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A NOVEL DIMENSIONING METHOD FOR HIGH THROUGHPUT SATELLITE DESIGN

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This work describes a novel methodology for the dimensioning of a Ka-Band high throughput satellite 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 and the service availability. The proposed methodology is adaptable to any kind of service area. A DVB-S2 air interface with an 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.

Nomenclature

$EIRP$	=	Effective Isotropic Radiated Power
C/I	=	carrier to Interference (ratio)
C/N	=	carrier to Noise (ratio)
$C/(N+I)$	=	Carrier to Noise plus Interference (ratio)
$DVB-S2$	=	Digital Video Broadcast – Satellite, 2 nd iteration
Eb/No	=	Energy per Bit to Noise Density
Es/No	=	Energy per Symbol to Noise density
dB	=	Decibel
$Gbps$	=	Giga bits per second
G/T	=	Gain-to-noise temperature ratio

I. Introduction

HIGH Throughput Satellites (HTS) orientate the satellite systems towards multi-beam coverages at high frequency bands in order to offer broadband access on a large area while maximizing the usage of frequency reuse. Indeed, the terrestrial broadband offer does not cover large territories and a satellite broadband alternative is considered as a complement rather than a direct competitor to fiber optics and ADSL(2)¹.

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There are numerous ways of designing satellite architectures and several possible trade-offs based on different 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 achieving the best trade-off between a set of input criteria and opens 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 designing phase of the satellite. Also, the resources can be quickly focused on a selected set of technical solutions that will be analyzed in detail.

First, we are going to show the issues to which the methodology is going to provide answers, then the steps for the reasoning, and finally present some technical solutions suggested for different scenarios.

II. Problem Description

When a satellite operator orders a new satellite, it invests effort to assess the different transmission scenarios and services by taking into account all the criteria. For instance, it is challenging to align the system requirements with the antenna requirements as one impact the other and vice versa. So it is important to achieve a hierarchy in those requirements to reach the best trade-off. A general approach has been defined by a satellite manufacturer, but in the frame of beam hopping and for a very industrial approach². Also another approach has been developed³ but takes into account very detailed traffic constraints and is quite specific.

Our methodology is based on the case where the satellite uses a multi-beam coverage with frequency re-use and spatial separation. Starting with a set of high level inputs (available DC power, antenna reflector size, etc.), the engineer has to choose first a number of spots and the frequency plan i.e. frequency/polarization organization over a given Service Area (SA). It then achieves the best architectural trade-off through an iterative approach by increasing or decreasing the number of spots for instance.

The chosen initial goals are the service area filling percentage (CP) and the availability (AV) of the communication system. Indeed, these criteria are very important for a satellite operator as the main aim is to guarantee the most robust communication system as long as possible and to be able to cover the largest area so as to reach bigger market opportunities or to strengthen already existent markets. Besides, this set of parameters, can be considered as "macro parameters" and can be provided by the commercial and marketing needs before the design constraints are specified. They also offer the possibility to test the system from the point of view of a satellite operator. Finally, the optimization criterion is the achieved maximum capacity.

In order 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 the following: first of all it is necessary to define the input parameters (frequency plan, DC power, terminal segment, etc.) and a service area covered by a certain number of spots. Then it is necessary to generate the *EIRP* or *G/T* radiation diagrams so that by using these diagrams, it is possible to calculate first the *C/I* performances at antenna level and then an advanced link budget in order to obtain the raw performances in terms of $C/(N+I)$.

Then through an iterative approach, it is possible by increasing or decreasing the number of spots to find out which antenna configuration satisfies the AV and CP criteria in terms of total capacity. Ultimately, the chosen system will be the one which provides the highest capacity while maintaining the initial goals.

This algorithm has been applied to several communication scenarios over different areas and a system has been achieved each time. Also by changing the AV and CP criteria, the method is flexible enough to provide a new solution.

The link budget model has been build upon data provided mostly by two references^{4,5} so as to be adapted to specific needs later on.

Finally, an improved model including mass and cost is also developed as an extension of this method.

The reasoning can be summed up in the following flow chart with all the specific explanations. Indeed, one can see the iterative approach with the loops at different decision levels and the hierarchy of the parameters.

