

On-Board Transmit Power Profile of a LEO Broadband Satellite Communication Service

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Abstract- The paper examines the utilization of onboard power resources of LEO satellites dedicated to broadband communication missions. It highlights the inefficiency of solely allocating transmit power for communication services, especially in regions with minimal service demand like vast oceanic areas. To address this issue, a realistic model of worldwide broadband demand is presented, considering factors such as population, purchasing capacity, technology, competition, and service availability. The analysis quantifies power usage based on the presented model, revealing opportunities to optimize resource allocation and enhance efficiency in hybrid mega-constellation operations beyond communication services.

Keywords—low earth orbit, broadband, satellite communication service, demand model, power profile, beam-hopping.

I. INTRODUCTION

In the last five years the space sector has undergone a great transformation, due to the emergence of new launch service providers and specially to the development of partially reusable rockets, what has drop down the access cost to space by half [1]. This has triggered the number of satellites in orbit and stimulated the deployment of constellations with thousands of satellites [2].

The use of onboard available resources within these mega-constellations, remains an unknown. In missions oriented into broadband communication services, due to the variability of the requested traffic demand among the globe, the available transmit power seems to be underused when solely thinking on the communication service. Huge oceanic regions with no service demand, implies counting with an available power onboard that for the best of authors knowledge is wasted.

With the objective of exemplifying the required onboard transmit power for communication services, the paper presents in Section II a realistic model of the expected worldwide broadband demand. The demand is calculated taking into account the potential users within the broadband service: the population, and then applying several correction factors to achieve realistic expected values: purchasing capacity, technological development of the region, service penetration, service concurrence, service availability, satellite service provider penetration, or time zone impact.

Based on satellite communication payload related assumptions presented in Section III, the demand model is then used to quantize the percentage of power usage in Section IV, highlighting in each time instant, the remaining available power that could have been used if additional services would have been included besides the communications one.

II. SERVICE DEMAND MODEL

To obtain representative power results, it is essential to count on a realistic demand model. The entire Earth surface is divided into pixels. The granularity of the grid and its form is modifiable, with a minimum granularity determined by the minimum available data resolution. The represented results are adjusted for maximizing the achievable gridding, with a model formed by square pixels of $1^\circ \times 1^\circ$ resolution in latitude and longitude. The model is particularized for terrestrial services, with the population as the potential users of the service. The model is completely extendible, apart from the terrestrial broadband service, additional maritime and air traffic communication services are intended to be included by following a similar approach. The complete results will be presented during the conference.

The main source of input data for the demand model is the population (P). The data associated to it is gathered from [3], adapting it to the required resolution. A uniform data rate of 20 Mbps for each user (D_u) has been estimated, obtaining the demand map represented in Fig. 1, which depicts the data rate in each pixel of the $1^\circ \times 1^\circ$ grid ($D_{raw\ 1^\circ \times 1^\circ}$).

$$D_{raw\ 1^\circ \times 1^\circ} = D_u \cdot P \quad (1)$$

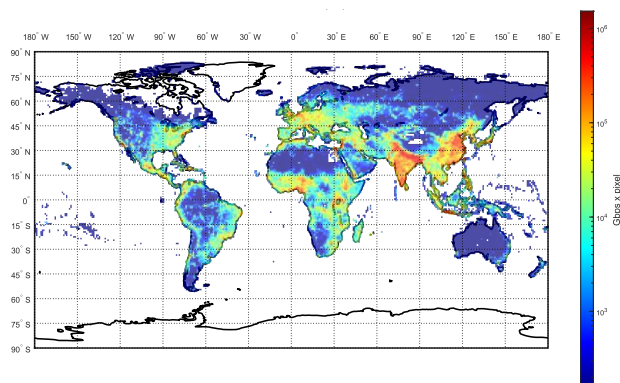


Fig. 1 Raw data rate per pixel $1^\circ \times 1^\circ$.

The results represent the raw demand, directly dependent on the population. From that point on several coefficients and factors are applied to obtain a realistic demand representation.

