)* state: The system will be in QV state at time t if the QoS rate requirement of the active users are not being met by the tMBS. In this state, the transmit power level of the tMBS saturates at P_{max} with some users $\mathbf{U}' \subset \mathbf{U}$ being unserved. Mathematically,
$$r_{ub}(t) < r_{th} \ \forall\ u \in \mathbf{U}' \subset \mathbf{U} \text{ such that, (10).} \quad (13)$$

In the upcoming subsection we explain the energy network in the system.

B. Energy network modelling

The solar provisioning at the tMBS (including the PV panels and storage batteries) and the power grid together form the energy network in the system. Depending on the green energy harvest and traffic profile being experienced by a tMBS, the energy network can be modeled as a three state system explained below. First, the green energy storage level at tMBS b is defined as

$$\begin{aligned} B'_b(t) &= B_b(t-1) + H_b(t) - E_b(t), \\ B_b(t) &= \min\{\max\{B'_b(t), \beta_{cr}\}, \beta_{max}\}. \end{aligned} \quad (14)$$

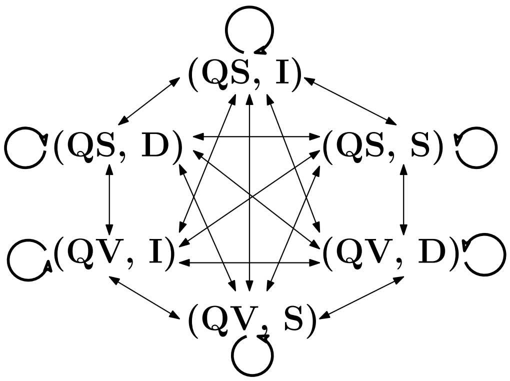


Figure 3: Proposed Markovian model.

Here, $E_b(t) = N_{TRX}\left(P_s + \theta_1 P_b^T(t)\right)$ denotes the net energy consumption by the tMBS, P_s denotes the static energy consumption of the tMBS, N_{TRX} denotes number of transceivers, and θ_1 a constant [5]. Depending on the battery level, the energy network can be discretely modeled as

1) *Deficit (D)* state: In this state, $B_b'(t) < \beta_{cr}$. This state signifies that the tMBS becomes energy-deficient thereby affecting user service. In this case, the network will have to offload users to the hMBS or buy some energy from the power grid.
2) *Intermediate (I)* state: In this state, $\beta_{max} \geq B_b'(t) \geq \beta_{cr}$.
3) *Surplus (S)* state: In this state, $\beta_{max} < B_b'(t)$, signifying that the storage battery cannot store excess energy, thereby necessitating energy sell to the power grid.

In the coming subsection, we discuss the joint communication-energy network Markov modelling and service provider network operations.

C. Joint Markov model

The communication and the energy network model discussed previously are not independent of each other, as both the models are a function of the tMBS energy consumption. Thus, both the models are influenced by the tMBS power consumption variation to meet the QoS requirement of the temporally active users. Hence, there is a need to analyse the communication network and the energy network jointly through an integrated Markovian model as shown in Fig. 3, with the states as explained below. Before detailing the integrated Markov model, it is imperative to discuss the possible service provider network operations.

1) Energy selling back to grid: The tMBS can sell excess energy in its storage back to grid.
2) Excess user offloading to hMBS: In the event that the tMBS is unable to satisfy QoS of all temporal active users, some users will be offloaded to the hMBS.

We do not consider the tMBS to purchase energy from the grid, rather aim to offload excess users to the hMBS as required. Next, we describe the integrated Markov model states and the corresponding network operations.

1) (QS, D): In this state, the tMBS satisfies QoS requirements of the temporally active users. But since battery level is at critical level, *some users require to be offloaded to the hMBS.*
2) (QS, I): The tMBS is sufficient to satisfy QoS of temporal active users and the battery level is in intermediate state, i.e., above level. *This state does not involve either of user offloading or energy selling back to grid.*
3) (QS, S): The tMBS is sufficient to satisfy QoS of temporal active users and battery level is in surplus state. *This state only involves energy selling back to the grid and does not involve user offloading to hMBS.*
4) (QV, D): The tMBS is insufficient to satisfy temporal QoS requirements, further the battery level is also in deficit state. *Hence, this state involves excess user offloading to hMBS.*
5) (QV, I): The tMBS is insufficient to satisfy temporal QoS requirements, but the battery level is not in deficit state. *Hence this state involves only excess user offloading to hMBS.*
6) (QV, S): The tMBS is insufficient to satisfy temporal QoS requirements, but battery storage is overflowing. *This state involves excess user offloading to hMBS and energy selling back to the grid.*

The transition probability matrix corresponding to this DTMC is denoted as $\mathbf{T} \in \mathbb{R}^{6\times 6}$, while the steady state probability matrix is given as $\underline{\pi} \in \mathbb{R}^6$. The following system of equations are solved in order to obtain the steady state probabilities,

$$\underline{\pi} = \underline{\pi}^T \mathbf{T}, \text{such that } \sum_i^6 \pi_i = 1. \tag{15}$$

In the upcoming section, we analyse the operator profit aspects towards designing a green communication system.