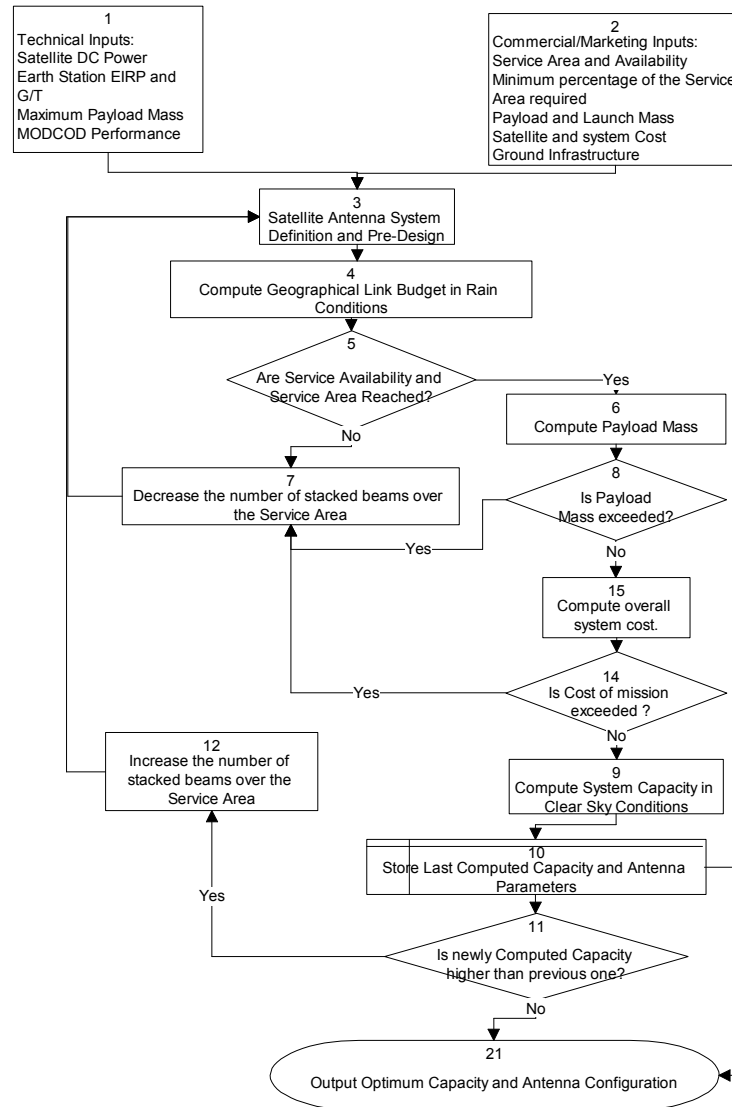


Figure 1: Methodology flow chart

First of all, the technical and commercial input constraints are defined (Box 1 and 2) and used for a complete antenna system design based on the appropriate colour scheme (Box 3). Afterwards, the complete data set is processed in a detailed Link Budget algorithm (Box 4) providing the raw performances for the complete system in terms of $C/(N+I)$. Then a first decision is made regarding the service area percentage and availability (Box 5). If successful there are two other decisions made for the spacecraft. First the mass and then the cost are calculated and tested (Box 6, 8, 15 and 14). If at any moment of those systems tests, the architecture doesn't achieve the required performance, usually the number of stacked spots in the coverage is decreased (Box 7). In any case, if the systems respects all the performance constraints, the capacity is calculated, stored and finally compared to the previous system (Box 9, 10 and 11). If it isn't the first system calculation and if the current system has a higher capacity than the previous one, then this means that more spots can be concentrated on the coverage, hence increasing the global capacity (Box 11 and 12). However, if the previous system is more efficient, then a limit is reached and the optimal capacity has been obtained for a given set of criterias (Box 21).

III. Proposed Models

To begin with, the model is based on several "modules" and input data which are used for all the calculations.

➤ Antenna Model

In order to start the reasoning, it is necessary to generate the antenna system with software tools and convert the radiation diagrams into usable formats for the link budget, in other words *EIRP* density or *G/T* matrices. The adopted reflector model is designed by taking into account the illumination taper and spillover losses but also by neglecting the scan aberration. It is based on the model proposed by Peter Balling⁶.