A. Terrestrial telecommunications infrastructure coefficient

The first factor corresponds to the existence of terrestrial telecommunications infrastructure (τ) and its purpose is to determine what places are better covered by the existing infrastructure in order to obtain a value that represents the need of satellite services. Worldwide cellular tower position data [4] is considered as a representative of the terrestrial

deployment, by taking into account all existing technologies: GSM, CDMA, UMTS, LTE, NR. Keeping the same $1^\circ \times 1^\circ$ grid, a map of cellular towers is created assigning a different value to each tower depending on the technology and expected data rate. LTE has been chosen as the normalizing technology due to its similarity in terms of throughput with Starlink. The rest of mobile technology weighting coefficients follow an approximated relative performance ratio: GSM and CDMA = 0.1, UMTS = 0.2, and NR = 2. The cell tower density map weighted by the corresponding technology coefficients is represented in Fig. 2, where developed regions such as Europe, North America and Japan count with the highest tower value. Besides the concentration of towers is even more visible in populated cities.

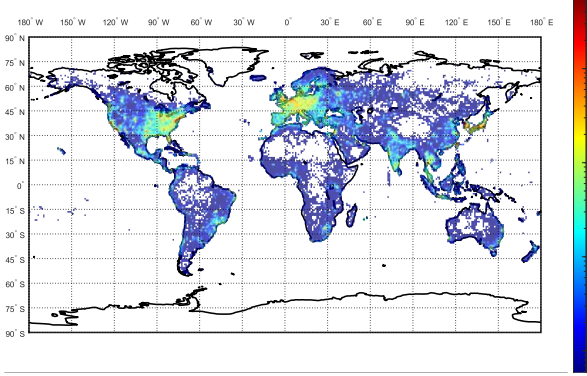


Fig. 2 Tower density per pixel.

For determining the quality service achievable by the terrestrial cellular infrastructure in each of the pixels, the data is combined with the population data by then applying an exponential normalization for obtaining a distribution from 0 to 1, being 1 a maximum need of satellite services and 0 the representation of an awesome terrestrial coverage. The maximum threshold value for the normalization is chosen considering that it is not expected to count with a high satellite demand in populated regions with a developed telecommunications infrastructure. The results in Fig. 3, represent that distribution, with red regions where solely from a terrestrial infrastructure perspective the inclusion of a satellite service is more expected and on the contrary, blue regions, developed urban regions (North America, Europe and Australia) where no satellite service demand is anticipated.

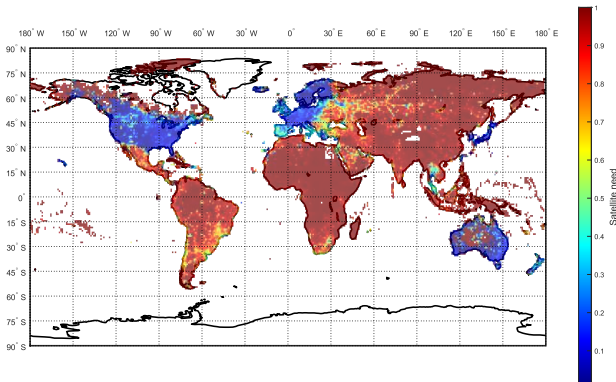


Fig. 3 Infrastructure coefficient.

B. Additional coefficients.

Apart from the terrestrial coefficient described in Section II-A, additional correction coefficients are considered for

computing the final varying demand expression ($D_{1^\circ \times 1^\circ}(t)$), those that are embedded within the $N_{u(t)}$ factor of Equation (2), with $N_{u(t)}$ representing the number of users for the satellite service.

$$D_{1^\circ \times 1^\circ}(t) = D_u \cdot N_{u(t)} \quad (2)$$

Where:

$$N_{u(t)} = P \cdot \tau \cdot B \cdot \alpha_p \cdot S \cdot \alpha_{sat} \cdot \alpha_s \cdot \alpha_c \cdot TZ(t) \quad (3)$$

