

Blockchain Applied in Decentralization of Ground Stations to Educational Nanosatellites

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Abstract— Space has increasingly attracted the attention of governments, large industries, and universities. One of the most popular strategies in recent years has been the adoption of nanosatellites to fulfill different missions, which can work alone or in constellations. Universities stand out among the agents launching nanosatellites, with more than 600 launches until 2022. Given the growth of entities that control space missions, it is necessary to implement new methods for communication between control and satellite to accelerate data transmission and provide a high-security degree. Our work proposes a consortium architecture between Ground Stations (GSs) so that a GS as a Service (GSaaS) works with low cost, reliability, and resource sharing. We simulated a nanosatellite mission in Low Earth Orbit (LEO) with MATLAB to obtain the parameters of average communication time, propagation loss, and at which angles the communication would be most affected by atmospheric phenomena. Then, we implement business rules for communication between GS and satellites using smart contract concepts. We set up a blockchain to provide the decentralization infrastructure and created a web service to provide a communication API between nanosatellite and blockchain. We simulated the firmware update process, showing that the nanosatellite took around 20 minutes to request all 32-byte fragments of 301 Kb firmware. Considering the time interval that the communication window between GS and nanosatellite remains active, the entire firmware transmission takes two to three communication slots. However, the transmission time is drastically reduced in a scenario with two or more GSs. Furthermore, the GSaaS decentralized infrastructure allows the consortium of GSs to communicate agnostically with the satellites, preserving firmware privacy due to the cryptography used in blockchain transactions.

Keywords— *Nanosatellite, Blockchain, Hyperledger Besu, Communication.*

I. INTRODUCTION

CubeSat is a standard cubic-shaped nanosatellite measuring $10 \times 10 \times 10$ cm³ that has become popular recently. A CubeSat is divided into units, with 1 U being the smallest unit in the standard. The format is popular due to its low development and release costs, being lightweight, and generally using Commercial-Off-The-Shelf (COTS) parts. According to the Nanosats Database, universities represent a significant part of the market share of nanosatellite builders launched in 2022. Around 640 new nanosatellites are expected by the end of 2022, which represents an increase of almost 98 percent compared to the previous year. In an environment where governments increasingly restrict education budgets, financial resources for universities and educational projects are limited. Some universities do not have a Ground Station (GS) for tracking, telemetry, and control of their CubeSats and need public and private partnerships to rent or use GSs from

other entities. In this scenario, solutions to reduce the costs of research and space missions can increase the participation of universities in the nanosatellite ecosystem.

The nanosatellites follow the same operating pattern as medium and large satellites; they exchange data with mission control, send and receive data, and can be tracked and alter their orbits. All these processes depend on antennas, operators, and compatible technologies to carry out the activities. The communication process between GS and nanosatellites is quite delicate. First, one of the bits may be flipped accidentally during data transmission and exchange, which may occur, for example, due to environmental reasons such as a solar storm or effects on the Earth's atmosphere. Second, there is another challenge regarding communication between GS and the nanosatellites. CubeSats operating in Low Earth Orbit (LEO) has between 5 to 15 min of communication window with GS [1]. Within such a short time window, the amount of transmitted data is minimal, and the communication must be done correctly, as the nanosatellite can take hours to be visible again to the station on Earth. Additionally, the CubeSats embedded firmware needs to be updated periodically [2][3], either because of a discovered vulnerability that needs to be corrected or due to the functions that the nanosatellite will perform. Given the high number of nanosatellites in orbit and the limited number of GSs, some issues are relevant for space projects, especially those with budget constraints.

This work proposes to decentralize the communication service between the mission control and the nanosatellite to increase the speed of dissemination of command and telemetry data (sensor reading, firmware update, mission change, or orbit correction). We implemented a Blockchain network that operates decentralized in the terrestrial stations, making the antenna “agnostic” to the satellite; any authorized satellite can communicate with the network using the Blockchain concepts of public and private keys.

II. BLOCKCHAIN BASIS

Blockchain is a linked and growing list of records grouped into cryptographically linked blocks [4]. A block is created when the network nodes obtain the consensus of those who have the authority to write a block new record [5]. Figure 1 exemplifies a blockchain with the main components:

- Data – a simple string, phrases, text fragments, or a list of transactions;
- Hash – a unique block identifier working as a digital print;
- Previous hash – the hash of the previous block; if the

previous block does not exist, the block current is called genesis, and the hash is a sequence of zeros;

- Metadata – information about the block number, date, and time.

