

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.

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Abstract

The increasing demand for high-speed mobile data services has led to the development of 5G and 6G technology, which promises to revolutionize the way people access and use the internet. However, the full exploitation of 5G network potential is often limited by the challenges related to the deployment of the physical infrastructure required to support these networks. In order to address these limitations, a new approach is needed to bring 5G services to areas that are currently underserved. This paper presents the results of a system design study that explores the use of a constellation of small spacecraft to deliver seam-less 5G connectivity to unmodified cell phones, through an end-to-end non-terrestrial network. Within the study, several use cases have been considered including offering enhanced service to cities and connecting areas not served by traditional mobile services such as remote regions, ships and offshore platforms, regions hit by natural disasters and contested battlefields. A trade space exploration approach was undertaken to identify the optimal solution for meeting stakeholders' requirements associated with the different use cases. The analysis explores the effects of key architectural decisions on overall system performance and lifecycle cost, benchmarking them against foreseen customers' needs and market demand. A variety of alternatives were evaluated including the number of satellites, types of orbits, number of orbital planes, satellite size, weight and power, antenna technologies, inter-satellite links technologies and routing schemes among others. As a result, it was proposed the use of a constellation of about 3000 satellites in a sun-synchronous Low Earth Orbit (LEO) orbit, with a satellite lifetime of 5 years. Each satellite is equipped with a phased array antenna in 5G non-terrestrial band frequency n256 for direct connectivity to unmodified user cell phones and free space optical telecommunication terminals for on-orbit backhauling. Commercial Off-The-Shelf (COTS) components for spacecraft subsystems and sensors were considered when available. With more than 95% of Earth coverage and high system scalability, the mission represents a promising solution for providing global 5G connectivity paving the way for a more connected world.

Keywords: 5G from space, satellite communication, 5G, non-terrestrial network, space technology.

Acronyms/Abbreviations

Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Geosynchronous Orbit (GEO), Commercial Off-The-Shelf (COTS), User Equipment (UE), Mobile Satellite Services (MSS), User Equipment (UE), Intersatellite Links (ISL), Intersatellite Service (ISS), Cross-Links (CL), Position, Navigation, and Timing (PNT), Preliminary Design Review (PDR), Attitude, Determination, and Control System (ADCS), Inertial Measurement Unit (IMU), International Telecommunication Union (ITU), Dilution of Precision (DOP), Size, Weight, and Power (SWaP), Chip Scale Atomic Clock (CSAC), Electrical Power System (EPS)

1. Introduction

1.1 Background

The field of satellite communications has experienced remarkable advancements since its inception in the mid-20th century, where MSS emerged

as a crucial category of these communication systems, providing continuous support to UE in motion across terrestrial, maritime, and aerial transportation networks [1]. As the demand for reliable communication solutions grows, direct-to-mobile phone satellite communications have become a popular area of exploration. This technology, which leverages LEO satellites, aims to deliver seamless connectivity to mobile phones without relying on terrestrial infrastructure.

LEO satellite constellations present unique advantages for direct-to-mobile phone communications. Their proximity to Earth reduces latency and path loss, enhancing the overall communication quality. However, deploying and maintaining a large constellation of satellites in LEO necessitates addressing several challenges, such as ensuring comprehensive coverage, accommodating numerous users, and facilitating intersatellite communication via ISL, ISS or CL [2].

One significant obstacle in direct-to-mobile phone satellite communication is signal blockage, which occurs when the line of sight between the spacecraft and the UE is obstructed by external objects [3]. This issue can be mitigated by using lower frequency bands, such as the L-band or S-band, that are less susceptible to interference [4]. As technology advances, researchers continue to explore innovative techniques to overcome such challenges and deliver reliable and uninterrupted communication services to mobile phones [5], [6].

The commercial potential of direct-to-mobile phone satellite communication from LEO has attracted significant interest from both established companies and start-ups [4]. However, the complexities and expenses associated with launching and managing a satellite constellation in LEO make it a high-risk investment [3]. Therefore, it is essential for businesses to conduct thorough feasibility studies, optimize trade-offs, and secure the appropriate financial resources before embarking on such ambitious projects.

