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The Satellite and Space Communications (SSC) Committee is a volunteer group actively involved in advancing satellite and space communication technologies within the IEEE. This committee is approved by the IEEE Communications Society and is governed by the constitution and bylaws of the IEEE as well as the other twenty-three Technical Committees in the Society. The committee belongs to the Technical Committee Clusters of Communication/Signal Processing (C/SP).

- JOIN US -

All conference attendees are welcome to join us in the SSC Committee meeting.

ONLINE MEETING URL: https://zoom.us/j/96371600053?pwd=yMVyxgsfLPrUhzSw8ZA4rQdfFZVeOg.1

Time: Wednesday, Dec 18, 2024

8:30 AM -9:30 AM ET

Future SSC Meetings

June 2025, Montréal, CANADA

December 2025, Taipei, TAIWAN

GLOBECOM 2024 SSC Committee Activities:

Symposium on Selected Areas in Communications:

SAC-SSC-S01 *December 10, 14:00-15:20*

SAC-SSC-S02 *December 10, 16:05-17:30*

SAC-SSC-03 *December 11, 08:30-09:50*

SAC-SSC-04 *December 11, 16:05-17:30*

SAC-SSC-05 *December 11, 16:05-17:30*

Interactive Sessions:

SAC-SSC-P01 *December 10, 15:20-15:30*

SAC-SSC-P02 *December 11, 15:20-15:30*

HOW TO JOIN SSC COMMITTEE AND MAILING LIST

If you like to join SSC Technical Committee: Please send your name and e-mail address to the SSC Secretary.

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e-mail: Halim.Yanikomeroglu@sce.carleton.ca

MESSAGE FROM THE CHAIR

Gunes Karabulut-Kurt

Dear SSC Colleagues,

As we conclude an extraordinary year for the space and satellite communications industry, I extend my heartfelt gratitude for your continued support, dedication, and active participation in our technical community. Serving as your Chair alongside the dedicated team of Committee Officers and SIG chairs has been an honor. Together, we have made significant strides in advancing the frontiers of satellite and space communications through innovation, research, and collaboration. We have organized numerous workshops, talks, and also a Student Competition on "Future 6G NTN Systems" to foster the interests of the next generation of researchers.

The satellite and space communications sector has witnessed unprecedented growth in 2024, driven by several transformative developments. The space industry saw a surge in new LEO satellite deployments by leading operators, with improved multi-orbit integration and higher service coverage. These expansions are rapidly transforming global connectivity and IoT-based services. With increasing satellite launches, regulatory agencies and private companies have also made strides toward mitigating space debris. New policies for collision avoidance and active debris removal systems gained momentum. Furthermore, several lunar missions advanced commercial exploration and scientific research, with many more to come soon. These developments surely trigger the need for interplanetary networking, as detailed in this edition's perspective article by Dr. **Juan Fraire**, entitled "Unraveling the Temporal Challenges of Interplanetary Networking."

As we enter 2025, several industry trends and predictions stand out, including AI-powered space operations and space-based quantum communication. Policies mandating space sustainability measures, including debris removal and efficient satellite design, will become central to industry compliance. I encourage you to continue contributing to our community through research, standards development, and mentorship. Our communities' insights, expertise, and commitment will be the driving forces behind our success.

Let's continue shaping the future of the satellite and space communications industry with bold ideas, groundbreaking technologies, and sustainable practices. Together, we can reach new heights in 2025 and beyond.

With best wishes for an innovative and successful 2025.

SCANNING THE WORLD

Giovanni Giambene

The convergence of lower launch costs, miniaturization, and cost reduction of satellite hardware has busted the opportunity to realize mega-LEO constellations (like Starlink by SpaceX, having about 6700 satellites in orbit as of November 2024) consisting of tens of thousands of satellites that can provide communications with latency levels that are now comparable with those of terrestrial systems.

