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Enhancing 5G Global Connectivity via Satellite Constellations: Preliminary Sizing of Phased Array Antennas using a Heuristic Solver with Genetic Algorithms

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Abstract

Satellite 5G connectivity to handheld devices is a critical technology that has significant benefits in various areas, such as remote healthcare, emergency response, and global connectivity. Achieving this requires state-of-the-art satellite constellations that can provide high-speed, reliable and low-latency connections. Phased array antennas are a key component of these constellations, providing directional, high-gain signals and beamforming capabilities to enable the delivery of high-speed and reliable data transfer. In this paper, we propose an approach to preliminary sizing of phased array antennas for 5G satellite connectivity accounting for stakeholders' requirements and use cases constraints.

To optimise the configuration of phased array antennas, we explore the tradespace of feasible design configurations using a heuristic solver approach leveraging genetic algorithms. The tradespace exploration has been constrained with link budget limit, launcher mass and volume, launch capacity and minimum system performance. Building on this information, the solver identifies the near-optimal configurations that meet design specifications while maximising satellite throughput.

The results, stemming from the application of the method and related tool, demonstrate the potential of our approach to build systems that deliver high-speed and reliable connectivity to handheld devices from space, enabling remote healthcare, emergency response, and global connectivity. Overall, this paper presents a novel and efficient approach to optimising the configuration of phased array antennas for satellite 5G connectivity, and our findings offer opportunities to enhance the design and performance of satellite constellations by quickly converging on the preliminary sizing of a viable option eventually refined in later stages of design and development of the spacecraft system.

Keywords: Optimisation, telecommunication, direct internet to mobile phone from space

Acronyms/Abbreviations

3rd Generation Partnership Project (3GPP)
Array Factor (AF)
Downlink (DL)
Element Factor (EF)
Frequency Division Duplex (FDD)
Genetic Algorithm (GA)
International Telecommunication Union (ITU)
Non-Terrestrial Network (NTN)
Quality of Service (QoS)
Radio-Frequency (RF)
Random Number Generator (RNG)
Signal to Noise Ratio (SNR)
Uplink (UL)

1. Introduction

Satellite communication continues to undergo rapid advancements, enabling new possibilities for global connectivity. Within this evolving landscape, delivering 5G connectivity from space is drawing significant attention [1]. This paper introduces a presizing tool developed to design the phased-array antenna, which is a critical component for such communication satellites [2]. The workings of this tool, its underlying methodologies, and its capacity to design satellites tailored for 5G communication are presented. This research also provides a validation of the tool by comparing its predictions with the known case of the future AST SpaceMobile satellite constellation. Additionally, it is shown how this presizing tool has been significant in shaping the design considerations for the "5G from Space" initiative. Through this exploration, it is aimed to demonstrate the tool's efficiency and potential for future 5G satellite constellation designs.

Some authors in the literature already developed similar tools to design communication satellite constellations [3]. This work develops a similar approach in the specific workframe of 5G satellite constellations and focuses on the design of the antenna connecting to the end user. This work only aims at covering the pre-dimensioning level, to quickly evaluate the feasibility of a project.

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2. Technical Background

This section presents the technical background for phased-array antenna technology and heuristic solving techniques based on genetic algorithms.

2.1 Phased-array antennas technology

Phased array antennas are composed of two or more antenna elements working together, thus *array*. A phase difference in the current delivered to each antenna element allows to generate a custom radiation pattern as a whole, thus *phased*. The radiation pattern is the ratio between power density distribution in the antenna and the one in an isotropic antenna. Modifying the radiation pattern is useful to reach performance requirements fixed by different use cases and applications.

Antenna arrays can be configured in several geometric forms. The most used ones are linear, circular, planar and conformal. For this system, two-dimensional beam steering is required. For this reason, standalone linear arrays are not considered as this design can only steer on one axis. Nonetheless, rectangular planar arrays can be modelled as a group of linear arrays, for this reason the mathematical model of a linear array is valid also for a planar array.

