engineering proceedings

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Proceeding Paper

Intelligent Interplanetary Satellite Communication Network for the Exploration of Celestial Bodies [†]

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[†] Presented at the 10th International Electronic Conference on Sensors and Applications (ECSA-10), 15–30 November 2023; Available online: https://ecsa-10.sciforum.net/.

Abstract: Recently, a significant interest in space exploration has emerged, driven by the lack of resources and the quest for answers to issues like climate change. New technologies give the possibility of exploring our solar system and its surroundings in greater detail. But current space communications operate with lack of efficiency, due to the vast distances between celestial bodies within our solar system. Also, factors such as bandwidth asymmetry contribute to disruptions in the satellite communication network. This paper proposes the definition of infrastructure of an interplanetary communication network, built upon a communications protocol featuring dynamic routing. This infrastructure aims to optimize information transmission by adapting communications to surrounding conditions. The envisioned infrastructure involves strategically placing network nodes at key Lagrange points around each planet within the asteroid belt. The nodes will be aware of their position integrating sensing capabilities and intelligent algorithms. Next to each planet, a node with more capabilities will collect information from nanosatellites orbiting a planet and will relay the information back to Earth. This structure will allow decision-making processes based on exploration data of the most significant celestial bodies within the asteroid belt, providing valuable insights such as constant monitoring of the dark side of the moon and difficult to reach zones in the Solar system.

Keywords: interplanetary internet; communication network; celestial bodies exploration

Citation: Urieta-Ortega, A.; Rosales, C.V.; Villalpando-Hernandez, R. Intelligent Interplanetary Satellite Communication Network for the Exploration of Celestial Bodies. *Eng. Proc.* **2023**, *56*, x. https://doi.org/10.3390/xxxxx

Academic Editor(s): Name

Published: 15 November 2023

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1. Introduction

Currently, we face challenges such as global warming and overconsumption of natural resources, and it is essential to continue seeking solutions on Earth. However, it is equally important to explore alternatives for resources beyond our planet to ensure the human species survival. Currently we face another issue, space explorations today are limited by the data communication capabilities of devices in space, primarily due to the lack of a space communications infrastructure.

This paper presents an innovative solution by proposing a network infrastructure consisting of strategically positioned nodes orbiting celestial bodies to address the lack of space communication infrastructure. These nodes work cooperatively to maintain efficient and stable communications for coverage of celestial bodies within the asteroid belt, addressing the proposed features of a unified communication architecture [1–3].

The paper is organized as follows. Section 2 describes the proposed communication network infrastructure, with hardware descriptions and their placement on celestial bodies. Section 3 outlines the network architecture, proposing routing protocols for different hierarchy levels within the network. Finally, the conclusions are presented in Section 4.

2. Communication Network Infrastructure

The infrastructure of the communication network aims to establish a physical link between network devices by using wireless optical communications technology, which is challenging since it relies on the line of sight (LOS).

The proposed infrastructure at the level of a planet as shown in Figure 1, will be replicated for all other significant bodies within the asteroid belt. It includes:

- Area Border Router (ABR)
- 5 Lagrange Subnet Routers (LSR)
- Swarm of Planet Monitoring Nanosatellites (PMN)

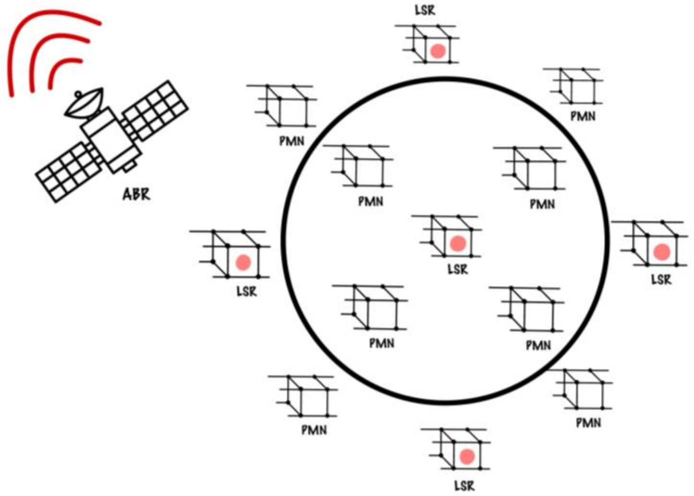

Figure 1. Arrangement of Network Devices for a Celestial Body.

2.1. Area Border Router (ABR)

This network node has the capability to establish and manage high-speed connections with the LSR satellites in the network, allowing effective interconnectivity of different subnetworks. Its high processing capacity with multiple cores is based on RISC architecture, offering a better balance between performance and energy consumption. This enables data processing for navigation, orbit control, and protocol management with low latency.