Despite the significant number of Low-Earth Orbit (LEO) systems in the design, deployment, or operational phases, Geostationary (GEO) satellite operators seek commercial alliances with LEO operators to achieve multi-orbit systems. For instance, this is the case with SES, which manages GEO and Medium-Earth Orbit (MEO) satellites but can also use LEO satellites via commercial agreements. Analogously, Eutelsat can count on both GEO and OneWeb's LEO satellites. The integration of different players will be even more effective under the push of 3GPP standards for NTN, with significant progress from Release 18 to the new Release 19. This approach will make it possible direct communications with normal smartphones.

In December 2024, the EU Commission signed a contract with the SpaceRISE consortium (composed of three European satellite network operators: SES, Eutelsat, and Hispasat) to build a multi-orbital constellation, called IRIS^2 (Infrastructure for Resilience, Interconnectivity and Security by Satellite), including 290 satellites in LEO and MEO orbits. This system is part of the EU GOVSATCOM plan.

Sky Perfect JSAT launched on November 2024 the Universal NTN Innovation Lab (NTN Lab), which will conduct technical trials of 5G NTN technology in Japan.

On October 2024, NASA's LCOT (Low-Cost Optical Terminal), a ground station with modified commercial hardware, transmitted its first laser communications uplink for about 3 minutes to the TBIRD (TeraByte Infrared Delivery), a payload onboard a cubesat. This system (expected to operate at 200 Gbps) will allow an ever-increasing amount of transmitted data for space missions. Moreover, this summer, NASA's Psyche spacecraft was able to communicate via a laser link at about 290 million miles (460 million kilometers) away. The experiment made by JPL was able to achieve uplink and downlink communications at the same distance between our planet and Mars when the two planets are farthest apart.

The European Space Agency launched the Non-Terrestrial Network Forum in July 2024, bringing together global experts, stakeholders, and industry leaders to advance the development and integration of NTNs in the evolving 5G Advanced and 6G networks. This Forum will address future use cases, covering several vertical sector needs and the augmented capacities of NTN networks.

An Overview of the Student Competition on "Future 6G NTN Systems"

To inspire innovation among students, foster new ideas and solutions in satellite and space communications, attract new SSC TC members, and encourage active participation from young innovators, the SSC TC officers—Dr. Güneş Karabulut-Kurt, Dr. Giovanni Giambene, and Dr. Peng Hu—organized a student competition on the theme "Future 6G NTN Systems." This initiative was supported by **IEEE ComSoc's Innovation Project.**

The competition (https://2024.iccspa.org/comsoc-challenge/) was held with the IEEE ICCSPA 2024 Conference in Istanbul, Türkiye, July 8–11, 2024. Students were invited to submit conference-style papers exploring a wide range of topics related to NTN system design, including integration with terrestrial and 5G/6G systems, high-altitude platform stations, quantum communication, IoT, edge computing, dynamic routing, physical layer technologies, AI/ML applications, and advancements in security, mobility, and simulation for next-generation satellite communications.

Out of ten submissions, five winners were selected by the organizing committee and invited to present their work during the challenge workshop on July 10, 2024. The winners and their projects are as follows:

1. **"Enhancing HAP Networks with Reconfigurable Intelligent Surfaces"**
   Islam Mohammad Tanash (Aalto University, Finland); Ayush Kumar Dwivedi (Tampere University, Finland & International Institute of Information Technology Hyderabad, India); Fatemeh Rafiei Maleki and Taneli Riihonen (Tampere University, Finland)
2. **"Goal-Oriented Vessel Detection with Distributed Computing in a LEO Satellite Constellation"**
   Antonio Mercado-Martínez (University of Málaga, Spain); Beatriz Soret (Universidad de Malaga, Spain); Antonio Jurado Navas (University of Málaga, Spain)
3. **"High Altitude Platform Station-Greedy Clustering of Wireless Sensor Networks for the Massive IoT"**
   Anastassia Gharib (Princess Sumaya University for Technology, Jordan)
4. **"Sailing the Cosmic Seas: Improving Dependability in IoT-Based Deep Space Exploration"**
   Jason Gerard and Sandra Céspedes (Concordia University, Canada)
5. **"Improved Adaptive Multi-Density DBSCAN Method for Radar Signal Sorting in Complex Electromagnetic Environment"**
   Yi Wei (Zhejiang University, China); Yubi Qian (Shanghai Aerospace Electronic Technology Institute, China); Xiaoxiao Zhuo (Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, China)

With the support from ComSoc TC, the challenge workshop was a great success, which saw participation from approximately 25 attendees and featured a lively and insightful Q&A session. Competition submissions will be published in the ICCSPA 2024 proceedings on IEEE Xplore.

