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A Novel Dimensioning Method For High Throughput Satellite Design

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Abstract—This work describes a novel methodology for the dimensioning of a Ka-Band *high throughput satellite* (HTS) for broadband communications. The method is based on the optimization of performance for a forward link, as a function of a set of input criteria and a given envelope of available power. This approach is based on a spacecraft architecture using a multi-beam coverage implementing frequency re-use. Among the input criteria, we use the percentage of covered service area with a certain type of earth stations, the service availability and the cost and mass of the system. The proposed methodology is adaptable to any kind of service area. A *digital video broadcasting satellite second generation* (DVB-S2) air interface with *adaptive coding and modulation* (ACM) is used as a reference. The method, employing iterative advanced link budget calculations including carrier-to-interference at antenna level, provides the highest capacity given a batch of antenna and pragmatic feed design.

I. INTRODUCTION

High throughput satellites (HTS) currently make use of multi-beam coverages at high frequency bands in order to offer broadband access on a large area for small user terminals. As the terrestrial broadband offer does not cover large territories, a satellite broadband alternative is considered as a complement rather than a direct competitor to fiber optics and ADSL [1]. There are numerous ways of designing satellite architectures and different types of possible trade-offs to achieve based on the chosen design parameters. Those parameters range from the ground segment (e.g. the level of complexity of a user terminal and a Gateway) to the space segment (e.g. the whole definition of the spacecraft system and subsystems including antennas). In order to provide a clarification of the choices, the logic presented hereafter aims at showing a novel methodology which helps obtaining the best trade-off for the highest achievable capacity. It is based on a set of input and design criteria, opening an efficient dialog between system engineers and antenna engineers. This provides a new level of comprehension and cooperation integrating these sometimes opposite engineering approaches and will accelerate the design phase of the satellite. Also, the resources can be quickly focused on a selected set of technical solutions identified by the methodology which can be analyzed in detail. First, we are going to show the problematics to which the methodology is going to provide answers to and how it is implemented in Section II. In Section III, we highlight the key models used in the process. Section IV highlights a technical solution suggested for a

given scenario. Section V concludes the study and gives a perspective of future possibilities.

II. PROBLEM DESCRIPTION

When a satellite operator orders a new satellite, it invests effort and time to assess the different transmission scenarios and services. For instance, it is challenging to align the system requirements with the antenna requirements as one impact the other and vice versa, all in a given budget envelope. A general approach has been defined by a satellite manufacturer, but in the frame of beam hopping and for a very industrial approach [2]. Also another approach has been developed [3] but takes into account very detailed traffic constraints and is quite specific.

HTS systems offer high total system capacities by reusing the spectral resources through frequency re-use and spatial separation of beams using the same frequency bands. However, those kinds of systems are often constrained by inter-spot interference and possible high attenuations.

Through our methodology, it is possible to combine different types of requirements and constraints both technical or commercial, thus obtaining in the end the system with the highest capacity. The methodology uses two distinct sets of “high system level” inputs:

- the **technical inputs**: available payload DC power, antenna reflector size, maximum payload mass, ...
- the **commercial inputs**: covered service area, quality of service, financial budget limitations, ...

Those constraints compose the initial system statement and are kept fixed along the process. The method will then use “design” parameters, which drive the optimization and translate the initial statement into performance criteria. The parameters are composed of:

- the **service area filling percentage** (SAP), which corresponds to the minimum percentage of service area where the initial statement has to be respected¹
- the **availability of the satellite link** (AV), as the percentage of time of activity of a service over a year,
- the **cost of the satellite** (CO), including manufacturing and launch costs,

¹it is considered that the areas that are not covered, can obtain however the service via other means (larger user antennas or even alternative systems)

- the **mass of the satellite (MS)** due to launcher constraints.