The overall correction factors are described as follows:

- Population (P): population in the pixel grid.
- Telecommunications infrastructure coefficient (τ): already explained in section 1-A.
- Purchasing power coefficient (B): it indicates the purchasing power capacity of the population of each pixel, the higher it is the more users can hire the service. The coefficient is obtained with the data from [5], which corresponds to the Gross Cell Product (GCP). The GCP is similar to the Gross Domestic Product (GDP) but referred to a region of $1^\circ \times 1^\circ$ resolution in latitude and longitude. The value is then divided by the population in each cell or pixel, obtaining what could be named as GCP per capita. Similarly to the process done with the telecommunications infrastructure coefficient, an exponential normalization coefficient is applied. In this case, the maximum threshold normalization value corresponds to a GCP per capita high enough to purchase a satellite service cost similar to the Starlink service.
- Satellite service provider penetration (α_p): the coefficient indicates the penetration of the provider in the market. The selected penetration follows once again the example of Starlink, one of the biggest providers of satellite telecommunication services for end users so far.
- Service availability (S): boolean factor that indicates if the provider's service is available in the region or not. As Starlink is not available in several countries (such as Russia, China, Cuba, North Korea, ...), some regions can be blocked. Using the population data per country in [6] a mask is developed with 0/1 values to restrict countries where no service can be given. For the results presented in this paper, no service restriction has been supposed.
- Visible satellites (α_{sat}): the coefficient indicates the number of satellites visible in a specific region at any time. Considering satellite footprint for a Starlink constellation type and the actual and future number of satellites in the constellation. It is assumed that at least 10 satellites are visible in the regions of more coverage ($\pm 55^\circ$ latitude), splitting the users among those satellites.
- Satellite service penetration (α_s): adoption rate of satellite-based communication services.
- Service concurrence (α_c): it indicates the simultaneous access of the users to the service. A typical value for broadband internet services is used.
- Local time correction ($TZ(t)$): the factor indicates the usage as a function of the local time in the region where the satellite is providing service taking into population habits, for example assigning a value of 0.2 during nights and 1 during main working hours. This value is applied directly in the

calculations of each satellite position, so it is not visible in the maps presented in Fig. 4.

The selected demand coefficients are summarized in TABLE I.

TABLE I
DEMAND COEFFICIENTS

τ	B	α_p	S	α_{sat}	α_s	α_c	$TZ(t)$
[0,1]	0.85	{0,1}	0.1	0.1	0.1	0.02	{0.2,0.3,0.5,0.8,1}

C. Demand results.

By applying all these coefficients, the map from Fig. 4 can be obtained. Comparing it with Fig. 1, the broadband demand is adjusted worldwide by considering previously described factors. It can be seen that, in high populated areas, like India or parts of Africa and South America, but with low-income rates the expected demand is notably reduced.

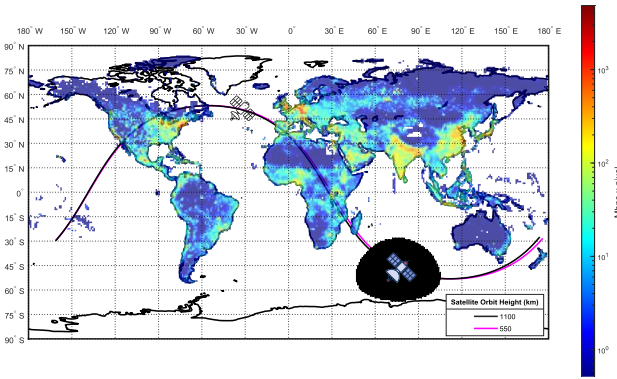


Fig. 4. Final demand map with satellite ground track and FoV.