The ABR is equipped with solar power systems for its payload systems and energy storage via supercapacitors for actions that require a higher amount of power, such as antenna orientation corrections. In addition to these energy systems, for locations and potential uncontrollable events where sunlight is limited, these satellites are equipped with radioisotope thermoelectric generators (RTGs).

Regarding navigability to maintain a correct path, the ABR adjusts its course based on position feedback from the LSR satellites in orbit to ensure uninterrupted communication.

2.2. Lagrange Subnet Routers (LSR)

These satellites operate similarly to Low Earth Orbit Relay Satellites (LEO Relay Satellites) and are crucial as they will be responsible for relaying the information collected from the PMNs to the ABR satellite. Therefore, in terms of communication payload, they are equipped with transponders and signal amplifiers capable of fulfilling the data relay objective. The LSR have solar power systems and batteries to ensure proper power supply for their payload and navigation system.

2.2.1. Lagrange Point Placing

To address the challenges associated with wireless optical communication technology, it is proposed that the five LSR be positioned at Lagrange points. Lagrange points offer advantages in terms of orbital stability for devices such as satellites. Taking the Earth-Moon system as an example, these points are named L_1, L_2, L_3, L_4, and L_5, see Figure 2. L_4 and L_5 are considered stable, making it relatively straightforward to maintain a position relative to the planet without significant orbital adjustments. However, a problem arises with L_1, L_2, and L_3 points, as they are considered unstable. Despite their potential utility in maintaining a certain position for devices, these points are susceptible to disturbances in their orbital paths due to gravitational and non-gravitational forces. When a nanosatellite moves away from its equilibrium point in these regions, it continues to drift away.

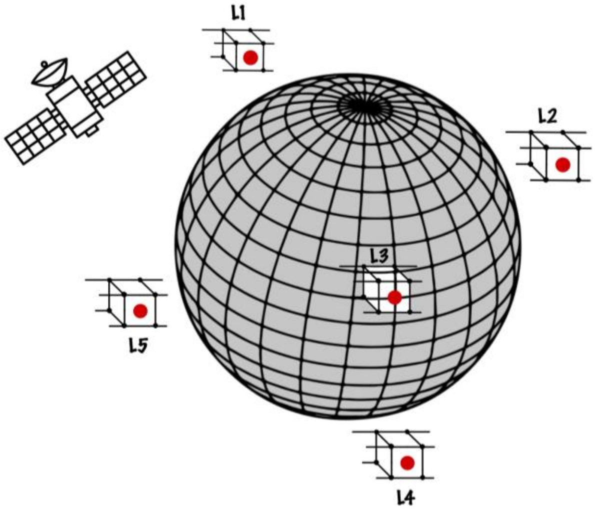

Figure 2. LSRs Arranged on a Planet.

The physical design of the LSR comes into play here. To utilize all five Lagrange points effectively, the LSR must have a significant amount of mass, enough to make them less susceptible to gravitational and non-gravitational forces that may disrupt their planned orbits.

2.2.2. Auto-Localization

Please note that additionally to the LSR design, the rest of the swarm, involves continuous orbit control and correction. For this purpose, the methodology of navigability through the analysis of local gravity maps, as proposed in [4] is suggested.

This methodology is based on the selection and analysis of gravity maps to support autonomous navigation. By converting these maps into grayscale images and performing statistical analyses based on frequency distribution (e.g., histograms, gradient values), characteristics related to gravitational anomalies in a specific area can be obtained. Authors in [4] note that larger gravity anomalies or differences within a zone enhance navigability. Consequently, this inertial navigation method is ideal for LSR satellites, given the significant difference in gravity between a Lagrange point and its surroundings. Thus, the navigation system can process the optimal route and adjust the course of the nanosatellites to maintain their positions at the Lagrange points [2].

Concerning navigation payload, the LSR is equipped with sensors like those used in submarines [5]. These sensors collect data about gravity anomalies in their surroundings and correct their inertial navigation system (INS) without depending on external feedback.

2.3. Planet Monitoring Nanosatellites

The potential of a swarm of PMNs is significant. With a payload focused on science, these nanosatellites aim to explore the celestial body to which they are deployed. They can be equipped with specialized sensors such as imaging sensors, spectrometers, magnetometers, radiometers, and high-resolution cameras capable of operating in space, as illustrated in [6,7]. The instruments and sensors on each PMN will depend on the mission's objectives and the area of the celestial body where they are operating.

