Traffic-Aware Satellite Switch-off Technique for LEO Constellations

Vaibhav Kumar Gupta, Hayder Al-Hraishawi, Eva Lagunas, and Symeon Chatzinotas
Interdisciplinary Centre for Security, Reliability and Trust (SnT), University of Luxembourg.
emails: {vaibhav.gupta, hayder.al-hraishawi, eva.lagunas, symeon.chatzinotas}@uni.lu

***Abstract*—Low Earth orbit (LEO) satellite constellations will be a fundamental part in future communication networks by providing seamless global coverage and extending data paths to the space, both in the standalone deployment and in the satellite-terrestrial integrated networks. However, LEO constellations still need to address a set of development challenges to ensure long-term viability; particularly, in terms of energy efficiency and satellite lifespan. In this paper, a traffic-aware satellite switch-off technique is proposed to minimize the power consumption in LEO constellations. This includes formulating and solving a mixed binary integer optimization problem under the constraints of satellite-user visibility and satisfying the demand requirements of all the ground users. The performance of the proposed technique is evaluated via simulations using practical constellation pattern and realistic traffic distribution. It has been shown that nearly 40% of the satellite nodes can be redundant and switched-off for energy saving, and thus, extending the constellation lifetime and alleviating the aggregated interference due to utilizing a large number of multi-beam satellites.**

***Index Terms*—Energy efficiency, LEO constellation, Non-terrestrial network.**

I. Introduction

Low Earth orbit (LEO) satellites offer faster communications with lower latency and often higher bandwidth per user comparing to geostationary orbit (GSO) and other non-geostationary orbit (NGSO) satellites [1]. Thus, the number of launched LEO satellites is currently soaring to establish mega-constellations for greater Internet connectivity and global coverage from space [2]. Within this direction, the third-generation partnership project (3GPP) standards group has identified several feasible pathways for leveraging LEO infrastructure along with terrestrial networks to deliver wide-ranging fifth-generation (5G) services and to bridge the digital divide [3]. Integrating satellite-based non-terrestrial networks (NTN) with the terrestrial communication systems has been part of the gradual shift of research focus and the industrial push towards 5G-Advanced leading into sixth-generation (6G) systems [4]. However, this fruitful integration has to confront the coexistence challenges of the emerging LEO constellations with other communication systems particularly in terms of spectral utilization and more importantly the aggregated interference issues due to the massive number of multi-beam satellites and the resulting inter-beam interference and inter-satellite interference [5].

Furthermore, LEO satellites have a stringent power constraint as they are equipped with solar panels and rechargeable batteries to be interchangeably used as energy sources to operate the satellite's components [6]. In order to retain the small size of LEO satellites, they operate with small sized batteries. In addition, they are in shadow phase for approximately half of their constellation period. Therefore, the battery lifetime is crucial for reliability of LEO satellites and this coupled with the fact that it is impractical to replace the satellite batteries, make employing energy-efficient mechanisms for extending their lifespan essential [7]. Beyond this, LEO satellites orbit the Earth with high-speed relative to a fixed position on the ground, which naturally yields a moving footprint to serve different geographical areas that have heterogeneous user distributions and variable traffic demands or occasionally no demand whatsoever as in the uninhabited regions [8]. Benefiting from this cyclic change in the traffic demands, developing a traffic-aware and dynamic satellite/beam switching off technique will not only save the onboard energy but also alleviate the aforementioned interference issues.

In this context, there are only a few prior related research on switching off the redundant satellites for boosting system energy efficiency. For instance, a framework to minimize the total number of active satellite beams required to cover all the ground terminals is proposed in [9]. Further, simple heuristic algorithms are developed in [10] for aggregating the distributed traffic in multiple satellites to a single satellite, and then, switching off the unnecessary satellite nodes. Similarly, the work in [11] has exploited the geographical variations and climatic conditions to power down satellite nodes during low traffic periods while guaranteeing the connectivity and quality-of-service (QoS) requirements. An energy efficiency maximization problem in a multi-beam single LEO satellite system was studied in [12]. Nevertheless, the existing works have neither considered the visibility constraints between LEO constellation and the ground users nor the dynamicity of the satellite constellation. Moreover, the aforementioned techniques have not been analyzed under practical channel models that take into account space-to-Earth propagation effects and the various path loss attenuation factors such as atmospheric gasses, ionospheric and tropospheric effects, etc.