Report from IEEE Future Networks World Forum Symposium 2024, October 15-17, 2024, Dubai, UAE

Giovanni Giambene

A symposium was organized on October 15, 2024, the first day of the Future Networks World Forum 2024 (https://fnwf2024.ieee.org/), Dubai, by Gunes Karabulut-Kurt (Polytechnique Montréal, Canada), Giovanni Giambene (University of Siena, Italy), and Peng Hu (University of Manitoba, Canada). This Symposium, entitled "Non-Terrestrial Communications in Future Networks," was an important opportunity for researchers to meet and discuss recent advances in NTN systems for future 6G systems. We had five papers presented, dealing with key topics, such as Orthogonal Time Frequency Space (OTFS) waveform application for a high-altitude platform station, downlink MIMO feeder link, AI-based prediction for atmospheric and path losses, efficacy and reliability of secret key exchange in UAVs, and the use of UAVs in remote uncovered areas. Speakers were from Istanbul Technical University, Turkey, Bundeswehr University Munich, Germany, Indian Institute of Space Science and Technology, Aarhus University, Denmark, and Cranfield University, United Kingdom.

FORTHCOMING CONFERENCES

ICC 2025
8-12 June 2025,
Montreal, Canada
http://icc2025.ieee-icc.org/
The International Conference on Communications (ICC) is one of the two flagship conferences of the IEEE Communications Society, together with IEEE GLOBECOM. Each year the ICC conference attracts about 2-3000 submitted scientific papers, a technical program committee involving about 1500 experts provides more than 10000 reviews, the conference being finally attended by 1500 - 2000 professionals from all around the world. IEEE ICC is therefore one of the most significant scientific events of the networking and communications community, a must-attend forum for both industrials and academics working in this area. IEEE ICC 2025 - Featuring the latest developments in telecommunications from a technical perspective.

GLOBECOM 2025
8-12 December 2025
Taipei, Taiwan
https://globecom2025.ieee-globecom.org/
IEEE GLOBECOM - IEEE Global Communications Conference (GLOBECOM) is one of the IEEE Communications Society's two flagship conferences dedicated to driving innovation in nearly every aspect of communications. Each year, around 3,000 scientific researchers and their management submit proposals for program sessions to be held at the annual conference. After extensive peer review, the best of the proposals are selected for the conference program, which includes technical papers, tutorials, workshops and industry sessions designed specifically to advance technologies, systems and infrastructure that are continuing to reshape the world and provide all users with access to an unprecedented spectrum of high-speed, seamless and cost-effective global telecommunications services.

CONFERENCES CALENDAR

CONFERENCE	DATE & LOCATION	INFORMATION
12th Advanced Satellite Multimedia Systems Conference 18th Signal Processing for Space Communications Workshop	26 – 28 February 2025, Sitges, near Barcelona (Spain)	https://www.asmsconference.org/
16th International Conference on Ubiquitous and Future Networks	8–11 July, 2025, Lisbon, Portugal	https://icufn.org/

To all SSC members: If your postal address, telephone or fax numbers have changed, please update them with the committee secretary. You can review our current records on our web page at http://committees.comsoc.org/ssc/.