Additionally, it was determined that a supplementary PNT service could be implemented with relatively little extra cost. Nevertheless, the biggest challenge was assessed to be the signal blockage, as the line of sight of the spacecraft can get some interferences due to external objects found between the transmitter antenna and the UE [7].

In conclusion, direct-to-mobile phone satellite communication from LEO represents a promising area of research and development in the satellite communications industry. By overcoming the inherent challenges and leveraging the advantages of LEO satellite constellations, this technology has the potential to revolutionize mobile communication and provide reliable, seamless connectivity to users worldwide. As the sector continues to grow, collaboration between academia, industry experts, and commercial entities will play a critical role in shaping the future of this innovative communication solution.

1.2 Aim

Develop a mission design concept offering seamless 5G connection to UE by using satellites while providing reliable, affordable, and stable connectivity everywhere at any given time. The mission would complete Pre-Phase A to Phase B, or the PDR, according to the NASA Systems Engineering Handbook [8].

2. Methodology

2.1. System Engineering Approach

The methodology we performed explains the process of a basic tradespace exploration used and is described as follows:

Firstly, we studied the problem and established a foundation to work on, writing first the mission and

system requirements to set the goals that we wanted to achieve with some assumptions on the stakeholder analysis to reduce the study and set some limitations of the investigation, while at the same time, visualize the challenges we had to address and the gaps to fill. It should be emphasized that each subsystem performed this methodology. We then focused on finding all the different possibilities of services and design solutions for these challenges and requirements, where we organize them into a set of feasible candidates for a baseline of the project. Once these solutions were found, a trade-off analysis of each of all the subsystems was done to find the optimal solution that would satisfy other subsystems and the overall project. After a comprehensive tradespace exploration, we narrowed all the possible solutions, and all the subsystems were satisfied in terms of functionality, a baseline was achieved, and the gaps were filled.

2.2 Assumptions

Before generating the requirements, assumptions were needed to narrow the research and the tradespace model. Then the following are the general assumptions made:

- People will mostly use basic internet services such as calls, messaging, video calls, web browsing, and watch online videos.
- The most populated areas of the world are typically served by ground infrastructure. Therefore, our aim is to provide connectivity to inaccessible places, people traveling (transportation use cases), and potentially serve as a redundant system.
- The spacecraft shall fall under “small satellite” category (mass below 500 kg).
- 5G might get surpassed soon by 6G, then a “short term” of 5G service shall be covered to avoid getting behind new technologies.
- People want easy use of technology, direct connectivity without external compartments is required.

Once stated the assumptions, then the requirements of the system and subsystems were the next step to follow for this research to start building up the system architecture.

2.3 Tradespace Exploration for the System Architecture Process

The architecture of Space Segment can be configured based on the altitude of the satellites and their delivered functions. In the following table it is shown the alternatives for the functions.

Table 1. System architecture design variables with alternatives

Delivered Function	Decision Variables	Alternatives		
5G to Customers	Altitude	LEO	MEO	GEO
Backhauling data	Altitude	LEO	MEO	GEO
Housekeeping data	Altitude	LEO	MEO	GEO
PNT	Altitude	LEO	MEO	GEO

It should be noted that not all designs from the table are possible, as 5G and PNT functions must be from LEO. Then the possible design vectors are the following:

- $x = [1, 1, 1, 1]$.
- $x = [1, 2, 1, 1]$.
- $x = [1, 2, 2, 1]$.
- $x = [1, 3, 1, 1]$.
- $x = [1, 3, 3, 1]$.

To choose an optimal solution, the following analysis of the delivered functions from Table 1 with the possible alternative solutions can be seen in the following table.

Table 2. Alternatives of the delivered functions of the possible alternative solutions.

Configurations H: Housekeeping B: Backhauling	Latency H [ms]	Latency B [ms]
H:LEO B:LEO	35	35
H:LEO B:MEO	35	95
H:LEO B:GEO	35	285
H:MEO B:MEO	95	95
H:GEO B:GEO	285	285

After establishing the possible solutions into the table, a qualitative analysis was done, and it is shown in the following figure.