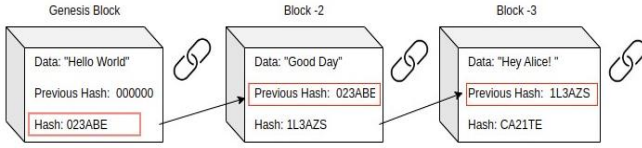


Figure 1. High-level representation of a blockchain example.

There are three types of blockchains: permissioned (or public), permissionless (or private) and hybrid. We will work with the concept of private blockchains.

In a permissioned Blockchain, the set of distributed ledgers can only be accessed by some people or nodes (computers) authorized to do it by the administrator. In the permissionless model, also known as a public blockchain, there are no restrictions, and an administrator does not control the membership of other nodes. Another widely used concept is the smart contract. The smart contract concept is not new, but Ethereum's Blockchain enabled it to be reliably implemented [6]. *Integrity Contracts* are codes automatically executed when reaching specific markers; they are decentrally stored in each network node.

III. DECENTRALIZATION AND SPACE APPLICATIONS

A. Decentralized Satellite Infrastructure

One of the most compelling examples of blockchain use in space applications and currently in operation is that of the Spacechain company [7], which aims to build an alliance consortium to create a Decentralized Satellite Infrastructure (DSI), a mesh network of heterogeneous spacecraft owned and operated in Low Earth Orbit (LEO) by multiple parties in multiple jurisdictions. One of its contributions is in the development of standards for this industry. Some examples of performance in this standardization:

- Minimum processing requirements applied to the participating satellites to enable activities under the Blockchain registry, smart contract 'bidding', mesh-network support, and routing protocol for the DSI;
- Minimum storage capacity established for storing and synchronizing DSI assignments, as well as uniform encryption standards;
- Minimum bandwidth for optical links and minimum hardware for APT systems established to maintain robust connectivity and throughput.

B. Blockchain and Earth Observation

Another interesting example is found in the European Space Agency (ESA) white paper called "Blockchain and Earth Observation", which presents the institution's interest in possible blockchain applications in the aerospace industry [8].

- Mission planning and operations, i.e., devising and monitoring the implementation of observation plans, including the management of tasking requests, logging and tracking of command and control events;
- Digital supply chains in both ground segment infrastructures and onboard satellite processing to track and resolve conflicts in data processing steps and to identify gaps;

- Physical supply chain in Earth Observation manufacturing to improve overall transparency and effectiveness of the flow of goods and financial services.

Many of the applications mentioned above use immutability and security features of blockchain decentralized ledgers.

C. Educational and small business nanosatellites

Our work has initially focused on providing educational space mission projects with a low-cost infrastructure for mission control to communicate with their devices.

When we observe the number of nanosatellites launched by educational institutions in the last year, we realize the great potential for research and formation of intellectual capital that these missions carry out, but often to communicate with their satellite, receive data and send commands; these institutions need to pass by bureaucratic processes and partnerships to obtain "time" to use the GS of an institution, government or official research group.

Figure 2 shows that Universities and educational institutions have the highest projections for launching nanosatellites.

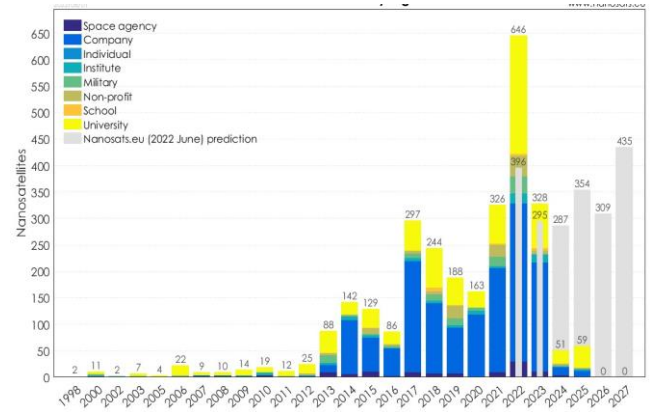


Figure 2. Launches by institutions.