To fill this gap, in this paper, the developed downlink channel models within the standardization efforts of the 3GPP non-terrestrial network (NTN) are considered [13]. The main contributions of this work can be summarized as follows:

- Developing a novel beam assignment, active beam power allocation, and satellite switch-off technique based on dynamic LEO satellite constellation pattern, practical 3GPP channel model, and realistic user traffic demands.
- Formulating an optimization problem to minimize the total power consumption of the LEO constellation while ensuring full satisfaction of the ground user demands. This problem is convexified by approximation and change of variable to find the optimal solutions.
- The performance of the proposed technique is investigated herein in terms of the number of satellite nodes/beams that can be switched-off. Simulation results including performance comparisons are provided to demonstrate the validity and gains of the proposed method.

The paper is organized as follows. In Section II we describe the system and channel model. Section III discusses problem formulation, its relaxation and the proposed solution. Section IV introduces the numerical results and finally Section V provides concluding remarks.

II. System and Channel Model

We consider a multi-beam LEO satellite constellation consisting of N LEO satellites to serve M ground users. Let $\mathcal{N} = \{1, \cdots, N\}$ and $\mathcal{M} = \{1, \cdots, M\}$ be the set of LEO satellite nodes and the ground users, respectively. Let N_B be the maximum number of users that can be simultaneously assigned to a satellite, i.e. the maximum number of beams per satellite. In this context, every user is assumed to be served by a single pencil-like beam as depicted in Fig. 1. In this system, both satellites and user terminals are equipped with tracking antennas. We use the general Walker constellation [14] in which the locations of all LEO satellites in the system are determined by the parameters in [15]. In LEO constellations, satellites are in a continuous motion and the coverage area of a specific satellite node changes over time, and hence, a certain user will be served by different satellites at different time instances based on satellite-user visibility. Thus, we define the visibility matrix $\mathbf{V}(t) = \{v_{n,m} | n \in \mathcal{N}, m \in \mathcal{M}\}$ as the available satellite collection to which the m-th user could be allocated at time instance t. Specifically, $v_{n,m} \in \{0, 1\}$ represents the binary visibility indicator, namely $v_{n,m} = 1$ indicates that the n-th satellite is available to the m-th user; else, $v_{n,m} = 0$. Typically, users have heterogeneous spatio-temporal traffic demands over the entire Earth. To account for this various demand distribution in the system, $D_m(t)$ denotes the data traffic demand of the m-th user at time instance t, and this demand should be satisfied by a satellite that is visible to the user. Furthermore, due to spectral and transmit power constraints, each satellite in the constellation has limitation on the maximum number of users or maximum demand that can be simultaneously served.

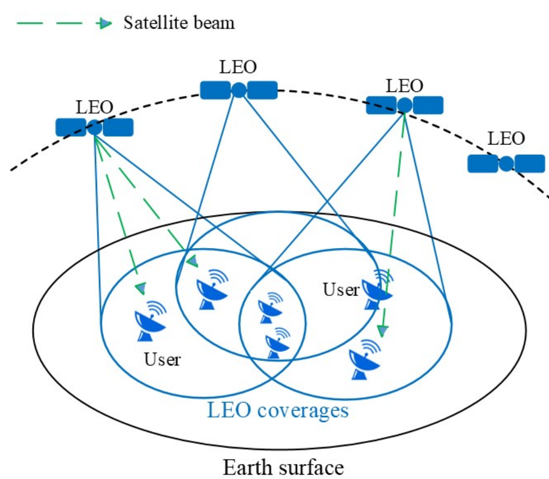

Fig. 1. This example illustrates a layout of multi-beam LEO satellite constellation coverage and ground users distributed over the Earth surface.