First, the aperture distribution from a single feed is calculated by:

$$g(r) = p + (1 - p) * \left(1 - \left(\frac{r}{a}\right)^2\right)^n$$

with:

- r , radius in spherical coordinate system
- a , the radius of the aperture
- p , the relative edge illumination
- n is typically 1, but may be changed in the illumination exponent field

The beams are approximated by a linear combination of Bessel functions:

$$F_j(\theta, \phi) = k * a * (c_1 * BF(1, k * ax_j) + c_2 * BF(n + 1, kax_j))$$

with:

- k , the propagation constant $\frac{2\pi}{\lambda}$
- θ, ϕ , coordinates in a spherical reference system
- x_j , the distance from beam center, $x_j = \sqrt{((u - u_j)^2 + (v - v_j)^2)}$
- $BF(n, x)$, Bessel functions given by:

$$\begin{cases} BF(n, x) = 2^n * n! * \frac{J_n(x)}{x^n} \\ BF(n, 0) = 1 \end{cases}$$

- The coefficients c_1 and c_2 depend on the edge taper p , and are normalized so that F_j^2 yields directivity. Balling uses an analytic approximation to determine directivity. We prefer perform a PO integration of an on-focus feed to determine the directivity, which is more accurate.

➤ Interference Model

Once these radiation files are created, it is necessary to define the cells for this multi-beam architecture. The cell definition is also necessary, as each user will be linked to a certain spot and the satellite has to be able to organize the traffic on every spot. Based on this cell division, it is possible to calculate the C/I ratio as a performance indicator at antenna level. Indeed, for a multi-beam antenna system implementing frequency reuse and spatial separation, it is important to calculate the interferences generated by all the beams on each other, as the more spots one includes, the more interference is generated. In a general way, it is possible to define the calculation of the C/I as follows.

Let's consider a certain spot k with a capacity of C_k . Considering, that the architecture is a multi-beam coverage with frequency reuse, there will be two type of interferers. Depending on the side of the transmission, there will be the interferers in co-polarization, which are at the same frequency and the same polarization but used in different spatial spots. Their contribution denoted as I_{co} can be quantified as:

$$I_{co} = \sum_{q=0}^N (D_q^{Co}(x))$$

with:

- q , the identifier for an interfering spot
- N , the total number of interferers in Co-polarization
- x , the point defined by a coordinate system

- D_q^{Co} , the directivity in Co-polarization for the interferer q

There are also the interferers related to the cross polarization, which are the spots at the same frequency but with a directly opposite polarization. Their contribution denoted as I_{cx} is as follows:

$$I_{cx} = \sum_{p=0}^M (D_p^{Cx}(x))$$

with:

- p , the identifier for an interfering spot
- M , the total number of interferers in the orthogonal polarization
- x , the point defined by a coordinate system
- D_p^{Cx} , the directivity in the orthogonal polarization of interfering spot p

Combined all together, the C/I_{tot} calculation is done as follows:

$$\frac{C}{I_{tot}} = \frac{C_k}{I_{co} + I_{cx}}$$

It is also important to include the *Beam Pointing Error* (BPE), which can influence heavily on the performances.

➤ Link Budget and Design Model

If the performances are acceptable for the coverage area, this data is injected into an advanced link budget model. This model takes into account all the different station parameters, link parameters and satellite parameters. Also, the different attenuations, both technical (such as the interferences) and natural (such as rain, clouds, ...), are taken into account for the final link calculation.

Once the data has been calculated, it is possible to apply the logic itself. To begin with, one of the results of the link budget is the performance of the $C/(N+I)$ under clear sky conditions i.e. no rain attenuations, but with all the other attenuations. Corresponding to the proper service area, a performance criterion is applied, in order to identify the users able to receive the lowest type of modulation and able to maintain a satellite communication. By applying a set of rain attenuations based on the models recommended by the ITU it is possible to extrapolate via an iterative procedure for the link budget, the availabilities that can be achieved.

Combining this data with the percentage of coverage allows obtaining a solid view of what antenna structure is the most efficient and interesting to go into detail.

In order to underline this approach, the next section will focus on two given antenna scenarios and show how the method can be applied.

IV. Results

There will be two scenarios that are going to be discussed in the following part. One will be based on four 2.8 meter antenna reflectors with a service area centered over France and a second one based on four 2 meter antenna reflectors with a service area centered over Central Africa. Both scenarios will use an orbital position of 0°E as an arbitrary position.

➤ Scenario 1

This scenario aims at providing a service over an elliptical polygon covering mainly France. The satellite is placed at an orbital position of 0°E. The antenna system is composed of four identical reflectors of 2.8m (state of the art) and the number of included spots is allowed to vary over the area.