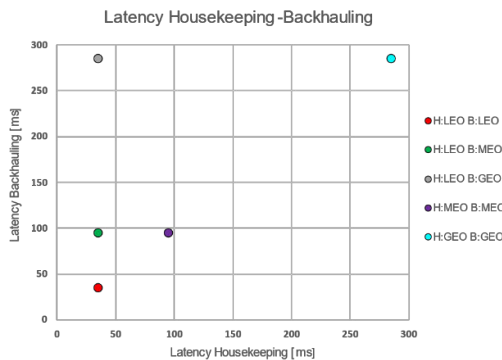


Fig. 1. Tradespace exploration results for housekeeping and backhauling option.

3. Results and Discussion

3.1 Requirements Definition

The requirements were built up according to the assumptions and needs of each subsystem, but the foundation of them are the main top-level requirements that describe what is needed to achieve by the system to meet stakeholder needs and objectives.

The top-level mission requirements are:

- The mission shall provide direct 5G connectivity to unmodified User Equipment mobile phones.
- The mission shall provide coverage at least to 82 degrees latitude.
- The mission service shall be available for more than 85% of the time.
- The mission service shall provide at least 8 Mbps data rate downlink to user equipment.
- The mission service shall provide at least 0.1 Mbps data rate uplink from User Equipment
- The mission service shall provide up to 35 ms end-to-end latency.
- The mission spacecrafts shall reach End of Life in 5 years.

Once stated the top-level requirements, the tradespace exploration approach was performed to get the optimal solutions.

3.2 Use Cases

Once revised the system architecture, we can define what are going to be the use cases and the capabilities of the system that we want to achieve., shown in the following list with the data rate required:

- Make or receive calls online – 0.5 Mbps.
- Use instant messaging – 1 Mbps.
- Play video games – 4 Mbps.
- Make or receive video calls – 5 Mbps.
- Web browsing – 5 Mbps.
- Watch online videos – 8 Mbps.

In terms of the latency, the following capabilities required the latency as follows:

- Use instant messaging – 250 ms.
- Watch online videos – 150 ms.
- Make or receive video calls – 150 ms.
- Make or receive calls online – 150 ms.
- Web browsing – 150 ms.
- Play video games – 100 ms.

Once stated the data rate and latency required, we can setup the use cases, mapping from travelling (by sea, land, and air), inaccessible locations (like remote areas, big cities, and high interference places), to redundancy (mass gathering of people or catastrophic event contingency plan).

3.3 System Architecture

The analysis shown in Table 1., establishes the possible combinations of the solutions, where the top configurations are the LEO-LEO and LEO-MEO. To select the optimal solution, a comparison of the 2 is shown below:

LEO-LEO Configuration:

- Minimum latency for both functions.
- Constellation functional from first launch.

LEO-MEO Configuration:

- Latency increases to ≥ 95 ms,
- Would require MEO satellites with too many optical heads.
- Not immediate functional constellation.

This shows then that the LEO-LEO configuration is the optimal solution, which was chosen for this project study.

3.4 Preliminary Baseline

Once performed the analyses of each system and the overall mission, the following solutions were obtained according to each subsystem.

3.4.1 Orbit and Constellation

In terms of the orbit selection parameters, the following results were achieved by following the same methodology of the tradespace exploration.

- 525 km altitude, LEO Sun-Synchronous circular orbit.
- Number of planes: 59
- Number of Satellites: 3009
- Indirect Insertion.
- More than 1 orbit per launch.
- Launch flexibility.
- Cheaper plane shift.
- Operational check (defective satellite removal).

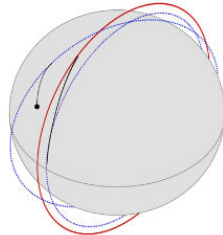


Fig. 2. Indirect insertion of each satellite.

- Parking orbit attitude: 390 km.
- Transfer Spacing: Thrust Modulation.

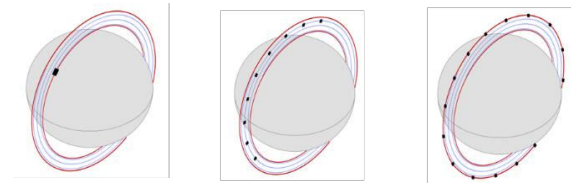


Fig. 3. Constellation distribution process.

- Constellation distribution over 9 km height: 520.5 km – 529.5 km.
- Constellation coverage: 82 degrees latitude.

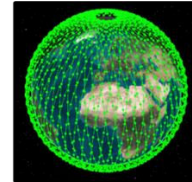


Fig. 4. Constellation coverage concept.