A. Channel model

The channel characteristics from LEO satellite constellation to the users are affected by a series of attenuation. In this context, the 3GPP in Release-15 gives several NTN channel models for different scenarios including our system model. Thus, it is more practical to investigate and analyze the studied system model by incorporating the developed 3GPP NTN channel model. Accordingly, the total path losses of the link between the n-th satellite and the m-th user is denoted as PL_m^n, and can be expressed as [16]

$$PL_m^n = PL_b(n, m) + PL_g + PL_s, \quad (1)$$

where $PL_b(n, m)$ represents the basic path loss from the n-th satellite and the m-th user, PL_g account for the attenuation due to atmospheric gasses, and PL_s is the attenuation due to either ionospheric or tropospheric scintillation. All these path loss components in (1) are measured in dB. Specifically, the basic path loss model $PL_b(n, m)$ accounts for the signal's free space propagation, clutter loss, and shadow fading. The free space path loss (PL_{FS}) in dB for a distance d_s (also known as slant range between the n-th satellite and the m-th user) in meter and frequency f_c in GHz can be calculated as

$$PL_{FS}(d_s, f_c) = 32.45 + 20 \log_{10}(f_c) + 20 \log_{10}(d_s). \quad (2)$$

Clutter loss (CL) represents the attenuation of signal power caused by surrounding buildings and objects on Earth. It depends on the elevation angle (α), the carrier frequency f_c, and the environment. The CL can be neglected when the user is in LOS condition, i.e. it should be set to 0 dB in the basic path loss model. Shadow fading (SF) is modeled by a log-normal distribution as $\mathcal{LN}(0, \sigma_{SF}^2)$ with zero-mean and σ_{SF} standard deviation. The values of σ_{SF}^2 and CL can be extracted from Tables 6.6.2-1 and 6.6.2-3 in the 3GPP Release-15. Hence, the basic path loss (PL_b) in dB unit is given as

$$PL_b(n, m) = PL_{FS}(d_s, f_c) + SF + CL(\alpha, f_c). \tag{3}$$

Essentially, PL_b, PL_g, and PL_s are the main sources of link attenuation, which vary with the satellite motion, and changes in path losses will cause changes in satellite service link capacity. Thereby, signal-to-noise ratio (SNR) from the n-th satellite to the m-th user can be expressed in dB as follows [16]:

$$SNR_{n,m} = G_t + G_r + P_{n,m} - PL_m^n - P_n \tag{4}$$

where $G_t, G_r, P_{n,m}, PL_m^n$ and P_n are all in dB and account for the satellite transmitting antenna gain, user receiver antenna gain, transmit power from the n-th satellite to the m-th user, the total path loss and thermal noise power at the m-th user, respectively. Alternatively, the SNR expression in (4) can be re-written in linear scale as

$$\gamma_{n,m} = \frac{g_t \; g_r \; p_{n,m}}{pl_m^n \; p_n} \tag{5}$$

where $\gamma_{n,m}$, g_t, g_r, $p_{n,m}$, p_n, and pl_m^n are the linear scale equivalent of the quantities defined in (4) and the total path loss in (1). Additionally, since the users are spatially separated by a few wavelengths, it is reasonable to assume that the channel realizations between the satellite and different users are uncorrelated [17]. Moreover, a 4-color reuse frequency scheme can be considered in such systems, that is allowing frequency reuse with minimal interference between neighboring beams [18], [19].

III. Problem Formulation and Proposed Solution

The focus of this work is to minimize the total power consumption of the LEO satellite constellation while satisfying the user demands over a time horizon T, which can be considered the constellation periodicity. The main objective is to minimize the number of active satellites. To this end, a binary assignment variable is defined to indicate whether a satellite is active or switched-off as follows

$$Y_n = \begin{cases} 1, & \text{satellite } n \text{ is active} \\ 0, & \text{satellite } n \text{ is switched-off.} \end{cases} \tag{6}$$

Similarly, a binary association variable is defined to indicate whether a satellite is serving a user as follows

$$X_{n,m} = \begin{cases} 1, & \text{satellite } n \text{ is serving user } m \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