All four parameters translate a key element of a satellite project. It is vital to find the proper equilibrium for a large service area in order to address large markets. From a QoS point of view, providing the highest service availability means a robust satellite link that can be maintained over a long period of time. From a financial point of view, designing a cost efficient satellite allows for a better service pricing and a good market penetration of a satellite broadband alternative. The mass of the satellite is critical for the possible launcher to select.

The method then achieves the best architectural trade-off for the highest achievable capacity by varying the number of spots in an iterative manner while testing the compliancy of the system to the four “design” parameters. All the selected systems are stored and compared to each other in order to find out the most efficient one.

To ease the procedure without loss of generality, the link budget calculations are focused on the Forward Link (from Gateway towards the end users) and more specifically on the Downlink (Satellite to terminals) as this link segment is the most constraining and system dimensioning for the capacity.

The key steps of the method itself are shown in the Flowchart 1.

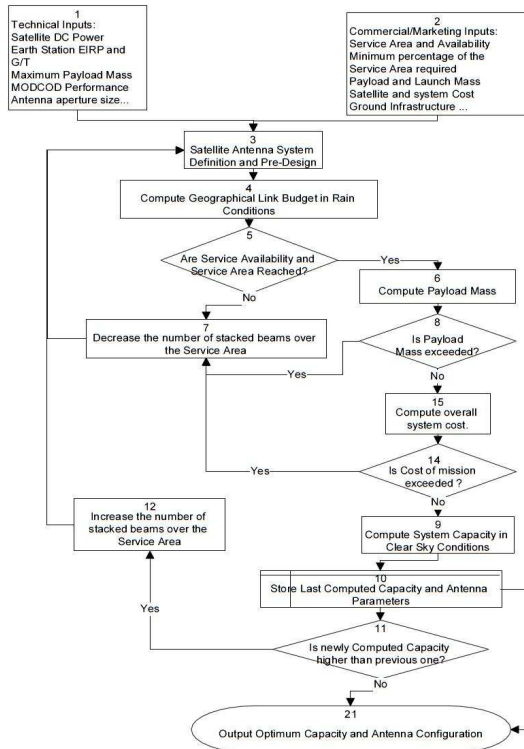


Figure 1. Flowchart of the methodology

III. PROPOSED KEY MODELS

A. Antenna Model

In our work, one of the antenna design choice is to keep the *focal length to diameter ratio* (f/a) constant to one. The reflector size, a , has to be chosen and also kept fixed for the whole performance assessment of the methodology.

In this work we use a classic antenna model, which can be easily interpreted in terms of *equivalent isotropically radiated power* (EIRP) or *gain over noise temperature* figure of merit. The adopted reflector model takes into account the illumination taper (the amount of reflected energy reflected by the aperture) and more precisely the edge taper and spillover losses. The antenna trade-off is a very complex process and results from different consideration ranging from the defined service area to the size of the reflector and the feed geometry. The consequences of a poor antenna choice conditions the overall satellite performances. So including a coherent antenna model into the methodology translates the effects (benefits or losses) of increasing/decreasing the number of beams for a given reflector size.

The chosen model for our study is based on the work done by Peter Balling [4] but more antenna models and simulation samples can be found in the references [5] and [6]. Balling’s model is based on a linear combination of Bessel functions and corrective coefficients taking into account the spillover losses and edge taper illumination. The position of the beams and their relative direction towards the reflector are also integrated.

Let us consider a feed j in a cluster and the reflector geometry shown in Figure 2.