PERSPECTIVE ARTICLE
December 2024

Unraveling the Temporal Challenges of Interplanetary Networking

Juan A. Fraire

Inria, INSA Lyon, CITI, UR3720, 69621 Villeurbanne, France

CONICET – Universidad Nacional de Córdoba, Córdoba, Argentina

December, 2024

Abstract – **Interplanetary Networking (IPN) presents unique challenges from extreme light-speed delays, planetary occlusions, and dynamic space environments. This paper examines the critical temporal issues influencing contact topologies, IPN models and algorithms, protocol architectures, and sociopolitical barriers to achieving sustainable IPNs. By identifying, enumerating, and analyzing these challenges, this work establishes a foundation for designing robust, time-aware networks crucial for humanity's transition to a multi-planetary future.**

Introduction

Time is a controversial concept debated extensively in physics and philosophy. In the framework of classical mechanics, Isaac Newton defined time as absolute, perfect, and universal, flowing independently of all external influences. Albert Einstein's general relativity revolutionized this understanding by intertwining time with space. It demonstrated that time can stretch depending on velocity and proximity to massive objects. Time's role remains elusive in quantum mechanics, as core equations are not inherently time-dependent. Contemporary theorists further challenge conventional notions, proposing timeless models for a unified theory of everything, where time is seen as a human construct imposed to organize cause and effect.

Having challenged humanity's greatest minds, the intangible nature of time unsurprisingly fuels controversial approaches to the design of time-dependent space data transport networks spanning the vast distances of interplanetary space. The effect of time in Interplanetary Networking (IPN) can be classified into two categories: delay and disruptions.

1. Delay: Propagation latency due to the finite speed of light can range from several minutes to over an hour, depending on the relative positions of Earth and the destination body, such as Mars or the outer planets. This latency requires innovative protocols that can operate asynchronously and autonomously.

2. Disruptions: Additionally, prolonged disruptions caused by planetary occlusions further complicate the design and operation of IPN. These occlusions occur when a planet blocks the line of sight between a spacecraft and Earth, leading to extended communication blackout periods and partitioned topologies.

This paper offers a comprehensive enumeration, analysis, and identification of the key time-related challenges that must be addressed to realize viable IPNs. It presents a critical review of existing approaches across the following key aspects.

1. Topology Determination and Design: IPNs are defined by time-bounded contacts rather than static links. Contacts must account for the challenges of light time delay and the apparent position problem compounded by the spacecraft's architectural limitations.

2. Models and Algorithms: Decision-making algorithms must rely on time-accurate models and abstractions, capable of handling dynamic network conditions while operating on constrained onboard computing resources in coordination with ground operations.

3. Architectures and Protocols: IPN protocol architectures must seamlessly incorporate time-awareness and store-carry-and-forward (SC&F) mechanisms while remaining compatible with the traditional Internet's static and synchronous structure.

4. Interoperability and Sociopolitical Context: Ultimately, all temporal definitions, models, protocols, and architectures must be standardized and accepted by nations, companies, and agencies to ensure interoperability and the long-term viability of IPNs.

The remainder of this paper is structured as follows. Section 2 provides a detailed background on the limitations of the modern Internet in addressing time-sensitive scenarios. Section 3 delves into the core challenges of IPN, including topological determination and design, model and algorithmic complexities, architectural and protocol pitfalls, and interoperability and sociopolitical dimensions of IPN. Finally, Section 4 outlines the key insights and future directions.

Background

2.1 Time in the Modern Internet

The Internet's design, rooted in its evolution from telephone systems, enables synchronous communication with bidirectional data exchange, low latency, and static topologies. The Internet relies heavily on static models, such as steady paths and low-latency round-trip communication.

Protocols like TCP depend on reciprocal data exchanges, short round-trip times (RTTs), and minimal link errors to maintain efficiency. This dependency on synchrony leaves traditional Internet architectures ill-equipped to address the needs of more dynamic environments. We highlight two successful yet provisional adaptations that bring time-awareness to the inherently synchronous Internet design.

1. Mobile IP: Mobile IP emerged as a stopgap solution to address the mobility problem, extending the Internet's static assumptions to accommodate node mobility [11]. However, it functions as a "patch" rather than a transformative architectural shift. By introducing routing mechanisms such as home agents and foreign agents, Mobile IP enables mobility but retains the Internet's inherent reliance on low latency and static path assumptions.