In principle, the total transmit power of each satellite should not exceed its power budget. Specifically, the total transmit power budget of each satellite is denoted as P_T, which is the summation of satellite transmit power to the covered users plus the fixed on-board circuit power consumption when the satellite is switched on. In this, the transmit power of the n-th satellite to the m-th user at time slot t is denoted as $P_{n,m}(t)$, while P_c accounts for the fixed circuit power consumption. Further, it is assumed that each active beam has the same maximum transmit power and bandwidth similar to the works in [12], [20], which are denoted as P_b and W, respectively. Accordingly, the maximum beam transmit power (P_b) can be computed as

$$P_b = \frac{P_T - P_c}{N_B}. \tag{8}$$

Thus, an optimization problem to minimize the total power consumption of LEO satellite constellation can be formulated as follows:

$$\begin{aligned}
\underset{\forall P_{n,m}, \forall X_{n,m}}{\text{minimize}} \quad & \sum_{t=1}^{T} \sum_{n=1}^{N} \sum_{m=1}^{M} P_{n,m}(t) + \sum_{t=1}^{T} \sum_{n=1}^{N} P_c \, Y_n(t) \\
\text{subject to C1:} \quad & 0 \le P_{n,m}(t) \le P_b X_{n,m}(t), \;\; \forall n, \forall m \\
\text{C2:} \quad & \sum_{n \in \mathcal{N}} X_{n,m}(t) \le 1, \;\; \forall \, m, \\
\text{C3:} \quad & \sum_{n \in \mathcal{N}} X_{n,m}(t) \le D_m(t), \;\; \forall m \\
\text{C4:} \quad & \sum_{m=1}^{M} X_{n,m}(t) \le N_B, \;\; \forall n \\
\text{C5:} \quad & \sum_{m=1}^{M} X_{n,m}(t) \le M_0 Y_n(t), \;\; \forall n \\
\text{C6:} \quad & X_{n,m}(t) \le v_{n,m}(t), \; \forall n, \forall m, \forall t \\
\text{C7:} \quad & \sum_{n \in \mathcal{N}} W \log_2\left(1 + \gamma_{n,m}(t)\right) \ge D_m(t), \; \forall m, \forall t \\
\text{C8:} \quad & X_{n,m}, v_{n,m}, Y_n \in \{0, 1\}.
\end{aligned} \tag{9}$$

The first term in the objective function in (9) represents the total transmit power of the satellite to satisfy user demands and the second term corresponds to the fixed on-board circuit power consumption when satellite is switched on. Constraint C1 expresses that satellite transmit power for a user cannot exceed the maximum beam power P_b. Constraints C2 and C3 state that each user can only be served by one satellite at a time and a user can only be served if it has a non-zero traffic demand, respectively. Constraint C4 is to ensure that each satellite cannot serve more than N_B users at a time. In constraint C5, M_0 is a very large number to imply that a satellite is switched on when serving at least one user in that time slot. Constraint C6 ensures that a satellite is serving a user only when it is visible, i.e. within its coverage area.

Constraint C7 is to satisfy users' traffic demands at every time instance. Finally, constraint C8 is the binary constraint of the allocation variables for $X_{n,m}$, $v_{n,m}$, and Y_n.

A. Proposed Solution

The formulated optimization problem is of combinatorial mixed integer nature due to binary assignment variables. Moreover, constraint C7 renders the problem into a non-linear and non-convex problem. For the sake of tractability, we can make some reasonable and practical assumptions to relax the above optimization problem and propose a solution. Specifically, the time horizon T is divided into equal time slots [1] and solve the optimization problem in each time slot. Considering the optimization problem in each time slot, we can omit the time index t and sum over all the time slots. Furthermore, constraint C7 can be approximated for high SNR regime in each time slot by invoking (5) as follows

$$\sum_{n\in\mathcal{N}} W\left(\log_2\left(P_{n,m}\right)+\log_2\left(\frac{g_t g_r}{pl_m^n p_n}\right)\right)\geq D_m \quad \forall m \quad (10)$$

However, the problem is still non-convex due to constraint in (10) that has the term of $\sum_{n\in\mathcal{N}}\log_2(P_{n,m})$. Introducing auxiliary variable $\hat{P}_{n,m}$, such that $\hat{P}_{n,m}=\log_2(P_{n,m})$, can circumvent this issue. Consequently, the constraints C1 and C7 in (9) are transformed into constraints C9 and C10 in (11), respectively. Thus, the optimization problem is reformulated as follows for each time slot.