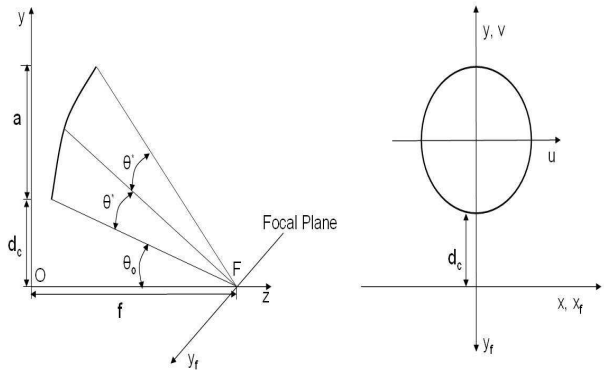


Figure 2. Side and front views of offset reflector with focus at F and $x_f y_f$ focal plane

The field amplitude generated by a feed can be expressed as:

$$F_j(\theta, \phi) = \kappa \times a \times (c_1 \times \chi(1, \kappa \times a \times x_j) + c_2 \times \chi(n + 1, \kappa \times a \times x_j)) \quad (1)$$

with:

- a , reflector diameter,
- κ , the propagation constant $\frac{2\pi}{\lambda}$,

- θ and ϕ , coordinates in a spherical reference system with the antenna boresight as the zenith direction,
- x_j , the angular distance between the field direction (u, v) and the feed, $x_j = \sqrt{((u - u_j)^2 + (v - v_j)^2)}$,
- (u, v) the coordinate system defined as $u = \sin \theta \cos \phi$; $v = \sin \theta \sin \phi$,
- n , number of feeds,
- χ is given by:

$$\chi(n, x) = \begin{cases} 1, & x = 0, \\ 2^n n! \frac{J_n(x)}{x^n}, & \forall x \neq 0. \\ J_n(x) = \frac{1}{2\pi} \times \int_{-\pi}^{\pi} \exp[-i(n\tau - x \sin \tau)] d\tau \\ J_n(x) \text{ is a Bessel function of order } n \end{cases}$$

The model is dependent on the number of feeds to accommodate and the coordinates of each one, with regard to the reflector. In addition to the feed cluster geometry, those elements are taken into account in the corrective coefficients c_1 and c_2 .

They can be expressed as:

$$c_1 = \frac{\zeta_o}{\sqrt{\frac{1+n+2 \times n \times \zeta_o + 2 \times n^2 \times \zeta_o^2}{1+3 \times n+2 \times n^2}}} \times L_{SO} \quad (2)$$

$$c_2 = \frac{1 - \zeta_o}{(1+n) \sqrt{\frac{1+n+2 \times n \times \zeta_o + 2 \times n^2 \times \zeta_o^2}{1+3 \times n+2 \times n^2}}} \times L_{SO} \quad (3)$$

with:

- ζ_o , average aperture edge illumination i.e reflected power
- L_{SO} , element-beam spillover loss

Finally, the antenna directivity D_{ir} in dB is:

$$D_{ir} = 10. \log_{10}(|F_j(\theta, \phi)|^2) \quad (4)$$

B. Interference Model

In a multi-beam coverage with frequency re-use, there will be two types of interference: the interference induced by the spots using the same frequency with the same polarization but spatially separated, called co-polar interference I_{co} , and the interference induced by the spots using the same frequency but with a directly opposite polarization, called cross-polar interference I_{cx} .

Let us consider a spot k , at the position defined by x , receiving the signal power of C_k in W and surrounded by a number of interfering spots.

The Co-polar contribution $I_{co}(x)$ can be evaluated as:

$$I_{co}(x) = \sum_{q=0}^{M_{I_{Co}}} P_{co}(q, x) \quad (5)$$

with:

- q , refers to the q^{st} interferer spot,
- $M_{I_{Co}}$, the total number of interferers in co-polarization,
- x , position of the user terminal,
- $P_{co}(q, x)$, the transmitted power by the satellite for the q^{st} interferer in co-polarization at position x .

The cross polarization contribution, $I_{cx}(x)$, can be evaluated as:

$$I_{cx}(x) = \sum_{p=0}^{M_{I_{Cx}}} P_{cx}(m, x) \quad (6)$$

with:

- m , refers to the m^{st} interferer spot,
- $M_{I_{Cx}}$, the total number of interferers in the cross polarization,
- $P_{cx}(p, x)$, the transmitted power by the satellite for the m^{st} interferer in cross polarization.