3.4.2 Launch Strategy and delta V

To send the constellation in a relatively short amount of time, a study of the forecasted launches showed a positive trend for Falcon 9, ISRO LVM3, and Atlas 5, however Atlas 5 is expecting its next launcher for replacement, so it is left out. Showing then that the ideal launchers are the Falcon 9 and ISRO LVM3.

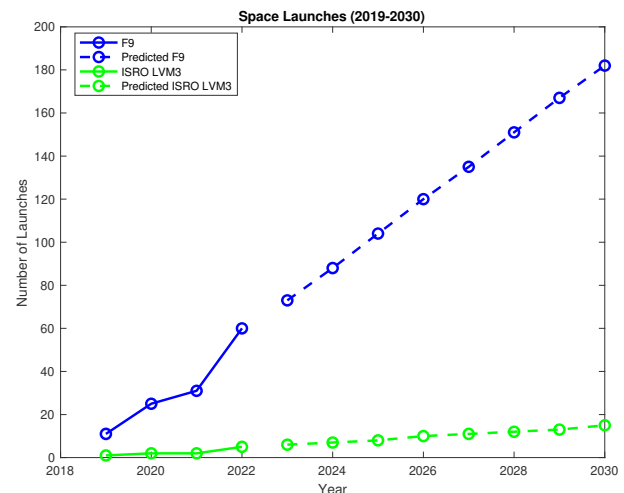


Fig. 5. Number of launches for ISRO (green) and Falcon 9 (blue) with predicted launches.

To fit the satellites in an optimal solution a study was made on the staking of the spacecrafts in the fairing, having 3 possible packing architectures where the hexagon packing is the ideal option out of the following:

- Plate stacking: 14 satellites.
- Bookshelf packing: 25 satellites.
- Hexagon packing: 30 satellites.

To send 3009 satellites, a sufficient launch capacity is required, while also forecasting future launches, to then obtain the number of launches and the time needed to attain the constellation geometry. The study then showed that the optimal launch strategy would be using the Falcon 9 rockets.

The propulsion system for this mission was chosen to be Hall Effect thruster, after studying the cost benefit analysis for minimizing the launch cost. Furthermore, the propellant mass is presented (in Table 3) with their respective ΔV made for a satellite with a mass less than 500 kg.

Table 3. Delta V budget and propellant mass.

Purpose	Delta V	Mass of Xe
Orbit	75.37 $\frac{m}{s}$	2 kg
Raising Station	159.57 $\frac{m}{s}$	12.5 kg
Keeping		
Total + 20% Margin	281.93 $\frac{m}{s}$	17.4 kg

3.4.3 Antenna

Through a series of different and comprehensive analyses and simulations, the antenna parameters and choice were achieved. As the main goal was to offer seamless 5G to unmodified cellphones from LEO satellite platforms, the following challenges were presented:

- Range: LEO satellite constellation.
- Number of users per satellite: performance based on demand.
- Size limitations: the total number of launches.
- Uplink: weak signals with minimum gain of around 33 dB needed.
- Downlink: multiple users and equipment at the same time, suggesting the need for multiple beams.
- Orbit velocity: In LEO, satellites move fast, then a fast beam steering is required.

To overcome these challenges, the phased array antenna configuration was the only technology, as it achieves the required gain within feasible size, has beamforming techniques and possess electronic steering. To design the appropriate antenna, 8 parameters were defined, which all together set around 24 billion possibilities, and these parameters are the following:

- Radiating elements: from 8 COTS and custom designs.
- Frequency of operation: 1 in S-band and L-band each.
- Bandwidth: 5 possibilities from ITU regulations.
- Number of elements: between 1-2500.
- Inter-element spacing: between 0.5 - 1 λ .
- Number of beams formed: 1 - 500.

- Modulation scheme: 3 variants of QAM.
- Geometrical arrangement: 8 possibilities.