2. Performance Enhancing Proxies: PEPs sought to circumvent the Internet's limitations in high-latency geostationary satellite links by breaking the end-to-end principle [12]. PEPs split TCP connections and optimize segments independently to mitigate the inefficiencies of long round-trip times. While effective in specific cases, PEPs compromise protocol transparency and interoperability.

These solutions demonstrate the adaptability of Internet architectures to specific challenging environments.

However, interplanetary communication's extreme delays and disruptions demand a more fundamental rethinking beyond simple extensions or patches.

2.2 Interplanetary Networking

IPNs represent the next frontier in communication systems, bridging vast distances and overcoming the unique challenges of space environments. Key actors, projects, and data handling paradigms are as follows.

Actors and Projects The historical milestones of space exploration, from NASA's launch of the Voyager missions to the deployment of several Mars rovers and orbiters, have underpinned the necessity for a robust and interoperable communication infrastructure [1]. In the context of the New Space era, a novel interaction between the private and public sectors is fostering a rapid increase of interest and innovation in the interplanetary sector [5]. Private entities like SpaceX and Blue Origin, along with legislative advancements in countries such as Luxembourg, have further underscored the potential of space industries, particularly in exploration and resource acquisition [14]. Recent space initiatives like NASA's Lunar Communication and Navigation System, ESA's Moonlight [10], and the joint LunaNet Interoperability Specification [9] are a testament to the growing demand for IPN solutions.

Data Handling Paradigm A cornerstone of IPN is the Delay-Tolerant Networking (DTN) architecture, which employs the SC&F data handling mechanism to overcome the challenges of extreme latency and intermittent connectivity. Unlike traditional Internet protocols that rely on end-to-end connectivity, DTN enables intermediate nodes to store data packets when no immediate forwarding path is available, carry them until connectivity is available, and then forward them to the next node or final destination. This approach and minimizing end-to-end messaging ensure effective data delivery across disrupted and time-varying IPN topologies.

2.3 The Long-Term Ambition of Interplanetary Networking

While human expansion into space is an evident long-term goal, IPN will first play a critical role in enabling a sustainable interplanetary economy. It envisions a future where industrial activities in space, such as asteroid mining, lunar resource extraction, and in-orbit manufacturing, are predominantly automated and supported by interconnected robotic systems. These robots will autonomously mine, process, and transport materials, creating self-sustaining "robotic villages" operating with minimal human intervention. Services like energy and fuel delivery, data relays, transport, and logistics will form the backbone of this economy. This vision underscores the need for robust IPNs to ensure reliable data exchange, operational monitoring, and coordination across these vast robotic systems. Naturally, success in this endeavor will pave the way for a sustained human presence in the interplanetary expanse.

Challenges

3.1 Topological Determination and Design Challenges

Instead of links, topologies in IPN are characterized by time-bounded contacts. A contact is defined by a start and end time, transmitter and receiver nodes, and optional arguments such as data rate during the period and channel quality. The main temporal challenges of contact are their accurate determination across interplanetary distances and the selection of contacts that can effectively be implemented according to the spacecraft's operational and architecture constraints.

3.1.1 Contact Time Determination

Accurate contact time determination is a critical challenge in IPN, rooted in the fundamental physical constraints of light propagation and the apparent position problem [2]. Both aspects, discussed below, are typically overlooked in related IPN literature.

1. Apparent Position The apparent position refers to the observed location of a celestial object or spacecraft. When a signal is transmitted, the object's position at the time of reception corresponds to where it was when the signal began traveling, not where it is during the actual interaction. For example, if a spacecraft near Mars transmits a signal to Earth, Earth's receivers must calculate where the spacecraft was approximately 15 minutes earlier, depending on the light travel time. Because celestial bodies constantly move in their orbits, their relative positions change dynamically during signal propagation.

2. Light Time The light time delay introduces asynchronous communication, where the feedback loop between transmission and reception spans several minutes to hours. Standard methods for determining light time delay involve iterative processes that converge on the value of $\Delta t = r/c$, where r is the range between two objects and c is the speed of light. These iterations must also factor in relativistic effects like aberration and the choice of inertial frame, as highlighted in [2]. However, most of the existing models in the literature ignore these time-dependent aspects and rely on idealized, static assumptions that do not reflect the realities of interplanetary communication.