Solutions that create infrastructure to reduce the costs of educational space missions or small businesses, sharing costs, and revenue generation are great innovation opportunities that our proposal seeks to explore.

Ground Station as a Service (GSaaS) [9] is a concept that currently offers an attractive solution for institutions that have nanosatellites orbiting the earth but do not have GSs; examples are the Azure Orbital Ground Station [10] and AWS-Ground Station [11]. Although these two solutions are not decentralized and do not use blockchain, we presented them in this section to exemplify market opportunities. Additionally, some works have already presented uses of the blockchain for communication between GSs and nanosatellites, where the space device is a client of the blockchain [12].

IV. DECENTRALIZATION OF GROUND STATIONS

The proposal to employ Blockchain to generate decentralized systems of control and communication between the mission control and the nanosatellite increases the interaction availability time, creating a GS network participating in the decentralized system; they can communicate agnostically with the nanosatellites participating in the network. This section presents the

advantages of using Blockchain to provide a decentralized infrastructure for GSs and the proposed architecture.

A. Advantages of using Blockchain at Ground Station

Table 1 summarizes the main advantages of using Blockchain to decentralize the communication between mission control and the nanosatellite.

Table 1. Decentralization of communication using Blockchain.

Feature	Benefit
Automation	Using smart contracts, routines, and processes, for example, sensor calibration or orbit corrections, can be performed without human intervention
Security	The decentralized Blockchain infrastructure can be combined with modern cryptographic techniques to preserve the privacy of codes, binaries and transactions, keeping each manufacturer's firmware code confidential
Tokenization	Tokenizing routines and some processes can generate an additional source of income for the institutions that maintain the service and even attract private initiatives to invest in projects
Availability	Suppose one of the GSs used by mission control fails or is unavailable in the decentralized system. In that case, the service continues to operate as long as there is an active computational node
Cost sharing	Universities can share communication costs between ground stations and nanosatellites, resulting in cheaper space missions

The Tokenization concept [13] presented in Table 1 enables the creation of a business layer over the decentralized infrastructure where the user pays to use a GS service. It is an advantage for the user that only pays when using the service and for the station owner that obtains a source of income when not communicating with the satellite.

B. Proposed Architecture

The proposed architecture is implemented in a decentralized GS network. Figure 3 represents the information traffic between the CubeSat nanosatellite and a computer responsible for the Mission Control; the information is propagated in packets with the aid of a Blockchain. A set of information blocks are exchanged whenever GS is in a communication window with CubeSat.

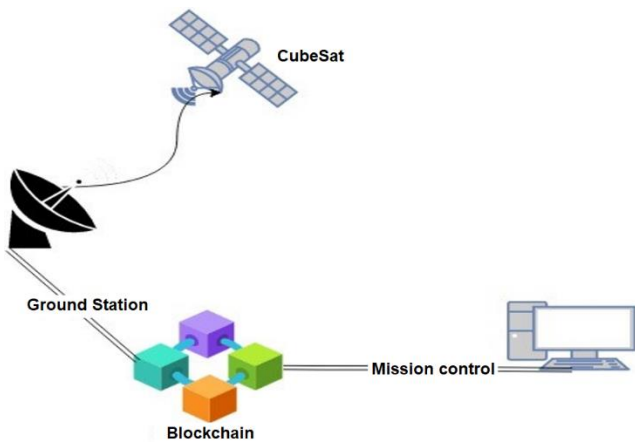


Figure 3. Basic information flow between Mission control and CubeSat.

Figure 4 displays the benefit of the decentralized architecture containing three ground stations (GS A, GS B, GS C), potentially placed in distant areas that allow disjoint communication windows. Therefore, the sum of all communication windows with a nanosatellite, called "CubSat

A", is potentially tripled, reducing the time for updating the information. Figure 4 exemplifies a message containing three packets; each GS transfers a packet. A typical application of this architecture is the nanosatellite firmware update.