The frequencies used are 19.7GHz and 20.2GHz in Ka-Band with four colors. The air interface is the DVB-S2 standard.

Figure 2 shows an example of EIRP coverage and the given C/I performances achieved over France for 100 spots.

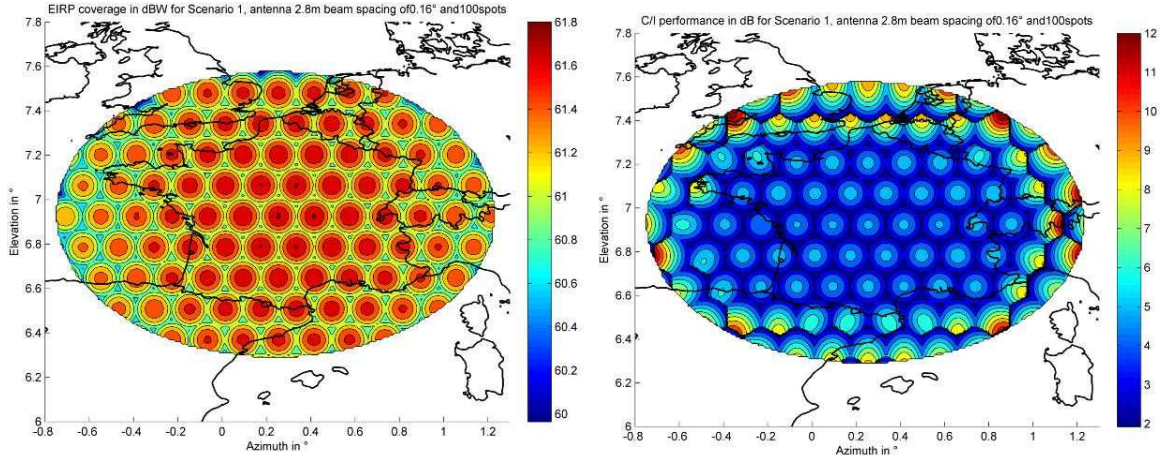


Figure 2: EIRP and C/I performance map over France

By using a $\frac{Eb}{No}$ of -1dB and an operational margin of 3dB, it is possible to obtain Figure 3, showing the behavior of the different antenna systems with a varying number of spots in terms of coverage percentage versus given availabilities.

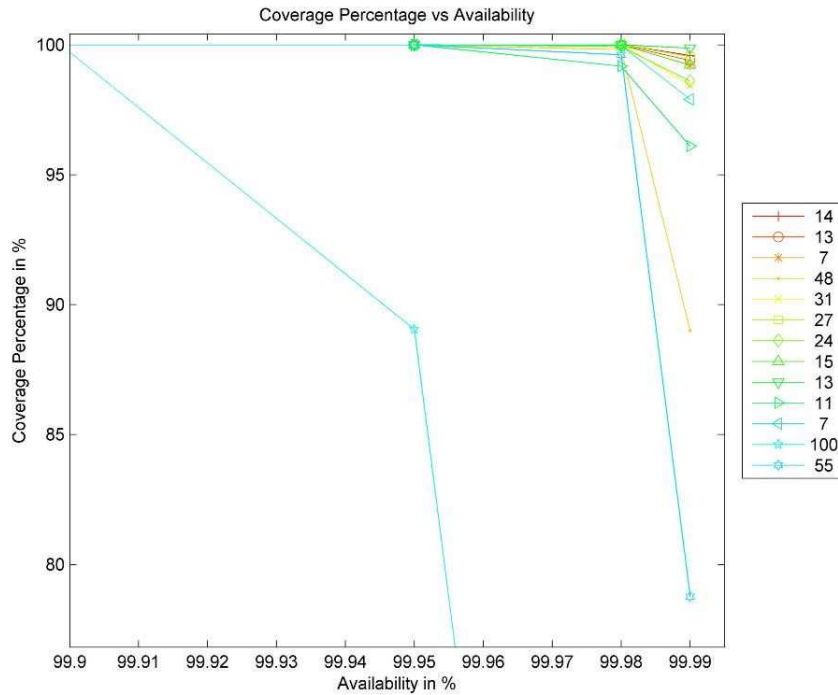


Figure 3: Coverage percentage vs availability, Scenario 1

With Figure 4, it is possible to see the performance of each antenna system and highlight a clear trend: the more spots you include for a given service area, the more your power is divided per spot and the more interference is generated. Consequently, lesser coverage percentage is achieved for every availability.