To find the optimal design in terms of max data rate in downlink to user, a heuristic solver (genetic algorithm) to explore “intelligently” the tradespace (only 1 million evaluations out of the 24 billion) was used. Then a preliminary model was designed with the following parameters:

- Element: Circular In-House S-Band (6.8 dB of gain, 4 W consumption, efficiency of 0.84).
- Frequency: S-Band 2.18 GHz, 25 MHz bandwidth (ITU compliant).
- Number of elements: 219.
- Spacing: 0.5 λ (68mm).
- Number of beams: 25.
- Modulation: 16-QAM.
- Geometry: Circular planar array with triangular grid.
- Gain: 33.8 dB.
- Size: 1.15 m diameter, 1.03 m², 10 cm thickness.
- Power consumed: 1300 W.
- Thermal dissipation: 550 W (included in 1300 W).
- Antenna mass: 175 kg.
- Throughput of one beam: 140 Mbps (28 5Mbps or 140 1Mbps simultaneous users).
- Size of one cell (one beam): 2.7 km diameter (6.4 km²).
- Total throughput (whole satellite): 3.5 Gbps (700 5Mbps or 3500 1Mbps simultaneous users).
- Area covered (whole satellite): 650 000 km².

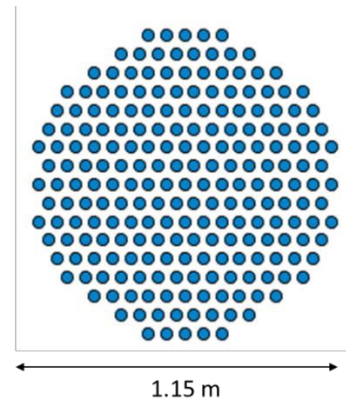


Fig. 6. Phased array antenna concept design of the prototype.

3.4.4 ISL

To be able to provide the service with the desired performance mentioned above, we need to have optical ISL to connect every satellite to the 5G network, as even with 50 ground stations some satellites would not

have ground station in visibility, meaning that up to 20% of the constellation might not have visibility.

Using ISL will help to achieve these goals and provide a better service. Using a total of four receivers/transceivers can provide intersatellite connectivity up to 5 Gbps each.

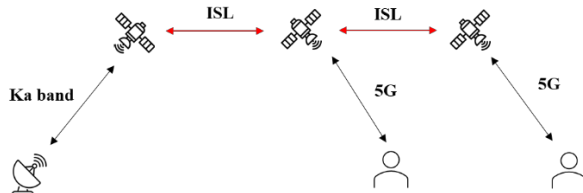


Fig. 7. Architecture of the ISL concept.

To achieve this, the use of Dykstra Algorithm is proposed on a dynamically updated Adjacency matrix, using ponderation according to data rate, number of links, and distance.

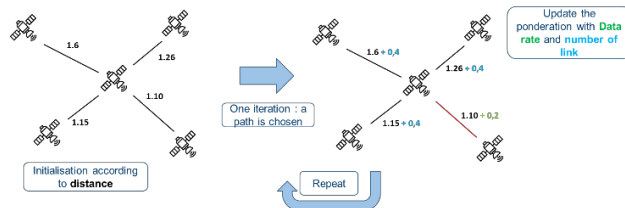


Fig. 8. Application of the Dykstra Algorithm.

3.4.5 PNT Configuration

A secondary payload providing PNT services was incorporated to both enhance the existing communications capability, and to create an additional source of revenue.

Two key advantages exist for LEO PNT. The first is the larger constellation offering redundancy, geographic differentiation of services, and improved DOP. The second is the significant reduction in free space path loss due to the lower orbits (525 km compared to 23,222 km), permitting the use of low SWaP antennas and power subsystems.

This payload will utilize two HCT400 Quadrifilar Helical antennas operating on 1196.91 MHz and 1595.88 MHz respectively, to enable ionospheric corrections and to mitigate jamming.

The onboard clock will be the SA65 CSAC, which has an Allan deviation of $3 \cdot 10^{-12}$ at $\tau = 900$ s (the update interval of the satellite clocks).

The system will leverage the existing ISL network to synchronize clocks and transmit updated navigation messages across the constellation.

The PNT system will be capable of providing positioning accuracies between 60 cm and 158 cm, with greater accuracy achieved at higher latitudes due to the near polar nature of the orbits. The dominant contribution to the positioning error comes from the

CSAC. Optical cavity atomic clocks represent a future innovation which may offer the precision of traditional atomic clocks in the small form factor required for LEO mega constellations, thus significantly improving the performance achievable.