III. COMMUNICATION PAYLOAD

To translate the demand into required satellite transmit power, it is essential to establish some key communication-based assumptions. As illustrated in Fig. 4, single satellite Low Earth Orbits (LEOs) are evaluated, comparing two possible orbital heights (h): 550km and 1100km, both with an orbital inclination (i) of 53.1° . In each time instant, the satellite's field of view (FoV), centered around the subsatellite point (SP), is restricted as per the minimum elevation angle criteria: 25° . Within the FoV, a fixed grid of 271 cells (N_C) is depicted, simultaneously illuminating (I) just 16 of those cells. The illumination scheme follows a pre-scheduled beam-hopping (BH) strategy, switching the illumination of the cells the satellite covers in a cyclic manner. For the limited illumination time, power and frequency resources are allocated just to 16 of the beams. The periodicity (T) of the proposed communications scheme is therefore determined by the ratio between the total number of cells within the FoV, and the achievable simultaneous illumination beams, almost 17 for the case under study.

User grouping plays an essential role when studying BH schemes, as illumination is usually driven by the user and therefore the traffic distribution. For the sake of simplifying the study, without evaluating the resource allocation process [7] from an illumination scheme perspective, a worst-case configuration is selected, where users are uniformly distributed within the FoV. The link budget therefore considers that the

varying aggregated demand (D) within satellite's FoV from Fig. 5, linked to Fig. 4, is equally splitted into those 271 cells.

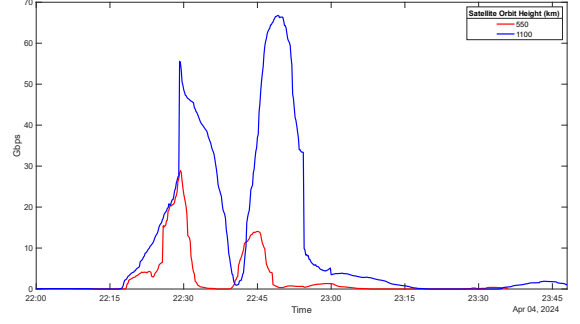


Fig. 5 Aggregated demand within satellites field of view.

TABLE II
SIMULATION SCHEME

Orbital Height (h)	1100km	550km *
Orbital Inclination (i)	53.1° *	
Elevation Angle (el_{min})	25° *	
Number of Cells (N_C)	271	
Simult. Illum. Cells (I)	16	
Illum. Periodicity (T)	17	
Beamwidth ($\Delta\theta_{3dB}$)	11.85°	13.92°
Operation Freq. (f)	11.7GHz *	
Bandwidth (BW)	500MHz *	
Free Space Losses (FSL)	174.64dB	168.62dB *
Transmit Gain (G_{TX})	22.81 dB	21.41 dB
Receiver Gain (G_{RX})	32.85 dB*	
Eq. Noise Temp. (T_{eq})	67.98 K	

*Values based on STARLINK 1029 and Starlink UT [10]

In the selected 16 beams the demand is $1/P$ portion of the total one (D), but, as the illumination is maintained only for $1/P$ seconds, the instantaneous demand that will need to be offered in each time instant by a given beam is required to be increased by a factor of P . The demand associated to the illuminated beams (D_{beams}) is computed as follows:

$$D_{beams} = \frac{D}{P} P = D \quad (4)$$

As per the uniform traffic distribution assumption, for the estimation of the single beam demand (D_{beam}), D_{beams} is divided by I .

$$D_{beam} = \frac{D_{beams}}{I} = \frac{D}{16} \quad (5)$$

The flow for computing the required transmit power per beam ($P_{TX_{beam}}$) for serving the requested demand (D_{beam}) is depicted in (6).

$$D_{beam} \rightarrow SE \rightarrow \frac{C}{N} \rightarrow P_{TX_{beam}} \quad (6)$$

The link budget from Equation (7) is calculated for each of the illumination beams, assuming that due to the special diversity of the beams selected for illumination, the total bandwidth (BW) can be allocated per beam. The rest of the parameters are presented in TABLE II.

$$\frac{C}{N} = (G_{TX} + P_{TX_{beam}} - FSL + G_{RX}) - (K + T_{eq_{noise}} + BW) \quad (7)$$

The required spectral efficiency (SE) and associated modulation and coding scheme (MODCOD) is determined by

the instantaneous D_{beam} , following an adaptative modulation and coding scheme (ACM) as per DVB-S2X [8]. With the fixed BW , a higher demand implies incrementing the required MODCOD complexity, for increasing the SE, and therefore increasing too the required C/N to close the link under those conditions. The beam transmit power is directly derived from the link budget equation: $P_{TX_{beam}}$.