Thus for spot number k :

$$\begin{aligned} I_k(x) &= I_{co}(x) + I_{cx}(x) \\ \left(\frac{C}{T}\right)_k(x) &= \frac{C_k(x)}{I_k(x)} \end{aligned} \quad (7)$$

Note that we consider the interference behavior identical in both polarizations.

C. Link Budget

The link budget calculation is based on well known link budget models [7], [8] and on the *International Telecommunication Union* (ITU) recommendations [9] to [10].

First we calculate (in dB):

$$\begin{aligned} \frac{C}{N_0}(x) &= E_{EIRP}(x) + \left(\frac{G}{T}\right)_{GroundTerminal} \\ &\quad - L_{FreeSpace}(x) + 228.6 - A_{tt}(x, p) \end{aligned} \quad (8)$$

with:

- x , position of the user terminal in consideration
- p , corresponds to the the link availability over a year
- $\frac{C}{N_0}(x, p)$, corresponds to the ratio between the total energy of a carrier over the thermal noise of the channel in dB
- $E_{EIRP}(x)$, the EIRP in dBW transmitted at the position x
- $\left(\frac{G}{T}\right)_{GroundTerminal}$, the figure of merit for the ground terminal given its thermal performances in dB/K
- $L_{FreeSpace}(x)$, the free space losses inherent to any satellite communication due to the distance to travel in dB
- 228.6, corresponds to the value in dB of $\frac{1}{k_B}$, where k_B is the Boltzman constant
- $A_{tt}(x, p)$, the total attenuations due to atmospheric phenomena at position x given a certain link availability p

Based on the ITU recommendations in reference [9] to [11], the total attenuation is calculated as follows:

$$A_{tt}(x, p) = A_G(x, p) + \sqrt{(A_R(x, p) + A_C(x, p))^2 + A_S(x, p)^2} \quad (9)$$

with:

- $A_R(x, p)$, corresponds to the attenuation due to rain for a fixed probability p at position x in dB [12] and [13] to [11]
- $A_C(x, p)$, corresponds to the attenuation due to clouds for a fixed probability p at position x in dB [14]

- $A_G(x, p)$, corresponds to the attenuation due to water vapour and oxygen for a fixed probability p at position x in dB [14]
- $A_S(x, p)$, corresponds to the attenuation due to tropospheric scintillation for a fixed probability p at position x in dB [10]

Note that for clear sky conditions, the attenuations due to rain are neglected.

Finally, the overall satellite link budget (in a linear manner) is:

$$\left(\frac{C}{N_0 + I_{tot}}(x) \right)^{-1} = \left(\frac{C}{N_0}(x) \right)^{-1} + \left(\frac{C}{I}(x) \right)^{-1} \quad (10)$$

where, $\frac{C}{I}(x)$ corresponds to the interference induced by the frequency re-use.

IV. RESULTS

In our study, we will discuss one scenario based on four 2m antenna reflectors with a service area centered over central western Africa. In this scenario, we use an orbital position of 0°E as an arbitrary position. The downlink frequencies used are 19.7 GHz and 20.2 GHz in the Ka-Band. The air-interface is the **DVB-S2** [15] standard. The payload power is kept fixed at 10 kW over the different spot scenarios and the power is distributed uniformly on every spot (i.e. all the TWTAs have the same amplification level). The user terminals use an antenna of 0.75m and can use a 500MHz bandwidth. The different design parameters are defined with the following thresholds:

- *service area filling percentage*, SAP of 80%,
- *availability of the satellite link*, AV of 80%,
- *cost* CO and *mass* MS not constrained.

For the sake of the technical analysis the cost and mass requirements are not a discriminating factor as mentioned in the previous scenario.

Figure 3 shows an example of EIRP(dBW) coverage over central western Africa for 448 spots.