$$\begin{aligned}
&\underset{\forall\hat{P}_{n,m},\forall X_{n,m}}{\text{minimize}} \quad \sum_{n=1}^{N}\sum_{m=1}^{M} 2^{\hat{P}_{n,m}}+\sum_{n=1}^{N} P_c Y_n \\
&\text{subject to} \quad \text{C2, C3, C4, C5, C6, C8} \\
&\quad \text{C9:}\ 0\leq \hat{P}_{n,m}\leq X_{n,m}\log_2\left(P_b\right), \quad \forall n,\forall m, \\
&\quad \text{C10:}\ \sum_{n\in\mathcal{N}} W\left(\hat{P}_{n,m}+\log_2\left(\frac{g_t g_r}{pl_m^n p_n}\right)\right)\geq D_m,\ \forall m.
\end{aligned} \quad (11)$$

The reformulated problem is a convex problem and then can be solved efficiently by using well-known optimization tools such as CVX, a Matlab software for disciplined convex programming [21].

IV. Numerical Results

In this section, the performance of the proposed satellite switch-off technique for LEO constellations is evaluated through simulations. The simulation setup includes a LEO broadband constellation designed based the Walker star systematic pattern [14]. The Earth surface is represented by a planisphere area with longitudes from $-180°$ to $180°$ and latitudes from $-90°$ to $90°$ as shown in Fig. 2 and detailed in [22]. The left half of the planisphere, namely the longitude range between $-180°$ and $0°$ is covered by the ascending satellites that are moving from the South to the North, while the right half of the planisphere, specifically the longitudes from $0°$ to $180°$, is covered by the descending satellites that are moving from the North to the South. Hence, each satellite orbit planes is splitted into two equal half planes each in the left and the right planisphere. In this setup, the LEO constellation consists of 140 satellites that are equally distributed in 7 circular orbital planes. Each orbital plane has an inclination of $98.6°$ so that both poles are also covered and the orbital period of each satellite is 120 minutes [15], [23]. Further, longitude and altitude of the i-th orbital plane is $180(i-1)/7$ degrees and $600+10(i-1)$ Km, respectively. The visibility between a user and a satellite is computed using the Earth-centered, Earth-fixed coordinate (ECEF) coordinates of the satellite and user coordinates. Typically, a satellite is visible to a ground user when the elevation angle (ϵ) is greater than a certain minimum value, where in this work ϵ_{min} is set to be $10°$. The slant range d_s from a user on the ground to a satellite can be calculated as follows [14]:

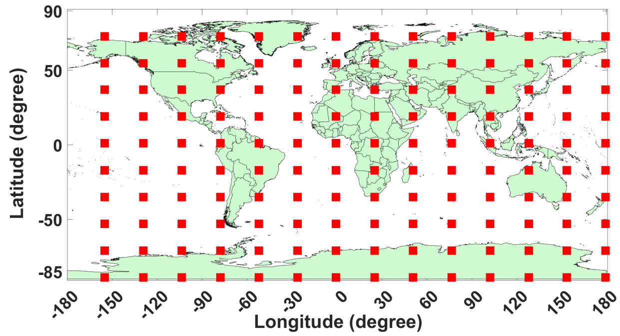

Fig. 2. A schematic diagram of the LEO constellation that includes 140 LEO satellites (represented as red squares) distributed over the Earth surface.

$$d_s = R_e\left[\sqrt{\left(\frac{H+R_e}{R_e}\right)^2-\cos^2(\epsilon)}-\sin(\epsilon)\right] \quad (12)$$

where R_e is radius of the Earth, and H is the altitude of the satellite orbital plane. Additionally, to incorporate the relative motion between the constellation and user terminals, a time horizon equals to satellite orbital period is considered, and then, divided into time slots of 5 minutes. The positions of all satellite nodes within the constellation are accordingly computed/updated and reflected in the visibility matrix for the consecutive time intervals. For users demand and distribution, we consider a realistic user locations obtained from a maritime dataset [24] for cruise ships having broadband connectivity from satellites during the day 30th June 2021.

[1]The duration of a time slot is selected such that the satellite constellation, downlink link budget, and the visibility matrix are changed with every time slot.