3.4.6 ADCS

The ADCS study showed that the disturbance environment had as a worst case the atmospheric drag of 5.43×10^{-3} Nm, then to manage it, a 3-axis control was selected. While for the sensors and the actuators, the following was selected.

Sensors:

- Star tracker
- Sun sensors
- IMU

Actuators:

- Thrusters
- Reaction Wheels

3.4.7 OBDH

High throughput data link on board implementing protocol conversion bus design can transmit data packets on board with up to 400 Mbps. Using space wire as the candidate, will require 1.5 V to 3.5 V, using 224 nodes, having low architecture complexity, full duplexity and serial communication protocol.

3.4.8 Backhaul Antenna

It was proposed that the use of a backhaul antenna will transmit 10 Gbps data rate to network core, as sizing the backhaul antenna will establish the link between the satellite to the gateway antenna.

3.4.9 EPS

The Electrical Power System (EPS) will require a power of 2.5 kW, as the mission is considered for a relatively short 5-year lifetime with an unregulated bus of 28 V. Then the EPS architecture is as follows:

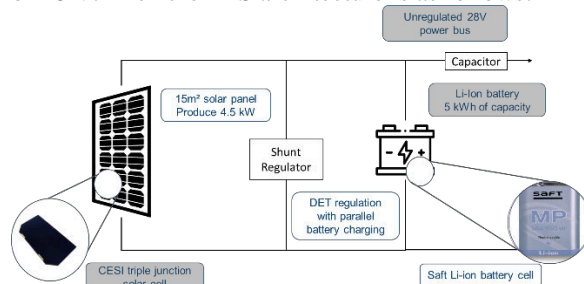


Fig. 9. Architecture of the EPS

3.4.10 Mechanisms and CAD model

As the EPS selected a solar array of 15 m² which takes up a significant percentage of the fairing area,

having an impact on the number of satellites per launch. Furthermore, the solar array needs to be constantly pointing towards the sun. To solve this issue, a mechanism was made with stepper motors that will allow to reduce the total area of the solar panel from 15 m² to 6 m², with a thickness of 112 mm. In this mechanism, it will provide rotation around one axis, and by using sun sensors, it will detect sunlight and activate the stepper motors for the deployment.

The final model was developed and designed in SolidWorks CAD software, as shown in the following images.

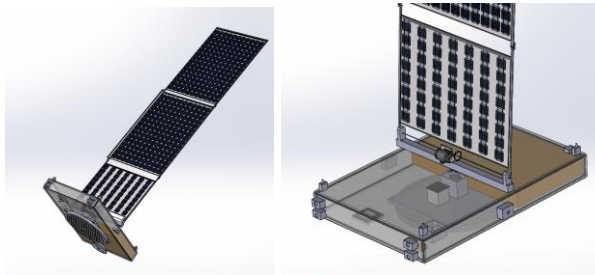


Fig. 10. CAD model of the spacecraft body.

3.4.11 Thermal Analysis

When developing the thermal analysis to maintain all the items of the spacecraft within their allowed temperature limits during all the mission phases while using minimum spacecraft resources*, some constraints were found, as shown below:

- Heat dissipated.
- Thermal environment.
- Spacecraft configuration and sizing.
- Temperature stability.
- Temperature uniformity

Table 4. Allowable range of temperature for different components.

Component	Allowable Minimum Temperature [°C]	Allowable Maximum Temperature [°C]
Batteries	-35	60
Propulsion Tank*	7	55
Radiator	-95	60
5G Antenna	0	60
OBDH*	-10	50
Array*	-105	110
ADCS*	0	45

To study the type of thermal control system, it was done a study based on extreme cases, due to the high number of orbital planes, this study is shown in the following graphs:

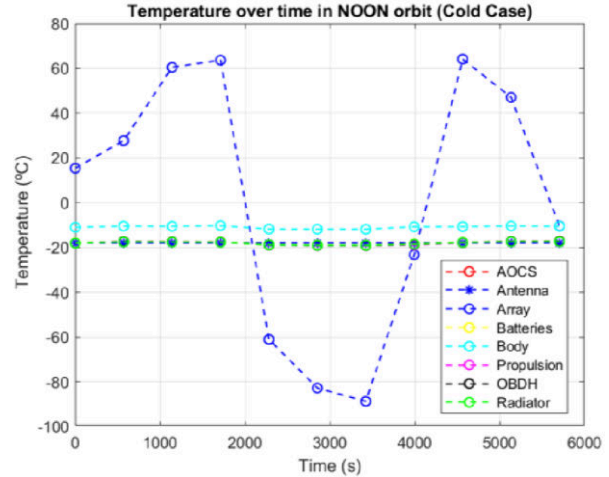


Fig. 11. Cold case study of the spacecraft.