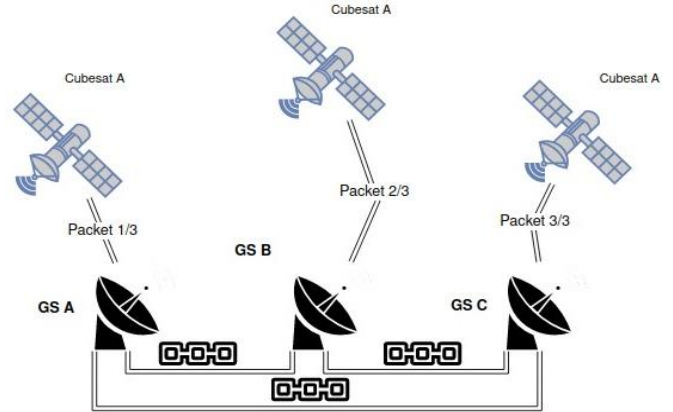


Figure 4. Decentralized architecture based on Blockchain for nanosatellite communication.

V. EXPERIMENTAL RESULTS

This section presents the development of the experiment in the subsections (i) *Experiment Implementation*, which presents the compilation of the development of the modules and performance of the experiments, and (ii) *Obtained Results*, which presents the analysis of the experiments.

A. Experiment Implementation

The experiment implementation encompasses the (i) *Space Mission* simulation with MATLAB; the (ii) *Software Implementation* that brings together the Blockchain elements creation and the python server to support the APIs, as well as carrying out the experiment and software tests; and the (iii) *Hardware Implementation* with the ESP8266 and PION CubeSat firmware [14].

1) Space Mission Simulation

The MATLAB simulation started setting up the nanosatellite mission in LEO, whose scenario was reproduced using the Satellite Communication Toolbox. The experiment employs two ground stations, one in northeastern Brazil (GS-Brazil) and the other in northern France (GS-France). The nanosatellite was placed at an altitude of 700 km. Figure 5 is a clipping of part of the mission showing the nanosatellite called "Sacode BR-1" and the two ground stations.

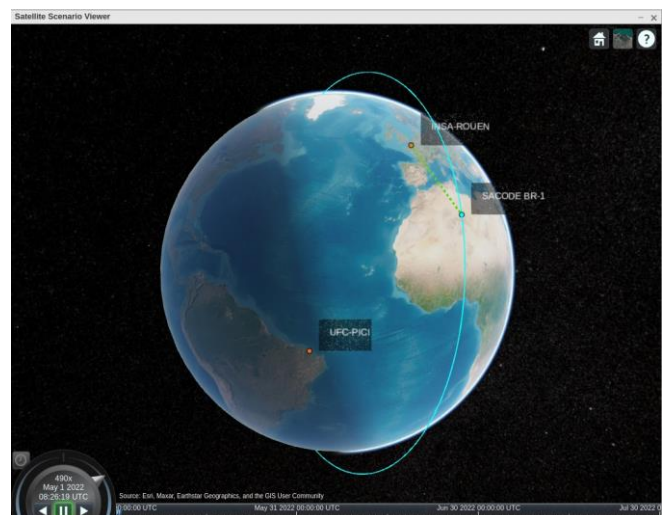


Figure 5. MATLAB simulation scenario.

Table 2 presents some simulation data, considering the duration of each active communication link between the nanosatellite and each GS, the number of communications, and the shortest time between communications.

Table 2. Communication information about nanosatellite orbit simulation.

Item	Description
Minimum communication duration	60 s
Maximum communication duration	840 s
Number of communications with GS-Brazil	396
Number of communications with GS-France	679
Less time between communications	4 minutes

2) Software Implementation

The software encompasses the Application Programming Interface (API) for REpresentational State Transfer (REST) and Blockchain implementations, which were performed in three parts:

- Installation and customization of the Hyperledger Besu Blockchain, an open-source Ethereum client developed under the Apache license and written in Java [15];
- Creation of the smart contract to manage the communication between GS and satellite; and
- Description of the API in Python to provide the application web service.

We chose to send a firmware update command to perform the communication process between GS and satellite. This firmware has 301 Kb that were fragmented into 32-byte blocks and stored on the Hyperledger Besu Blockchain, resulting in 9,566 blocks sent one by one to the nanosatellite.

3) Hardware Implementation

The hardware implementation also used the previous step as the produced software modules such as the API REST and Blockchain. Figure 6 presents an overview of the PION CubeSat we used to communicate with the server that simulated a GS. As PION's CubeSat is educational, its communication was done using ESP32 and HTTPS. We also created the framework for deploying the firmware on the board.