TABLE I
SIMULATION PARAMETERS [15]

Parameter	Value
Constellation type	Walker Star
Number of LEO satellites	140
Number of orbital planes	7
Altitude of orbital plane $i \in \{1, ..., 7\}$	$600 + 10(i - 1)$ Km
Orbital period T	120 minutes
Time slot duration	5 minutes
Orbit inclination	98.6^o
Max number of beams per satellite N_B	30
Bandwidth W	200 MHz
Downlink carrier frequency f_c	20 GHz
Satellite transmission power P_T	1000 Watt
Fixed circuit power P_c	10 Watt [12]
Satellite antenna gain G_t	38.5 dBi
User antenna gain G_r	39.7 dBi
Atmospheric loss	0.3 dB
Scintillation loss	0.5 dB
Noise figure	1.2 dB
Noise temperature	354 K

Additionally, the main simulation parameters are summarized in Table I.

In Fig. 3, a snapshot of the constellation coverage of the active satellites based on the proposed technique along with the users distribution at a particular time slot. Specifically, the coverage area of the satellites that are currently active to the users is shown in green colour while the remaining satellites that are shown by small black hexagons are off at this moment. Clearly, a set of the satellite nodes can be activated to fulfil the instantaneous demand of all users while the remaining satellite nodes can be shut down for energy conserving.

In Fig. 4, the proposed satellite switch-off approach is evaluated versus the traditional mechanism of always keeping all satellite nodes active. In particular, the number of satellite nodes that need to be active in each time slot and the average number of active satellite required over the considered time horizon are presented. In particular, it can be deduced that on an average approximately 40% of the total satellites can be shut down while satisfying the demands of all users. This is because the users in the unpopulated regions which are in the coverage of multiple satellite nodes can be associated with already active satellites.

Next, Fig. 5 presents a comparison in terms of the total power consumption of the satellite system which includes transmission and fixed circuit power of the active satellites over an orbital time period for two different values of the parameter N_B. Obviously, the total power consumption of the constellation averaged over an orbital period can be further decreased by increasing the number of beams per satellite. This is intuitive because less number of satellites are active when number of satellite beams are more. Finally, Fig. 6 represents the average number of active beams for each of the satellites over the considered time horizon. More specifically,

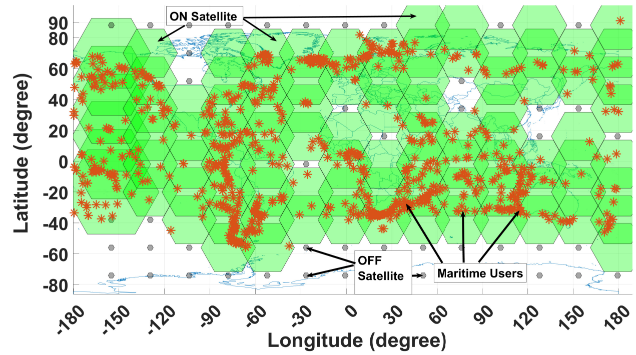

Fig. 3. A snapshot of the constellation coverage showing the association of the active satellites and the users obtained from the proposed solution to satisfy demands of maritime users over the Earth surface

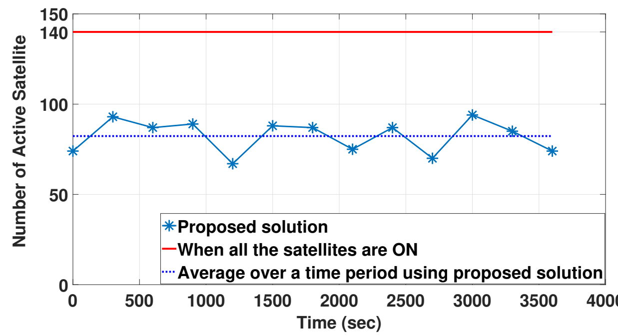

Fig. 4. The plot shows the number of active satellite required to satisfy the demand of all the user vs time when every satellite has $N_B = 30$ beams.