The model of a phased array antenna can be broken down into two separate and independent parts: antenna element (acts as EF) and array (acts as AF) [4]. To continue with the independent consideration of both parts, it shall be stated the assumption of not considering coupling between adjacent antenna elements, which is valid for the design level covered in this work.
In addition, the tool considers a hybrid architecture for the RF chain. This is reflected in the mass and power models (where the number of RF chains equals the amount of beams needed plus one). Moreover, the hybrid architecture provides the flexibility to use digital beamforming techniques that, together with beamhopping algorithms, allow the adaptation of the service provided to users depending on their needs and location. Notably, beams are not fixed and can be steered individually.

2.2 Heuristic solving techniques based on genetic algorithms

Genetic algorithms (GAs) have emerged as a powerful tool in the field of global optimization due to their ability to efficiently explore complex solution spaces and identify optimal configurations. These algorithms draw inspiration from the principles of natural selection and evolution, making them particularly well-suited for solving optimization problems where numerous variables interact in intricate ways [5].

At the heart of a genetic algorithm lies a population of potential solutions, each represented as a set of parameters or genes. These solutions undergo a process of selection, crossover, and mutation in each generation, mimicking the biological processes of survival, reproduction, and genetic variation. Through this iterative optimization process, GAs can efficiently navigate large and nonlinear search spaces, allowing them to find near-optimal solutions in a timely manner.

The choice of using a heuristic solver with genetic algorithms for the preliminary sizing of phased array antennas is rooted in their ability to handle the inherent complexity of antenna design (discrete variables, large search space). Phased array antennas require careful consideration of numerous design parameters, such as element spacing, number of elements, and frequency, which often exhibit intricate dependencies. By harnessing the power of genetic algorithms, this approach can systematically explore the vast design space, offering the potential to quickly get to antenna configurations that may not be immediately apparent through traditional analytical methods. In essence, the utilisation of genetic algorithms provides a promising avenue to tackle the challenging optimization problems posed by phased array antenna design, offering a valuable tool for engineers and researchers in the field.

3. Methodology

Solving an optimization problem can be seen as a succession of steps, which are quasi-independent of the problem at hand:

- Identify the tradespace to be explored *i.e.* define the design variables and their possible values,
- Identify the objective function and express it as a function of the design variables,
- Identify the constraints and express it as a function of the design variables,
- Solve the optimization problem.

3.1 Design variables

A set of eight variables was chosen to describe a phased-array antenna. This number of parameters may seem low to describe a complex system. The approach followed in this paper is pre-dimensioning. Thus, the goal is not to accurately describe the system, but to have a decent enough description for the optimization process. Moreover, keeping the number of variables low is making the problem easier to optimise, which can be a concern when the number of variables is high.
The eight variables are as follows:

- Antenna element, which is a physical component to be chosen from a catalogue
- Number of elements
- Number of beams formed

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- Geometrical arrangement of elements, chosen from a range of patterns
- Physical spacing between elements
- Frequency of the signal
- Bandwidth of the signal
- Modulation scheme

Bounds were put on the variables to reduce the number of possibilities to a finite number. Moreover some bounds already impose constraints on the design: for example, possibilities for frequency and bandwidth correspond to what is allowed by the 3GPP 5G standard [6] and the ITU frequency bands regulation [7].

NTN Satellite operating band	UL operating band	DL operating band	Duplex mode
n256	1980MHz – 2010 MHz	2170 MHz – 2200 MHz	FDD
n255	1626.5 MHz – 1660.5 MHz	1525 MHz – 1559 MHz	FDD

Table 1: Frequency bands eligible for 5G NTN

Other bounds are taken by common sense, and it is checked after the optimisation process that they are not limiting the design.