IV. Operator Profit Analysis and Sustainable System Design

In this section we first present lower bounds for capital expenditure (CAPEX) provisioning at hMBS. Then we analyse the system from a service provider's perspective, analysing the various cost parameters involved and aim to design a green network.

A. HAPS CAPEX provisioning for sustainable RAN

The current literature assumes that the HAPS is sufficiently powered with renewable energy sources for its sustenance in stratosphere as well as for RAN functioning [11]. Since the hMBS deployment involves CAPEX (including solar panels and storage batteries) to the telecom provider, thus it is not practical to consider user offloading to hMBS free of cost.

The hMBS is equipped with a uniform planar antenna array to mitigate the free space path loss. The energy consumption by the hMBS is assumed to be similar to a tMBS as proposed in [11]. Accordingly, $E_H(t) = N_{TRX}^H(P_s + \theta_1 P_H^T)$ denotes the temporal energy consumption by a hMBS when radiating P_H^T power through N_{TRX}^H antenna elements. For sustainable RAN, the hMBS should be equipped with sufficient CAPEX such that on an average the daily energy harvest at the hMBS (for RAN) be greater than the hMBS RAN energy consumption. The lower bounds for minimum CAPEX provisioning in a hMBS are,

$$\begin{aligned} N_{PV}^{H} &\geq \frac{\sum_t \mathbb{E}\left(E_H(t)\right)}{\eta \times \sum_t \mathbb{E}\left(H_{1\text{KW}}(t)\right)} \\ N_{B}^{H} &\geq \frac{\left(\sum_t H_{N_{PV}}(t) - \sum_t E_H(t)\right)}{\delta \times \beta_c}. \end{aligned} \tag{16}$$

Here, $H_{1\text{KW}}$ denotes the energy harvested by a 1 KW (i.e., unit rated) PV panel and η denotes the efficiency of the PV panels. It may be noted that the CAPEX provisioning at a hMBS is a function of the number of antenna elements in the array equipped with hMBS to mitigate the free space path loss, and is computed as

$$CAPEX^{H} = C_{PV} N_{PV}^{H} / L_{PV} + C_B N_B^{H} / L_B. \tag{17}$$

Here, C_{PV}, L_{PV} and C_B, L_B denote the cost and lifetime of unit PV panel and battery, respectively.

B. Energy sustainable system design

The main objective of this paper is to use the grid infrastructure only for selling energy back to the grid and not for grid energy procurement. The probability of selling excess energy and offloading excess users to the hMBS is given as

$$\begin{aligned} \mathbb{P}_{sell} &= \pi_{QS,S} + \pi_{QV,S} \\ \mathbb{P}_{offload} &= \pi_{QS,D} + \pi_{QV,D} + \pi_{QV,I} + \pi_{QV,S}. \end{aligned} \tag{18}$$

The network aims to maximize the network user service by ensuring that the QoS of all temporally active users can be fulfilled. Accordingly the following rate maximization problem is formulated.

$$\begin{aligned} \mathcal{P}1 \max_{\pi_{ub}, \pi_{uh}, \mathbf{P}} & \left(\pi_{ub}(t) r_{ub}(t) + \pi_{uh}(t) r_{uh}(t)\right) \;\; \forall u \in \mathbf{U} \\ & \text{such that, } \; \pi_{ub}, \pi_{uh} \in \{0, 1\}; r_{ub}(t), r_{uh}(t) \geq r_{th} \end{aligned} \tag{19}$$