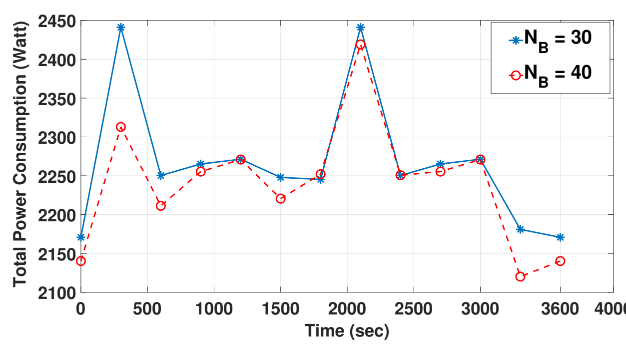

Fig. 5. The figure plots a comparison in terms of the total power consumption of the constellation during an orbital time period for two different values of number of satellite beams N_B using the proposed solution.

it can be seen that large number of satellites do not require to active more than 33% of beams averaged over an orbital period to satisfy user demands. This is mainly due to non homogeneous traffic demands and user density.

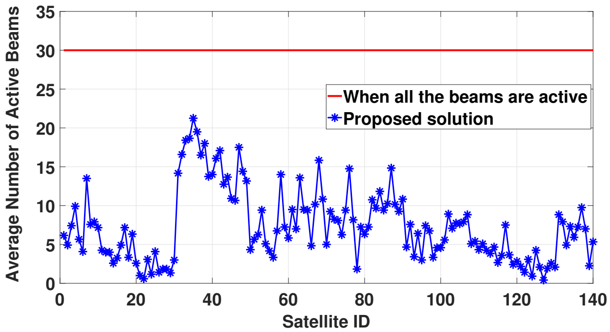

Fig. 6. The figure plots a comparison in terms of the average number of active beams required to satisfy the demand of all the users over an orbital time period with and without using the proposed solution.

ACKNOWLEDGMENT

This work has been financially supported by the Luxembourg National Research Fund (FNR) under the project MegaLEO: "Self-Organized Lower Earth Orbit Mega-Constellations" (C20/IS/14767486).

V. CONCLUSIONS

In this paper, a dynamic traffic-aware satellite switch-off approach is proposed to minimize the power consumption in LEO satellite constellations. The heterogeneous distribution of users in terms of time and location as well as the satellite relative motion have inspired the concept of shutting down a number of satellite nodes not only during low demand periods but also over the unpopulated regions. To this end, a mixed binary integer optimization problem has been formulated and solved to minimize the total power consumed by the LEO constellation without causing any demand dissatisfaction. The proposed approach has been evaluated via simulations under practical constellation pattern and using realistic traffic demands obtained from maritime dataset. The results have shown that a considerable percentage of the satellite nodes can be dispensable and switched-off, which may reach 40% in some cases. In short, the developed technique in this paper can significantly reduce energy consumption of satellites, and consequently, extending their lifespan and diminishing the interference impact on the concurrent communications.

REFERENCES

[1] R. Deng, B. Di, H. Zhang, L. Kuang, and L. Song, "Ultra-dense LEO satellite constellations: How many LEO satellites do we need?" *IEEE Trans. Wireless Commun.*, vol. 20, no. 8, pp. 4843–4857, 2021.

[2] H. Al-Hraishawi, H. Chougrani, S. Kisseleff, E. Lagunas, and S. Chatzinotas, "A survey on non-geostationary satellite systems: The communication perspective," *IEEE Commun. Surveys Tuts.*, 2022.

[3] X. Lin, S. Rommer, S. Euler, E. A. Yavuz, and R. S. Karlsson, "5G from space: An overview of 3GPP non-terrestrial networks," *IEEE Commun. Stand. Mag.*, 2021.

[4] T. Heyn, A. Hofmann, S. Raghunandan, and L. Raschkowski, *Non-Terrestrial Networks in 6G*. John Wiley & Sons, 2022, pp. 101–116.

[5] H. Al-Hraishawi, S. Chatzinotas, and B. Ottersten, "Broadband non-geostationary satellite communication systems: Research challenges and key opportunities," in *IEEE Int. Conf on Commun. (ICC)*, Jun. 2021, pp. 1–6.

[6] J. A. Fraire, G. Nies, C. Gerstacker, H. Hermanns, K. Bay, and M. Bisgaard, "Battery-aware contact plan design for LEO satellite constellations: The ulloriaq case study," *IEEE Trans. Green Commun. Netw.*, vol. 4, no. 1, pp. 236–245, 2020.