Computing the number of possibilities for the problem at hand yields several billions possible configurations (in typical combinatorial explosion fashion). This means that, unless the evaluation time of one possible design is extremely quick, exploring all possibilities is not an option.

3.2 Objective

The goal of a global communication constellation is to maximise the service offered to the end user, as this is what creates commercial value. Depending on the stakeholders choices, the focus could be put on the number of users served, or on the quality of service provided to each user. For this work, it was chosen to *maximise the total usable downlink (satellite to user) data rate*. This approach represents a middle ground between quality and quantity, as the total data rate can theoretically be divided between users as necessary (ignoring other technical constraints).

3.3 Constraints

The constraints translate everything that is limiting the design. They must be as exhaustive as possible, as anything missed will not be taken into account at all by the optimiser. To keep the computation time as low as possible, constraints were expressed analytically, without requiring simulations. Assumptions and simplifications were thus made.

The first constraint is relative to the coverage of one satellite, and by extension, the achievement of global coverage by the constellation. In this work, the constellation was fixed (not a variable), so the coverage requirement directly translates to a fixed minimum steering angle for the antenna. As a reminder, a phase array antenna does not steer mechanically, but electronically (no moving parts), so this is something the design of the antenna will control.

The second constraint is probably the most important. Since the goal is to exchange data with a customer, it is important to ensure that the signal is strong enough to be received and demodulated. This is done by putting constraints on the SNR, forcing it to be high enough.

Computing the SNR requires a link budget, taking into account antenna gain and power (which depends on the design) as well as losses (internal losses, atmospheric *etc*).

The last major constraint is the size constraint. Even if the constellation (size, number, position of satellites) is fixed, launching it is still a major issue. As the antenna is the driving design factor in a telecommunication satellite, its size and power consumption should be limited.

Considering the number of launches at hand is known, a constraint can be put on the mass and volume of the satellite to ensure that the whole constellation can be sent with the available launches. Relating the mass/volume of the antenna to the mass/volume of the satellite then puts direct constraints on the antenna design.

3.4 Solver

The solver used in the workframe of this paper is the *ga* function of the Global Optimization Toolbox of MATLAB®. This function implements a classical genetic algorithm capable of handling non-linear constraints (usage of penalty function as proposed by [8]) and integer constraints (based on [9]). This function proved to be robust enough to handle the problem at hand.

The genetic algorithm was configured with a population of 500 individuals, a 10% mutation rate and 10% elite proportion. The algorithm usually converged to a solution in a few hundred generations (computation time of 1-2 min on a commercial laptop). Each case was run 10 times with different RNG seeds to confirm that the global optimum was found.

4. Results

In this chapter, the results of using the developed algorithm within the context of the "5G from Space" project [1] are presented. Furthermore, with the aim of validating the model, the algorithm has been executed with constraints derived from AST SpaceMobile

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BlueWalker 3 mission. Then, the output is compared with the performance published by AST SpaceMobile.

4.1 5G from Space version

The work from previous stages of the project provided different constraints that are integrated into the model to obtain a phased-array antenna configuration. The constraints are an orbital height of 525 km (circular) and a minimum steering angle of 40 degrees, derived from the constellation design. Then, driven by the research on launch capacity, maximum values for both mass (421 kg) and volume (4.4 m^3) per satellite were defined. The number of users per beam range corresponds to the criteria of quality of service (QoS) presented in "5G from space" publication [1]. This QoS states that each user should receive a downlink data rate between 1 and 10 Mbps and an uplink data rate of 0.1 to 1 Mbps.