It may be noted that π_{uh} denotes the association of a user with the hMBS. Since the above problem is a combinatorial mixed-integer non-linear problem, it is NP hard in nature. It is solved by Algorithm 1 having complexity $\mathbb{O}(T \times U)$. For a general network having B tMBSs, the complexity will be $\mathbb{O}(T \times U \times B)$. Algorithm 1 outputs the number of user served in the network N. The operator profit is computed considering the following factors: revenue earned by serving users R_{ser}, revenue earned by selling excess energy to the grid R_{sell}, and capital expenditure $CAPEX$. It may be noted that in order to realize green network, the tMBS does not procure energy from grid, rather offloads the user to hMBS. The offloading at hMBS is not free to the operator. The operator incurs CAPEX in solar provisioning the RAN at hMBS as discussed in Section IV-A. Net profit $\mathcal{P}_1 = R_{ser} + R_{sell} - CAPEX^{H} - CAPEX^{B}$. Here, $CAPEX^{B} = (C_{PV} N_{PV} / L_{PV} + C_B N_B / L_B)$ denote the CAPEX incurred in solar provisioning tMBS. Revenue earned by serving users is computed as $R_{ser} = C_{ser} \sum_t N(t)$, while revenue earned by selling energy is computed as $R_{sell} = \sum_t (B'_b(t) - \beta_{max})$ in the event of battery overflow.

As a competitive approach, in case the operator doesn't wish to offload users to hMBS, and resorts to purchasing energy from the grid, the net operator profit will be computed as $\mathcal{P}_2 = R_{ser} + R_{sell} - CAPEX' - C_{buy}$. Here $C_{buy} = C_b \sum_t (\beta_{cr} - B'_b(t))$ with $CAPEX' \neq CAPEX^{B}$. In the upcoming section we will discuss the results and inferences.

Algorithm 1: User association and offloading

Result: $N = \sum_u \pi_{ub} + \sum_u \pi_{uh}, \mathbf{P}$
Input: $\mathbf{U}, \rho(t), \mathbf{g}(t), W, f, \sigma^2, P_{max}$
Initialize: $N = 0$
for $t = \{1, \ldots, T\}$ **do**
  for $u = \{1, \ldots, U(t)\}$ **do**
    $d_{ub} \longleftarrow \sqrt{(x_u - x_{bs})^2 + (y_u - y_{bs})^2}$
    Compute $SINR_{ub}$ from (1)
    $r_{ub}(t) \longleftarrow W_{ub} \log_2(1 + SINR_{ub}(t))$
    if $(r_{ub}(t) \geq r_{th})$ **then**
      $N \longleftarrow N + 1$
      $\pi_{ub} \longleftarrow 1$
      Compute P_{ub}, P_b^T from (10)
    end
    else
      Compute P_r from hMBS using (1) – (8)
      Compute $r_{uh} = f \log_2(1 + SINR_{uh})$
      if $(r_{uh}(t) \geq r_{th})$ **then**
        $\pi_{uh} \longleftarrow 1$, $N \longleftarrow N + 1$
      else
        user remains unserved
      end
    end
  end
end
end

V. Results and Discussion

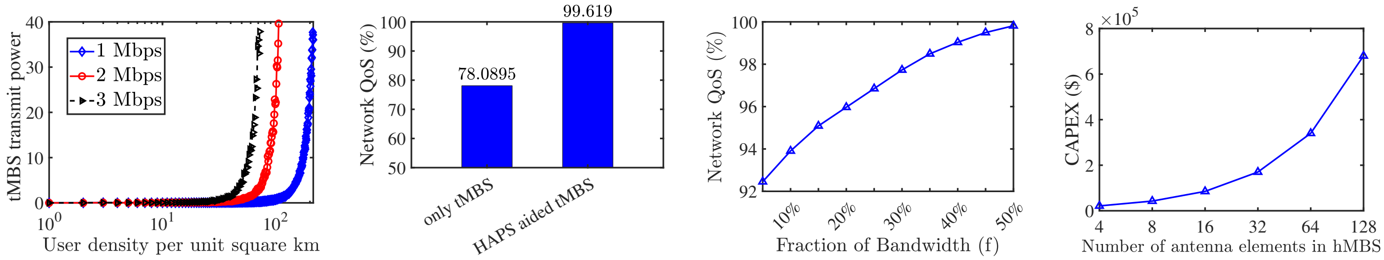
In this section we discuss the simulated results, generated through MATLAB software. The values of the simulation parameters considered are provided in Table I. The entire analysis is conducted for an annual time frame, $T = 8760$Hr.