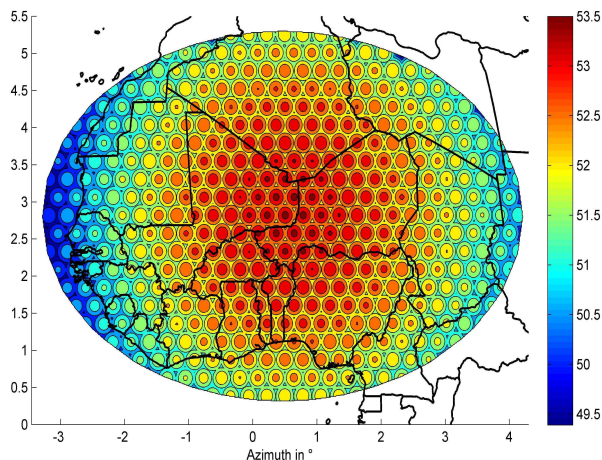


Figure 3. EIRP performance map over central western Africa

By running the iterative optimization process for this scenario, we obtain the results of Figure 4.

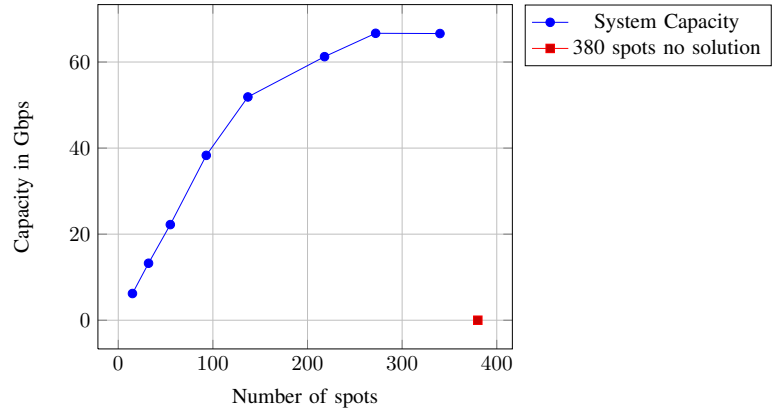


Figure 4. Total system capacity and channel capacity

Figure 4 shows that increasing the number of spots increases the capacity in Giga bits per second (Gbps). The bandwidth re-use factor is increased, underlining a higher reuse of the spectral reuse. A stagnation and a slight decrease in capacity takes however place for beam patterns of more than 250 spots due to very high interference and low aperture efficiency. The feed diameters being smaller, more directive beams are illuminating only a small area of the reflector i.e. low illumination taper. The red dot indicates the number of spots at which the optimization procedure fails to find a solution.

The stop in the method is incurred to the fact that the SAP criteria combined with the AV criteria are no longer matched as shown in figure 5.

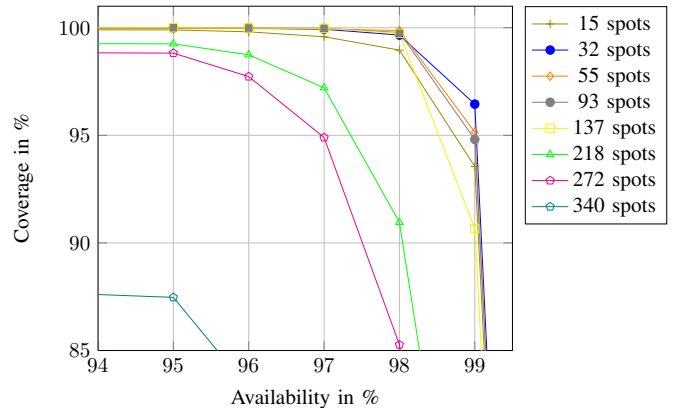


Figure 5. Coverage percentage versus availability

Figure 5 presents for each beam pattern the curve in terms of service area percentage versus availability. One can see that, the more beams are covering the service area the lower the SAP is for high availabilities. The availability is primarily linked with the attenuations. This implies that the system needs to compensate higher attenuations for higher service availabilities in addition to higher interference for higher beam densities. By confronting the SAP with the achievable availability, it is possible to link those two effects together

as they are part of the $C/(N_0 + I)$. On the Figure, it appears also that given the requirements, the next iteration of the spot pattern is no longer reliable enough for the SAP and AV criteria combined, thus saving processing time.