The design determined by the presizing tool is presented in the following Table 2:

Parameter	**Value**
Operating frequency (GHz)	2.18
Frequency Band	S-Band
Bandwidth (MHz)	25
Number of elements	374
Antenna Gain (dB)	37.5
Antenna diameter (m)	1.8
Number of beams	31
Total consumed power (W)	3506
Total dissipated power (W)	2720
Mass (kg)	136.5
Modulation	16-QAM
Total downlink datarate (Gbps)	4.3
Individual beamwidth (deg)	0.13
Individual cell diameter (km)	1.2
Users per beam (range)	[28, 140]

Table 2: Configuration for 5G from Space

4.2 Validation with AST SpaceMobile's Blue Walker 3

Based on some of the specifications available from the Blue Walker 3 satellite [10], the following constraints are input into the model: (1) an orbital height of 700 km; (2) a covered area of 2.4 million square miles which defines a minimum steering angle of 58,5° ; (3) a maximum satellite mass of 1500 kg and (4) a maximum antenna surface area of 64 square metres.

The design determined by the presizing tool is presented in the following Table 3:

Parameter	**Value**
Operating frequency (GHz)	1.54
Frequency Band	L-Band
Bandwidth (MHz)	30
Number of elements	826
Antenna Gain (dB)	38.84
Antenna diameter (m)	3.15
Number of beams	109
Total consumed power (W)	14454
Total dissipated power (W)	11150
Mass (kg)	456.8
Modulation	16-QAM
Total downlink datarate (Gbps)	18.3
Individual beamwidth (deg)	0.034
Individual cell diameter (km)	0.42
Users per beam (range)	[33, 168]

Table 3: Configuration for Blue Walker 3

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5. Discussion

This section initially focuses on validating the model by comparing its outputs with the real-world specifications of the AST SpaceMobile's Blue Walker 3 satellite. Following this, the findings from the model's output for the "5G from Space" project are put side by side with those of the Blue Walker 3 to discern patterns and relationships.

5.1 Validation

When we compare the model's predictions for the "AST SpaceMobile's Blue Walker 3" satellite with the actual (public) specifications, some differences stand out. The real Blue Walker has around 2.94 times more antenna elements than the model's prediction. In terms of physical space, the real antenna, with its 8 x 8 metre dimensions, occupies an area that's about 8.21 times bigger than what the model suggests. This difference may be explained by the exact antenna architecture chosen by AST Spacemobile; as they plan to work in several frequencies (including frequency lower than L-band), it could be necessary to space antenna elements further apart, and thus get a larger antenna overall. They may also use more advanced design (such as subarrays) to their advantage, which is outside the scope of the model developed in this paper.

The computed antenna mass of 456.8 kg is around one third of the real satellite total mass of 1500 kg, which is a sounding order of magnitude ratio. There is no information about the mass of the antenna and RF chain of the real satellite, so this cannot be validated.

Gain is another area where there's a noticeable difference. The actual gain of the Blue Walker is 40 dB, a bit more than the model's 38.84 dB prediction. When we look at this difference linearly, the actual gain is only about 1.31 times the predicted value. As the model used to compute phased array antenna performance in this work is analytical, this difference may come down to inaccuracies.

Overall, apart from the surface metrics, the model seems to predict the right order of magnitude for the physical metrics. The power consumption predicted is high, but still in the range of what solar panels can provide (ViaSat-2 generated 18 kW with solar panels).

It is difficult to judge the relevance of the performance metrics (downlink data rate) as these specifications are not public. However, they do not seem unreasonable.

5.2 Comparison

In the comparison between the configurations of the "5G from Space" and the "AST SpaceMobile's Blue Walker 3" satellites, a clear correlation between design constraints and the resulting design outputs is observed. The Blue Walker 3, operating at a greater orbital height and equipped with a larger antenna surface and mass allowance, exhibits enhanced performance metrics such as increased gain, datarate, and beam count. However, this heightened performance corresponds with a substantial increase in power consumption, potentially attributed to its enlarged antenna diameter and increased number of antenna elements but also to the increased distance of operation due to its orbital height. On the other hand, the "5G from Space" satellite, constrained by tighter specifications due to launch capacity availability (the constellation is much larger than AST Spacemobile constellation), presents a more compact design with somewhat diminished performance indicators. Notably, regardless of these differences in design parameters, the user capacity per beam range for both configurations remains relatively similar. This is due to the common limit of the maximum bandwidth available in the spectrum, imposed by the ITU, which cannot be overridden.