[7] H. Tsuchida, Y. Kawamoto, N. Kato, K. Kaneko, S. Tani, S. Uchida, and H. Aruga, "Efficient power control for satellite-borne batteries using Q-learning in low-earth-orbit satellite constellations," *IEEE Wireless Commun. Lett.*, vol. 9, no. 6, pp. 809–812, 2020.

[8] H. Al-Hraishawi, M. Minardi, H. Chougrani, O. Kodheli, J. F. M. Montoya, and S. Chatzinotas, "Multi-layer space information networks: Access design and softwarization," *IEEE Access*, 2021.

[9] S. Liu, J. Lin, L. Xu, X. Gao, L. Liu, and L. Jiang, "A dynamic beam shut off algorithm for LEO multibeam satellite constellation network," *IEEE Wireless Commun. Lett.*, vol. 9, no. 10, pp. 1730–1733, 2020.

[10] Z. Tang, C. Wu, Z. Feng, B. Zhao, and W. Yu, "Improving availability through energy-saving optimization in LEO satellite networks," in *Inf. and Commun. Technol. EurAsia Conf.* Springer, 2014, pp. 680–689.

[11] M. Hussein, A. Abu-Issa, I. Tumar, and A. Awad, "Reducing power consumption in LEO satellite network," *Int. J. of Elect. and Comput. Eng.*, vol. 11, no. 3, p. 2256, 2021.

[12] Q. Liao and M. Kaneko, "Global energy efficiency optimization of a ka-band multi-beam leo satellite communication system," *IEEE Access*, vol. 9, pp. 55 232–55 243, 2021.

[13] 3GPP TR 38.811V15.1.0, "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on New Radio (NR) to support Non Terrestrial Networks (Release 15)," 3rd Generation Partnership Project, Tech. Rep., 2019.

[14] J. G. Walker, "Satellite constellations," *Journal of the British Interplanetary Society*, vol. 37, pp. 559–572, 1984.

[15] I. Leyva-Mayorga, B. Soret, M. Röper, D. Wübben, B. Matthiesen, A. Dekorsy, and P. Popovski, "Leo small-satellite constellations for 5g and beyond-5g communications," *IEEE Access*, vol. 8, pp. 184 955–184 964, 2020.

[16] A. Guidotti, A. Vanelli-Coralli, A. Mengali, and S. Cioni, "Non-terrestrial networks: Link budget analysis," in *IEEE Int. Conf on Commun. (ICC)*, 2020, pp. 1–7.

[17] A. Adhikary, J. Nam, J.-Y. Ahn, and G. Caire, "Joint spatial division and multiplexing—the large-scale array regime," *IEEE Trans. Inf. Theory*, vol. 59, no. 10, pp. 6441–6463, 2013.

[18] R. Wang, M. A. Kishk, and M.-S. Alouini, "Ultra-dense LEO satellite-based communication systems: A novel modeling technique," *IEEE Commun. Mag.*, vol. 60, no. 4, pp. 25–31, 2022.

[19] A. Al-Hourani, "An analytic approach for modeling the coverage performance of dense satellite networks," *IEEE Wireless Commun. Lett.*, vol. 10, no. 4, pp. 897–901, 2021.

[20] J. Tang, D. Bian, G. Li, J. Hu, and J. Cheng, "Resource allocation for leo beam-hopping satellites in a spectrum sharing scenario," *IEEE Access*, vol. 9, pp. 56 468–56 478, 2021.

[21] M. Grant and S. Boyd, "CVX: Matlab software for disciplined convex programming, version 2.2," http://cvxr.com/cvx, Mar. 2014.

[22] J. Galtier, "Real-time resource allocation for LEO satellite constellations," *Wireless Netw.*, vol. 15, no. 6, pp. 791–803, 2009.

[23] S. Cakaj, "The parameters comparison of the "starlink" LEO satellites constellation for different orbital shells," *Frontiers in Communications and Networks*, vol. 2, p. 643095, 2021.

[24] H. Al-Hraishawi, E. Lagunas, and S. Chatzinotas, "Traffic simulator for multibeam satellite communication systems," in *10th Advanced Satellite Multimedia Syst. Conf. and the 16th Signal Process. for Space Commun. Workshop (ASMS/SPSC)*, 2020, pp. 1–8.