By applying the AV criteria of 99.96% and the CP criteria of 98%, the method highlights which antenna systems (with a fixed antenna aperture of 2.8m) is the most optimized in terms of capacity as shown in Figure 4. **Error! Reference source not found..**

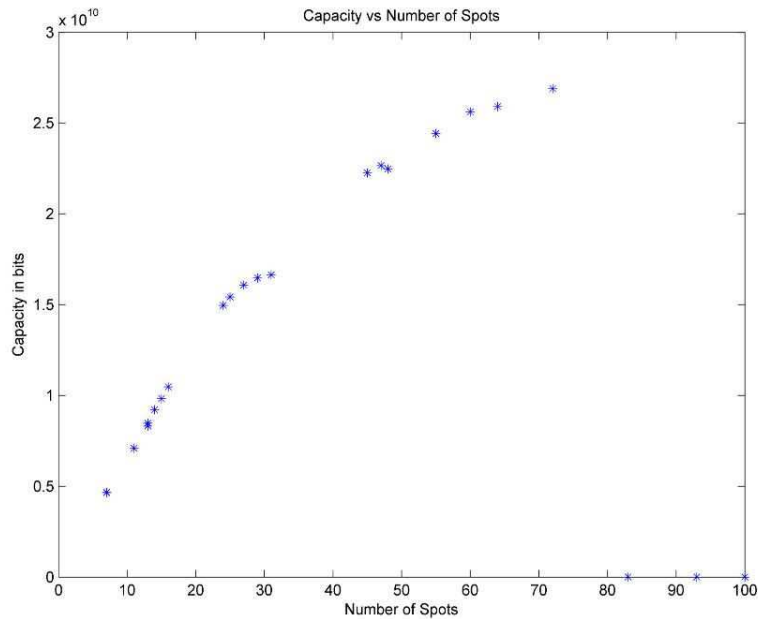


Figure 4: Capacity vs number of spots, Scenario 1

Based on this set of figures, it appears that the antenna system providing the highest capacity while achieving the criteria is the system with a beam spacing of 0.19° (72 spots) which corresponds to an approximate spot size of 0.21° . Also, a trend is highlighted for the service area: the more spots are included the more capacity is available but beyond a given number of spots, the criteria are no more respected.

So, if a satellite engineer wants to develop a Ka-Band multi-beam Satellite on this kind of region, more fine tuned analysis could be focused around a spot architecture of seventy-two spots corresponding to a beam spacing of 0.19° .

➤ Scenario 2

This scenario is based on an elliptical polygon covering Central Africa. The satellite is placed at an orbital position of 0°E . The antenna system is composed of four identical reflectors of 2 m and the number of stacked spots varies over the area.

The downlink frequencies used are 19.7 GHz and 20.2 GHz in Ka-Band. The air-interface is the DVB-S2 standard.

Figure 5 **Error! Reference source not found.** shows an example of EIRP coverage and the given C/I performances achieved over the central Africa region for 442 spots.

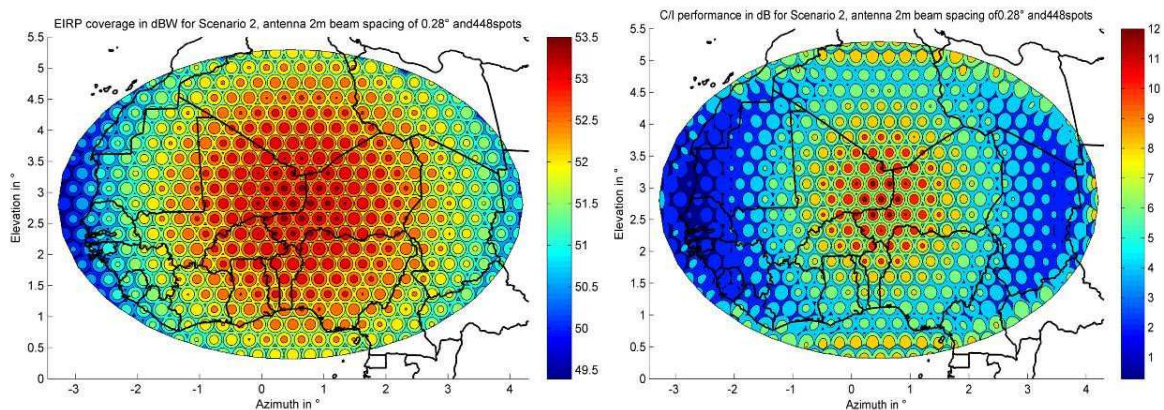


Figure 5: EIRP and C/I performance map over Central Africa

By using a $\frac{Eb}{No}$ threshold of -1dB and an operational margin of 3dB, it is possible to obtain Figure 6 showing the behavior of the different antenna systems with a varying number of spots in terms of coverage percentage versus given availabilities.