6. Conclusions

Comparing the model's predictions with real-world data highlights the complexities of satellite design. The tool was able to reproduce some of the characteristics of a real satellite. However, this description was still imperfect on some points showing that there is room to improve the predictions of the tool to make it match real-world results better.

In the comparative analysis between the "5G from Space" and the AST case, it can be seen that the relation between the imposed constraints and the resulting performance is complex. The predicted performance seemed to correctly scale in regard to the constraints imposed. In its current state, this model, while not able to cover complex designs, stands out as a useful presizing tool, to quickly get a design to elaborate on, or to evaluate the potential of a certain constellation. It offers a robust foundation upon which satellite designs can be conceptualised and subsequently refined.

As the convergence time of the optimiser was still fast, there is also room to add complexity. More design variables could be considered to better describe the phased array antenna, or to extend the scope of the optimizer to the whole satellite constellation. Finally, adding a demand model and economics consideration could yield a complete tool to identify the most profitable/efficient way to provide global 5G coverage from space.

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References

[1] G. V. Avila, S. Ravishankar, I. L. Buqué, E. Capell, A. Koenig, Z. Liao, M. Anastasopoulos, S. T. Kommareddy, G. Haynez, A. Morea, D. Larrauri Ruiz, A. Cordova, N. Garzaniti, "system design study of a constellation of small spacecraft to deliver seamless 5G connectivity to unmodified cell phones through an end-to-end non-terrestrial network" in *IAC 2023 Congress Proceedings, 74th International Astronautical Congress (IAC)*, Baku, Azerbaijan, 2-6 October 2023

[2] N. Garzaniti, Z. Tekic, D. Kukolj, and A. Golkar, "Review of technology trends in new space missions using a patent analytics approach," Progress in Aerospace Sciences, vol. 125, p. 100727, 2021, doi: https://doi.org/10.1016/j.paerosci.2021.100727.

[3] Inigo del Portillo, S. Dolan, B. Cameron, and E. F. Crawley, "Architectural Decisions for Communications Satellite Constellations to Maintain Profitability While Serving Uncovered and Underserved Communities," *International Journal of Satellite Communications and Networking*, Oct. 2022, doi: https://doi.org/10.1002/sat.1464.

[4] F. B. Gross, *Smart Antennas for Wireless Communications with MATLAB*,
1st ed. McGraw-Hill, 2005.

[5] David Edward Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*. Addison-Wesley Professional, 1989.

[6] 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; NR; User Equipment (UE) radio transmission and reception; Part 5: Satellite access Radio Frequency (RF) and performance requirements (Release 17). 2023. Available at: http://www.3gpp.org

[7] ITU, Radio Regulations - Articles - Edition of 2020. 2020. pp. 99–116.

[8] K. Deb, "An efficient constraint handling method for genetic algorithms," *Computer Methods in Applied Mechanics and Engineering*, vol. 186, no. 2–4, pp. 311–338, Jun. 2000, doi: https://doi.org/10.1016/s0045-7825(99)00389-8.

[9] K. Deep, K. P. Singh, M. L. Kansal, and C. Mohan, "A real coded genetic algorithm for solving integer and mixed integer optimization problems," *Applied Mathematics and Computation*, vol. 212, no. 2, pp. 505–518, Jun. 2009, doi: https://doi.org/10.1016/j.amc.2009.02.044.

[10] winpickles4life, "AST SPACEMOBILE - The Starlink of Smartphones," Oct. 12, 2021. https://www.reddit.com/r/ASTSpaceMobile/comments/q6tqw8/ast_spacemobile_the_starlink_of_smartphones/ (accessed Sep. 14, 2023).



https://dspace.org/

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