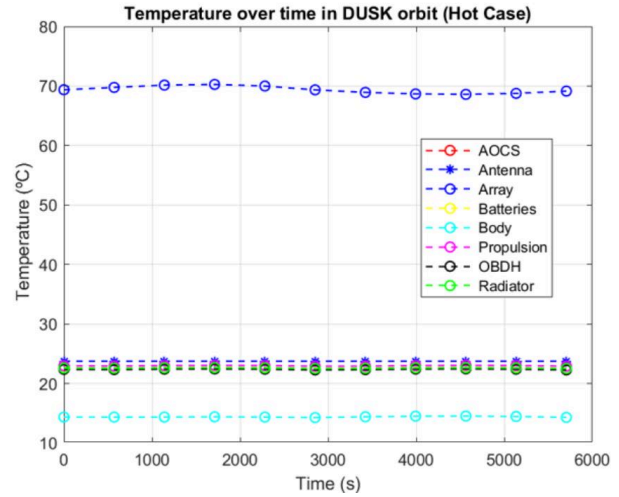


Fig. 12. Hot case study of the spacecraft.

Then to keep the satellite in the adequate temperature it was needed the use of passive cooling. Selecting different coatings for each part of the spacecraft as shown below:

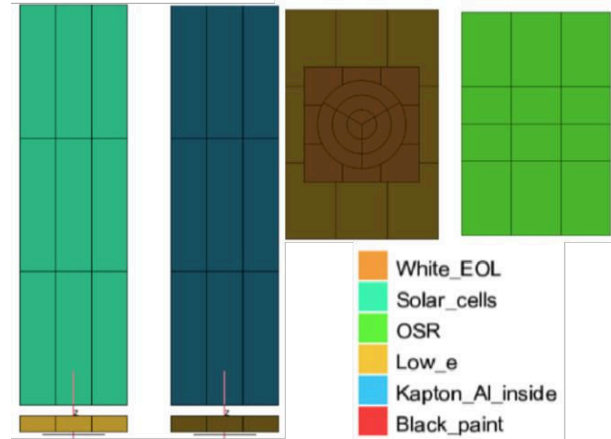


Fig. 13. Representation of the coating's distribution for the solar array.

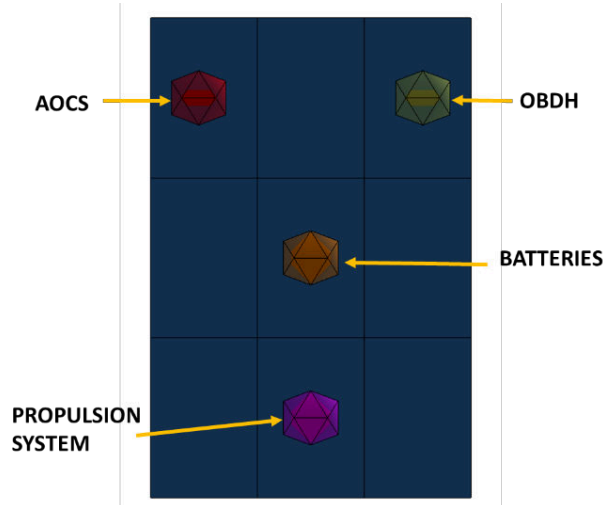


Fig. 14. Representation of the coating's distribution for spacecraft configuration.

3.4.12 Mass Budget

To observe the entire mass of the system, the mass budget analysis was made using the SMAD model [9] for spacecrafts in LEO with propulsion, adding the margins for the COTS, design and some additional on the final mass, and compared to the SMAD the final mass for most subsystems is lower than predicted. The mass budget is shown below:

Table 5. Mass budget with margin included.