This discrepancy requires iterative calculations using inertial frames and first-order relativistic corrections to estimate the transmission and reception time accurately. Failure to incorporate these factors leads to inaccurate predictions of contact windows, compromising mission-critical operations such as data relays, command uplinks, and navigation updates.

3.1.2 Contact Plan Design

Contacts are organized into so-called contact plans. Existing research often oversimplifies the design of contact plans in interplanetary networks. This typically assumes that a contact is feasible if visibility conditions are met. However, this overlooks critical architectural constraints that fundamentally impact the practicality of point-to-point links in space networks [7]. These limitations, listed below, arise from spacecraft's resource-constrained nature and the complexity of dynamic interplanetary environments.

1. Limited Transponders: Most spacecraft are equipped with a finite number of transponders, restricting the number of simultaneous communication links they can support. Even when multiple contacts are theoretically feasible within a network topology, resource constraints necessitate prioritizing some links over others [7].

2. Power and Energy Restrictions: Spacecraft operate under strict power budgets. High power communication links, particularly over interplanetary distances, consume substantial energy and cannot be enabled persistently as in classical terrestrial networks [8]. Many studies oversimplify contact feasibility, reducing it to a binary condition based solely on visibility while neglecting critical architectural and operational constraints. In real IPNs, effective

contact plan design demands meticulous planning to optimize transponder utilization and ensure consistent network performance. This requires prioritizing which contacts to establish and determining their duration, introducing significant complexity to the process.

3.2 Modeling and Algorithmic Challenges

IPNs require modeling and algorithmic innovations that address space environments' unique temporal, spatial, and resource constraints, tailored specifically to their asynchronous and delay prone nature.

3.2.1 Network Models

The modeling of IPNs is a critical challenge due to their inherently dynamic and resource constrained nature. Central to this challenge is the choice of representation for network connectivity and communication opportunities materialized in contacts. As discussed in [6], three principal models are used: contact plan tables, time-evolving, and contact graphs, described below.

1. Contact Plan Tables: A contact plan is a precomputed schedule of communication opportunities between network nodes, typically expressed as a tabular representation. Each entry specifies the start and end time, sender, receiver, data rate, and other parameters. While contact plans provide an intuitive and compact connectivity summary, they lack the granularity and flexibility required for complex routing computations. Their static nature makes them inadequate for capturing the dynamic interplay of multiple contacts and the temporal dependencies inherent in IPN.

2. Time-Evolving Graphs: Time-evolving graphs attempt to address the temporal dynamics by representing network connectivity as a sequence of snapshots, each corresponding to a static graph valid for a specific time interval. This approach captures the dynamic nature of IPN better than contact plan tables but suffers from scalability issues. The number of graph states snowballs with the number of nodes, contacts, and the length of the planning horizon. This growth significantly increases computational complexity, making time-evolving graphs less practical for large-scale or long-duration missions. Furthermore, the representation of delay effects requires additional states, further exacerbating scalability concerns.

3. Contact Graphs: Contact graphs are a specialized representation designed to optimize routing in DTNs. They model network connectivity as a directed acyclic graph, where vertices represent contacts and edges represent potential data transfers. This abstraction facilitates using graph-based algorithms, such as adapted versions of Dijkstra’s algorithm, to compute optimal routes efficiently. Contact graphs overcome many limitations of the other models, particularly their ability to integrate temporal storage and propagation delay into routing calculations directly. However, they require a separate graph for each source-destination pair, which can be computationally expensive in scenarios involving multiple destinations Despite each model’s advantages and disadvantages, the research community has yet to agree on a standard approach. Many studies still rely on oversimplified representations, such as assuming static connectivity or neglecting the impact of delay and disruptions. This divergence in modeling practices leads to fragmented insights and hinders the development of unified solutions for IPN.