To capture data from different angles or locations within the deployment area, PMNs are equipped with control and maneuverability systems [7]. These systems allow them to adjust their orientation and change their orbit, which is determined based on reference points provided by the LSRs. On the other hand, due to their limited physical size, nanosatellites have constraints when it comes to energy. PMNs utilize solar panels with maximum power point tracking (MPPT) algorithms. These algorithms automatically track the maximum power point on the solar panels, maximizing the efficiency of solar energy conversion into electricity. Additionally, they work together with voltage and current sensors to always monitor energy consumption efficiency on the PMN.

3. Network Protocol

Each selected celestial body within the infrastructure design will have its independent communication network, which will be interconnected with other networks of the same size (subnets), creating a unified network that reaches all selected celestial bodies. The entire network, including the communication subnets of the infrastructure is modeled according to the Open Systems Interconnection (OSI) Model.

3.1. Routing Protocol

In this layer, network segmentation is defined, playing a crucial role in device interconnection. For the network proposed, the use of the Open Shortest Path First (OSPF) routing protocol is considered, which bases its costs on link bandwidth.

All routers in the network are programmed with the same protocol. This enables them to share information among themselves and learn routes from the entire network topology, not just from their neighbors. Figure 3 illustrates the structure of an OSPF area in the network, i.e., the subnet covering a celestial body.

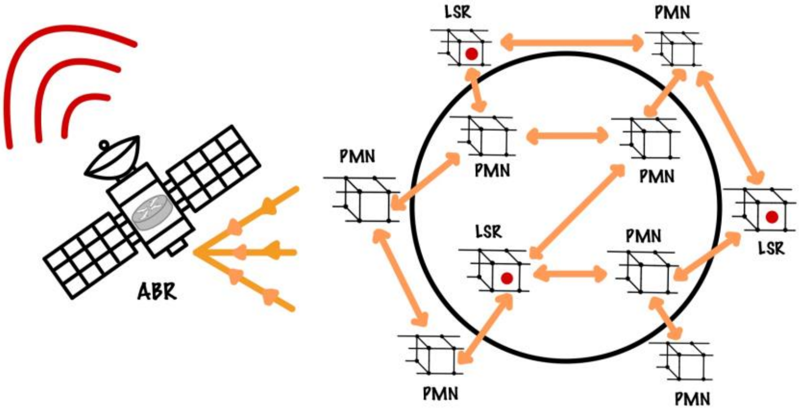

Figure 3. Representation of interconnections among ABR, LSR and PMN swarm.

Within this subnet, nanosatellites orbiting the celestial body act as devices. Satellites marked with a red dot represent those located at Lagrange points (LSR), which serve as routers within the subnet. The larger, higher-ranking satellite in the OSPF protocol is an Area Border Router (ABR), facilitating data intercommunication with other areas and providing information for routing decisions.

As the network topology is dynamic, both LSR and the ABR routers must react and select the best available route based on metrics associated with each end-to-end route interface's cost.

3.2. External Routing Protocol

Currently, there is no common standard for space-based communications. To establish communication links with other space-based devices, a public IP is required, which is where the EGP protocol comes into play.

Building on the Link State (LS) routing algorithm and scaling up within the network that reaches all celestial bodies within the asteroid belt, interconnection links are proposed to be established through router satellites ABR. These router satellites will be responsible for constructing the algorithm's database, generating their respective routing tables using the Dijkstra algorithm [8] to find the shortest path to all possible destinations within the network and determining which interface to use to reach them. Lastly, they will update the network topology as it changes, regenerating routing tables when the state changes.

4. Conclusions

To enable more active exploration of celestial bodies, this paper proposes a satellite infrastructure that covers the most significant celestial bodies within the asteroid belt. It establishes specifications for the distribution of various satellites within the network, utilizing Lagrange points as strategic placement locations for router nanosatellites around celestial bodies, along with the technical requirements that the infrastructure must meet to achieve proper communication. Furthermore, it presents a network architecture with dynamic routing that allows for adaptation to potential changes or variations within the network, establishing both IGP and EGP routing protocols.

Author Contributions: Conceptualization, A.U.-O. and C.V.R.; methodology, A.U.-O.; validation, A.U.-O. and R.V.-H.; investigation, A.U.-O.; resources, C.V.R. and R.V.-H.; writing—original draft preparation, A.U.-O.; writing—review and editing, C.V.R. and R.V.-H.; supervision, C.V.R. and R.V.-H.; project administration, C.V.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement:

Data Availability Statement: Data sharing not applicable.

Acknowledgments: We would like to acknowledge the support from the Smart Digital Technologies and Infrastructure Research Group, the project "Digital Technologies to Create Adaptive Smart Cities" of the Challenge-Based Research Funding Program, and the School of Engineering and Science at Tecnologico de Monterrey for providing the means to develop this collaborative work.

Conflicts of Interest: The authors declare no conflict of interest.

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