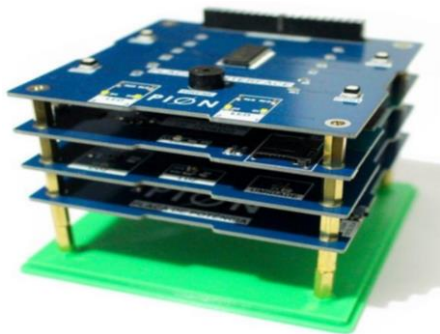


Figure 6. CubeSat PION [14].

B. Obtained Results

The first result observed was the time required to transmit all 9,566 firmware packets stored on the Blockchain to the nanosatellite without considering the communication window restriction. This time is an ideal situation where GS and satellite are in active communication 100% of the time, and all packets are transmitted without error. This experiment, which serves as an ideal best-case analysis, resulted in 1.149s

(19.15 min) to send all 9,566 firmware packets. It should be noted that we compared the hash of the fragment stored in the Blockchain with the fragment received by the nanosatellite; this comparison was performed using the SHA1 algorithm for checksum calculation. In case of divergence, the communication protocol requests a new packet, increasing the time to send the entire firmware.

The second experiment simulated a 90-day mission and only one GS, in this case, GS-Brazil. The simulation resulted in 396 communications between GS and nanosatellite, an average of 4.4 communications per day. Furthermore, depending on the nanosatellite orbit, the communication channel between GS and satellite is active within a range between 60s and 840s (1 min and 14 min), with an average of 648s (10.8 min); i.e., although there are small communication windows, most are windows with longer communication times.

We considered a time of 1200s (20 min) to calculate the number of communication windows needed to transmit all the firmware; we used the ideal time of 1,149s as a base and added a time margin to consider the packet identification and retransmission in case of error.

The 90-day mission simulation resulted in the need for at least two windows and a maximum of three windows, showing that the small windows (e.g., 60s) are interspersed with the large windows (e.g., 840s). Besides, the total time to update the entire firmware also depends on the interval between communication windows; the spacing between the communication windows adds a considerable time, resulting in a total interval for firmware transmission between 1 hour and 26 minutes and 10 hours and 43 minutes. This range is acceptable and consistent with current missions.

In a third experiment for a similar 90-day mission, we used two ground stations, GS-Brazil and GS-France. This experiment showed a significant reduction in the minimum firmware transmission time to 4 minutes; this is the case where it is possible to transmit all packets with only two consecutive communication windows.

However, there are still situations where three communication windows are required, implying a significant increase in the time to transmit all the firmware. Furthermore, the time between the packet availability and the first encounter with a communication window was not considered in any experiment. These two issues suggest the importance of implementing a decentralized system using Blockchain, as the more GSs are present in the communication network, the shorter the time between communication windows, resulting in a shorter overall time to complete the sending of packets.

VI. CONCLUSIONS AND FINAL REMARKS

Data throughput is a bottleneck for communication between GSs and satellites due to the orbit of satellites, which implies (i) a small communication window, i.e., the time interval when GS and satellite transmitters and receivers are within communication range and (ii) due to time lag between two communications; i.e., the time the satellite takes to start a new communication window.

One way to increase the communication throughput is to increase the number of GSs, consequently increasing the communication coverage. One way to democratize and facilitate access to GSs is through the concept of GSaaS; however, the costs of space missions can be high, especially

for universities, educational institutions, or small companies, not to mention the unavailability of the service or limitation of the number of communications within the contracted package.

Our project presented an effective method of uniting the concept of decentralizing GSs using Blockchain to offer a new approach to GSaaS. The proposed architecture enables the creation of tokens based on any currency or cryptocurrency. On the one hand, the owners of a GS can grant their service or hours of access to their equipment. On the other hand, the institutions that launch satellites only pay for the resource used, leaving the Blockchain itself to automate the communication process.

We designed and prototyped a web interface as a dashboard for each institution to load firmware images and access nanosatellite data. Therefore, the complexity of using the Blockchain and updating the nanosatellite firmware is transparent to the user.

Another positive point of this work is allowing educational institutions with a small team of researchers and students to focus on the experiment they are carrying out, leaving the communication infrastructure process in GSaaS.

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