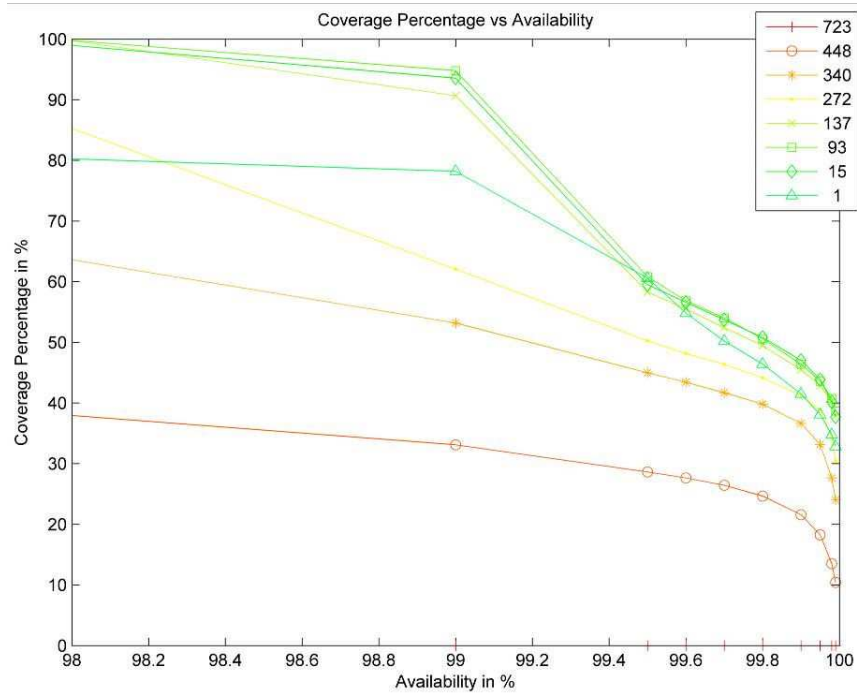


Figure 6: Coverage percentage vs availability, Scenario 2

With Figure 7 it is possible to see the performance of each antenna system and also the same trend as in Scenario 1. Compared to the previous scenario, the curves have more losses due to the high attenuation region close to the equator causing a clear “break” at an availability of around 99%.

By applying the AV criteria of 98% and the CP criteria of 97%, the method will highlight which antenna system with what kind of beam spacing is the most optimized in terms of capacity as shown in Figure 7.

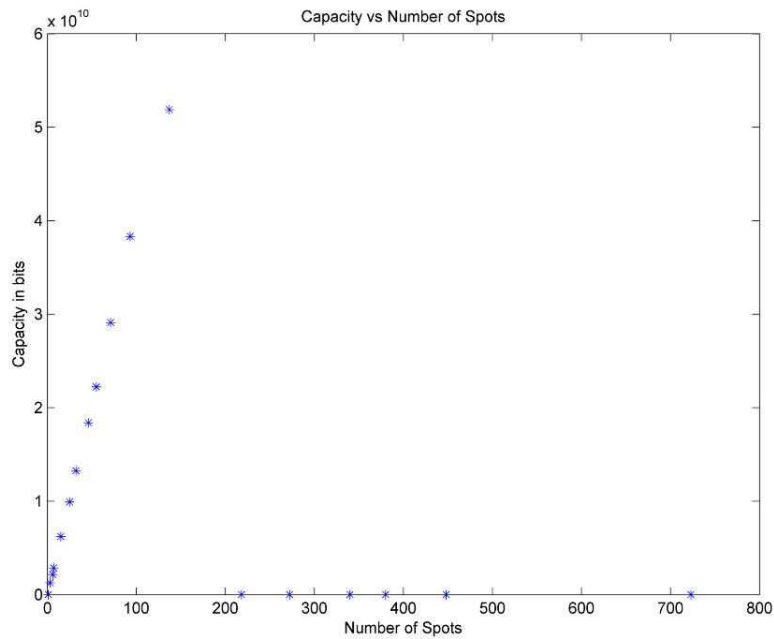


Figure 7: Capacity vs number of spots, Scenario 2

Based on this set of figures, an antenna system with a beam spacing of 0.5° (137 spots) appears to offer the best trade off in terms of capacity. On a side note, due to the high attenuations and inter-spot interferences, it appears clearly that the criteria have to be reassessed compared to the first scenario.