Subsystem	Mass [kg]	Margin [%]	Final [kg]
Payload	66.60	10.00	73.26
Structure & Mechanisms	106.23	20.00	127.48
Thermal Control	4.30	20.00	5.16
Power (incl. harness)	49.10	20.00	58.92
TT&C & ISL	51.80	20.00	62.16
On-Board Processing	10.74	20.00	12.89
ADCS	14.37	10.00	15.81
Propulsion	9.80	10.00	10.78
Other (balance + launch)	6.45	20.00	7.73
Total	319.38		374.18
Propellant	35.00	20.00	42.00
	354.38		499.42

4. Discussion

Our group has explored the potential of 5G satellite communications, extending the reach of these networks to areas that are currently underserved by terrestrial networks, such as rural and remote regions, with some critical applications as disaster response.

4.1 Baseline

To understand better the overall mission final concept, here is presented the final baseline as follows:

Table 6. Final baseline of the project.

Parameter	Result
Antenna	Phased Array Antenna
Frequency	S-Band 2.18 GHz, 25 MHz bandwidth
Energy	2100 W
Size (Circular)	1.5 m diameter
Gain	40 dB
Orbit Choice	Circular LEO Sun-Synchronous
Altitude	(525 ± 5) km
Latitude	97.49 deg
Total Satellites	3009
Total Planes	59
Max Eclipse	35.6306 min
Shape	Flat- Rectangular
Material	Aluminum Alloy 7075.T6
Configuration	Spaceframe
BOL – EOL	5 years
Total Mass	449.42

5. Conclusion

In conclusion, we have discussed and addressed the challenges that the project has, such as the high cost of launching a constellation, the size and mass of the spacecraft, and the antenna to provide such technology directly to unmodified cellphones.

The exploration of direct-to-mobile phone satellite communication from Low Earth Orbit (LEO) has illuminated a promising path forward for the satellite communications industry. This technology, which harnesses the benefits of LEO satellite constellations, has the potential to usher in a new era of mobile communication by delivering reliable and seamless connectivity to users across the globe, with advantages of LEO satellites, including reduced latency, lower path loss, and enhanced communication quality, are undeniable.

The commercial allure of LEO-based direct-to-mobile phone satellite communication has attracted considerable interest, but it is a high-risk endeavor that demands meticulous feasibility studies, optimization of trade-offs, and secure financial resources. Businesses embarking on such ambitious projects must navigate a complex landscape to succeed.

Moreover, the potential for supplementary PNT services as part of this communication ecosystem presents an intriguing possibility, albeit one that requires careful consideration and planning.

By addressing challenges, optimizing system design, and leveraging the unique advantages of LEO satellite

constellations, the promise of direct-to-mobile phone satellite communication from LEO could indeed revolutionize mobile connectivity, paving the way for a more connected and accessible world.

References

- [1] J. N. Pelton, "Satellite Communications Overview," in *Handbook of Satellite Applications*, 2017, pp. 21–29.
- [2] J. N. Pelton, "Satellite Orbits for Communications Satellites," in *Handbook of Satellite Applications*, 2017, pp. 99–120.
- [3] J. N. Pelton, "History of Satellite Communications," in *Handbook of Satellite Applications*, 2017, pp. 31–71.
- [4] J. N. Pelton and B. Jacqué, "Distributed Internet-Optimized Services via Satellite Constellations," in *Handbook of Satellite Applications*, 2017, pp. 249–269.
- [5] N. Garzaniti, Z. Tekic, D. Kukolj, and A. Golkar, "Review of technology trends in new space missions using a patent analytics approach," *Prog. Aerosp. Sci.*, vol. 125, no. June, p. 100727, 2021, doi: 10.1016/j.paerosci.2021.100727.
- [6] ITU, "ITU, Radio Regulations," 2020. www.itu.int/publ/R-REG-RR/en.
- [7] S. Camacho-lara, "Current and Future GNSS and Their Augmentation Systems," in *Handbook of Satellite Applications*, 2017, pp. 781–819.
- [8] NASA, "NASA System Engineering Handbook Revision 2," *Natl. Aeronaut. Sp. Adm.*, p. 297, 2007, [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf.
- [9] J. R. Wertz, D. F. Everett, and J. J. Puschell, *Space Mission Engineering: The New SMAD*. Torrance, CA: Microcosm Press, 2018.



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