IV. ON-BOARD TRANSMIT POWER PROFILE

The results discussed in this section represent the variation of the total transmit power requirement for the communication service (P_{Tx}). Assuming single feeding per beam, the total transmit power is calculated as the summatory of the required power by each beam's dedicated amplifier to close the link budget:

$$P_{Tx} = \sum_{beam=1}^{16} P_{Tx_{beam}} \quad (8)$$

Applying the Equation (8), the total required transmit power during a complete satellite orbital period is depicted in Fig. 6, comparing the results for 1100 km and 550 km orbital heights. By following the ground track of Fig. 4, it can be seen that for most part of the period, the power needed in the satellite is minimum compared to the peak power, corresponding to European and North American areas. The maximum power required for the orbital height of 550 km is almost 90W being 3.65W the average power. For the 1100 km case, the required maximum power is increased to 491W, and the medium power corresponds to almost 88W.

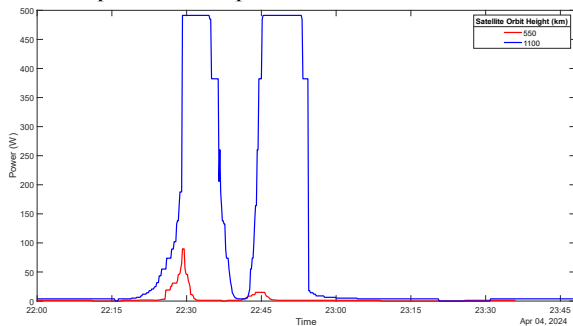


Fig. 6 Required satellite TX power.

It can therefore be affirmed that satellite resources are clearly underused most of the time. The difference in terms of power between orbital heights is based on the satellite's FoV, depicted in Fig. 4 too. A higher FoV in the 1100 km case implies a higher aggregated demand that will need to be supplied, Fig. 5, which is directly translated into a higher transmit power requirement, Fig. 6. The 550 km orbital height is more affordable from a single satellite power perspective, but at the same time, more satellites are required to offer a full coverage broadband communication service. By analyzing the 1100 km total demand, it can be affirmed by looking into the power profile from Fig. 5, that not all of it will the satellite be able to supply. Required transmit power for both peak regions saturates, with the same value in both power peaks, but with an aggregated demand higher in the second European peak compared to the North American one. In those cases, the system does not cover the data rate that is being demanded as with the given BW , there is no SE capable of closing the satellite to user link.

V. CONCLUSIONS

A comprehensive and realistic model has been presented throughout the paper, to forecast the expected demand for broadband internet services worldwide. Subsequently, this demand model is used for the assessment of the power profile, i.e. the percentage of power consumed by a LEO satellite, taking as a reference a Starlink constellation satellite. As it was expected, satellite power resources are underused most of the time when solely evaluating broadband communication services. The presented results can be extrapolated for the rest of the satellites of the constellation by achieving a total percentage of power used by the constellation. If the percentage of use is low, the remaining on-board power can be employed for other use cases where power could be demanded, such as edge computing. The availability of this green source of power is expected to diminish the carbon footprint of data storage and cloud computing services [9].

The analysis is also applicable for other mega-constellations, such as OneWeb (Eutelsat) or Kuiper (Amazon).

ACKNOWLEDGEMENTS

This work has been supported by the Spanish Government, Ministry of Economy, and the National Program of Research, Development, and Innovation under the project New Array Antenna Tech. and digital processing for the FUTURE integrated terrestrial and space-based millimeter-wave radio systems, UPM-InTerSpaCE, under Grant PID2020-112545RB-C51.

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