V. Further Analysis

This methodology also underlines another aspect by looking at the evolution of the Carrier-over-Interferences CDF (Cumulative Distribution Function). By comparing several coverage possibilities in terms of spot density in scenario 1 and 2, it is possible to highlight the drastic decrease in C/I. Indeed, the more spots are concentrated, the higher are the interferences and the lower are the link budget performances.

This proves that this parameter is not going to increase heavily the capacity of a given system as it impacts only at a very late stage of the Link Budget. It is rather more a stabilizing system parameter, as it can generate high losses and heavy design constraints on the final C/N+I.

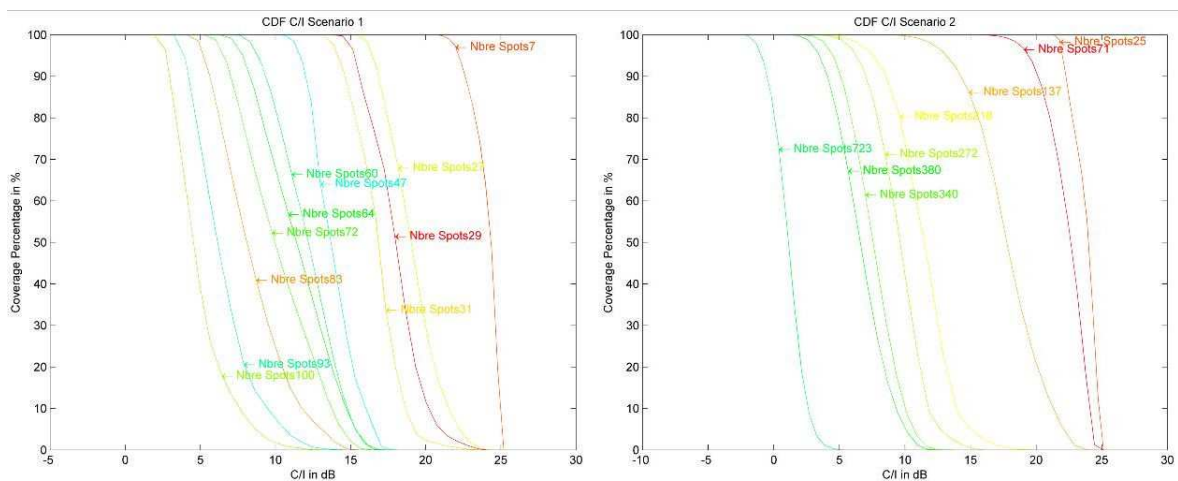


Figure 8: CDF of C/I performances for Scenario 1 and 2

Figure 8 shows clearly that depending on the coverage area two elements are impacting the beam density. On one hand the size of the area and on the other hand the focal length of the apertures.

Indeed, the bigger the area is the more spots can be concentrated without impacting too much the C/I performances as the distance between beams is larger. For instance it is possible to see that for a given C/I of 15dB, it is possible to compact around 50 spots in scenario 1 but around 140 spots in scenario 2. Also, having the optimal focal length improves the systems directivity and helps to limit the interferences of each beam.

Consequently, driving the design primarily with a coverage parameter and a availability parameter, integrates automatically the C/I performance in the global performances in other words the benefits and losses due to a given beam density.

This methodology aims at including this impact and shows that in order to properly dimension a satellite implementing a multi-beam coverage it is crucial to find the right number of spots as it can not be chosen randomly.

VI. Further Work

Further work will be spend on using real antenna data generated with more accurate models taking into account the complete antenna system including real clusters and all kind of losses. These calculations shall provide a solid view on the behavior of the methodology. Also a new module will be added to this model taking into account the mass and cost of the different antenna structures and add a new layer of design.

VII. 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 focus quickly and efficiently the design optimizations around only a few cases and find the best trade-off.

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.

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