Either way, there are two options. One can say that the best system is at 340 spots corresponding to a beam spacing of 0.32° and that more detailed studies can be done on this structure. Or one can say that there is an optimization area around 340 spots, where a more fine tuned study with the methodology can be performed. No cost or mass related constraints have been taken into account in order to keep the focus of the methodology on the technical side. However, a cost model has been developed based on data of current and short term satellite broadband projects [16]. In [17], an article submitted for publication, the cost model is as follows:

$$sat_{cost} = 180 + 1.8 \times N_{spots} \quad (11)$$

with:

- sat_{cost} , cost of the satellite in million euros
- N_{spots} , corresponds to the number of spots composing the coverage

By using a reference metric in terms of *cost per Giga bits per second*, one can translate the financial “efficiency” of the complete satellite project. Given the studied system, Figure 6 highlights an optimum system from a cost perspective.

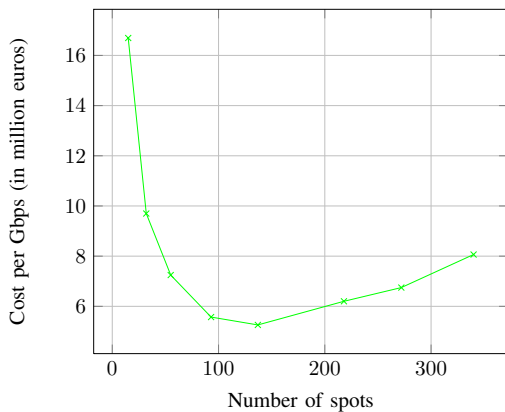


Figure 6. Cost per Gbps, Scenario 2

V. CONCLUSIONS

It has been demonstrated that the methodology gives very consistent and reliable results for the different scenarios. Indeed, by using this methodology it is possible to obtain quickly an optimized satellite system compliant to a given statement of work with the highest achievable capacity. In addition, it is necessary to choose the right reflector size as it can be easily under or over sized, either losing the communications or over constraining the antenna requirements for a given service area. The results provided in this paper highlight the different effects of each design parameter and being able to combine all those together is beneficial in the design phase of a satellite. The service area filling

percentage (SAP), the availability (AV), the cost (CO) and the mass (MS) of the satellite are all vital parameters in order to build a coherent and feasible satellite project. Based on the provided results two kinds of optimization thresholds are achieved: on one side the technical optimization is achieved with the SAP, AV and MS criteria and on the other side the commercial optimization is achieved with the CO criteria. All together, the methodology achieves a system balance taking onto account both system views. As shown in the two scenarios, no matter which area is studied, a possible trade-off can be found according to the requirements set by the system designer. This shows also how adaptive the methodology is and that the reasoning itself is system defining and not area dependent. The reflector study has proved that the choice of the antenna size is far from evident and that care has to be taken in order to find the right solution thanks to the iterative approach. This methodology proves to be a reliable top level tool for finding the most beneficial system trade offs. Further work will be spend on combining the “core selection” process into high level optimization loops. These calculations shall provide a solid view on the behavior of the methodology when input system constraints can be modified. A full study is on going in order to achieve the best system with the smallest satellite antenna reflector. Also a new optimization scheme will be integrated in order to share equally the capacity for each spot given its cell size and handle the need to support “hot spots” as the traffic will not be uniformly distributed over the service area. For this part, the method will implement power optimization.

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