Table I: Parameter values used in simulations

Parameter	Value	Parameter	Value
$\mathcal{A}$	1 Km^2	H_{hap}	20 Km
W	20 MHz	R_e	6378 Km
β_c	2460 Wh	f_c	2.5 GHz
σ^2	-150 dBm/Hz	CL_{NLoS}	25.5 dB
P_{max}	40 W	CL_{LoS}	9.2 dB
P_{uH}^T	49 dBm	X_{LoS}	$\mathcal{N}(0, \sigma_{LoS})$
θ	90°	X_{NLoS}	$\mathcal{N}(0, \sigma_{NLoS})$
σ_{NLoS}	0.6dB	σ_{LoS}	1.2dB
N_{TRX}^H	32 elements (8 dBi each)	η	0.5
C_{PV}	1300$	C_B	216 $

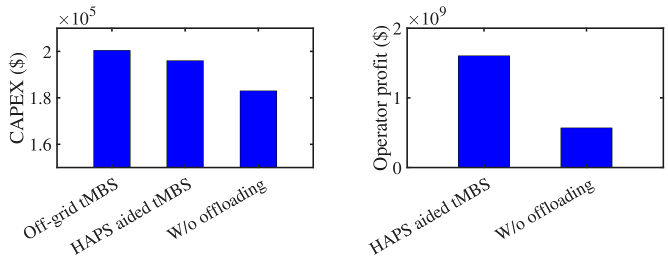
In Fig. 4(a) we first illustrate the influence of QoS guarantee on the number of users being served in the network. It is observed that as the minimum QoS requirement per user increases, the tMBS is able to serve much lesser number of users in a given closed area. In this paper we consider the minimum QoS requirement, $r_{th} = 1Mbps$.

Figs. 4(b)-(c) illustrate the variation of network QoS. It may be noted that network QoS is measured with respect to the percentage of users served by the network, especially during the peak hours (9AM - 6PM) in accordance with the traffic profile considered in Fig. 2. It is observed from Fig. 4(b) that the tMBS alone is able to serve only about 78% of the users, while a hMBS (operating at 50% frequency) aided tMBS network provides a gain of roughly 21.6%, serving close to 99.6% users. On varying the capacity of hMBS available to serve the considered close area (as in Fig. 4(c)), it is observed that the hMBS aided tMBS network still performs better than



(a) (b) (c) (d)

Figure 4: (a) Effect of minimum QoS on variation of tMBS transmit power level with user density, (b) Network QoS variation at peak hours (9 AM - 6 PM) in only tMBS scenario (no offloading) and HAPS aided tMBS scenario (hMBS operating at 50% capacity), (c) Network QoS variation in peak hours with limited hMBS capacity in HAPS aided tMBS network, (d) Variation of hMBS CAPEX for RAN with number of antenna elements equipped with hMBS.



(a) (b)

Figure 5: (a) Comparison of optimal CAPEX in purely off-grid tMBS, proposed HAPS aided tMBS framework, and without (w/o) HAPS based offloading scenario, (b) Comparision of operator revenue in proposed HAPS aided tMBS framework and w/o HAPS based offloading scenario.

a purely tMBS network. Fig. 4(d) illustrates the solar CAPEX provisioning required in a hMBS for RAN functioning as a function of number of antenna elements equipped with the hMBS. It is observed that the CAPEX of hMBS increases exponentially with increasing number of antenna elements.

In Fig. 5(a) we illustrate the CAPEX incurred to the mobile operator. As a benchmark we consider an off-grid standalone tMBS framework [12] and a without (w/o) offloading framework wherein the tMBS has flexibility of grid energy procurement in addition to energy selling. It is observed that the CAPEX incurred in the proposed HAPS aided tMBS network (which is also purely green network, as tMBS does not procure energy from the grid) is lesser than the off-grid scenario, but is higher than the w/o offloading framework.

Finally, in Fig. 5(b) we compare the net operator profit earned annually through the proposed HAPS aided tMBS network and a w/o offloading framework. It is observed that the proposed HAPS aided tMBS network results in a significant revenue profit to the operator (gain close to 64.51%) over the w/o offloading framework. This can be attributed because, despite incurring higher CAPEX, the proposed framework obtains higher revenue by user service (higher QoS service as shown in Fig. 4(b)). Further, there is no grid energy procurement in the proposed HAPS aided tMBS network, resulting in reduced operational expenditure to the operator, thus consolidating the net profit earned.

VI. Conclusion

The paper has proposed an analytical framework of a hMBS offloading aided and smart grid connected green communication network. To realize green network, the framework has aimed to limit the flexibility of tMBS to procure energy from grid, rather has used grid connectivity purely for energy selling purpose. The analytical framework has been modeled as a six state DTMC by studying the communication and energy aspects in the considered system. The proposed HAPS aided and grid connected tMBS network has been observed to provide significant gains in user QoS and operator profit despite incurring higher CAPEX. The proposed framework is expected to incentivize mobile operators, achieve grid energy independence, and pave the way towards green communication systems.

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