3.2.2 Network Algorithms

The design of network algorithms for IPN is critical to ensuring efficient, reliable, and scalable communication across vast and dynamic topologies. These algorithms must address three interrelated challenges: routing, congestion control, and reliability.

1. Routing and Forwarding: Routing in interplanetary networks relies on DTN principles, where paths are not persistent but evolve based on the availability of contacts over time. Contact Graph Routing (CGR) is a widely used approach that leverages contact graphs. CGR operates in three stages: i) contact graph construction, ii) route selection (computes optimal paths using algorithms like Dijkstra’s, adapted for time-dependent networks), and iii) forwarding decision (the next hop is selected among computed routes).

2. Congestion Management: Congestion in interplanetary networks arises when multiple data bundles compete for limited bandwidth or storage at intermediate nodes. Unlike terrestrial networks, where congestion can be mitigated through rapid feedback loops, the high propagation delays in IPNs make traditional congestion control mechanisms infeasible. Advanced methods, such as predictive congestion modeling and prioritization of critical data, are needed to prevent bottlenecks.

3. Reliability and Storage Control: Reliability in IPNs is achieved through a custody transfer mechanism, where intermediate nodes take responsibility for ensuring data delivery if the next hop becomes unavailable. Also serving to manage storage depletion, this approach shifts reliability from the end-to-end paradigm of traditional networking to a hop-by-hop model more suited to DTNs.

However, routing and congestion face scalability challenges as potential routes increase with network size and planning horizon length. Additionally, dynamic changes in contact availability can render precomputed routes suboptimal, necessitating real-time adaptability. Custody transfer for reliability also introduces several challenges, including storage management (nodes must allocate limited buffer space judiciously), timeouts and retransmissions (challenging to set in time-dynamic networks), and prioritization.

3.3 Architectural and Protocol Challenges

The architectural evolution of IPN has spurred debate over the best protocol stack for managing the complexities of space communication. Two primary visions have emerged: the Bundle Protocol (BP)-centric approach, rooted in DTN principles, and the IP-centric approach, which extends the traditional Internet Protocol (IP) stack with SC&F capabilities. Both approaches aim to address intermittent connectivity, high latency, and resource constraints but differ fundamentally in their design philosophies.

1. BP-Centric Approach: The BP-centric approach is a cornerstone of the DTN framework, explicitly designed to manage disruption-prone and high-latency environments. Jointly standardized by IETF [13] and CCSDS [4], BP introduces a SC&F mechanism, storing data bundles at intermediate nodes until a viable forwarding path becomes available. This approach excels in handling the dynamic and sparse topologies of deep-space networks. BP introduces a new overlay protocol layer and employs endpoint identifiers (EIDs), which are more flexible than traditional IP addresses. EIDs address applications instead of interfaces and enable the so-called late-binding [3]. However, BP integration involves encapsulation overhead and increased processing delays, demotivating its integration

in high-performance LEO constellations.

2. IP-Centric Approach: The IP-centric approach seeks to adapt the ubiquitous IP stack to accommodate delay-tolerant scenarios by embedding SC&F capabilities directly within its operations. IP's best-effort delivery model and compatibility with existing terrestrial networks make it a compelling choice for maintaining interoperability

and backward compatibility. Recent efforts in the deepspace IETF mailing list propose the exploitation of QUIC protocol flexibility to adapt to high latencies and develop custom proxies to deal with temporal storage. However, the IP-centric approach lacks these builtin mechanisms or solutions to handle custodial responsibilities or manage data persistence. Modifying IP and QUIC to fully support SC&F features would require extensive protocol reengineering or custom proxies, potentially undermining its simplicity and adoption.

BP offers robustness and proven reliability in extreme conditions but requires a new overlay protocol. On the other hand, IP aligns with existing infrastructure but requires embedding significant features to handle SC&F-specific challenges effectively. Possibly, future efforts should focus on hybrid architectures that combine and integrates the strengths of both approaches. This includes exploring the utilization of dynamic protocol selection mechanisms based on network conditions and developing interoperability layers to bridge BP and IP.

3.4 Interoperability and Sociopolitical Challenges

While IPN missions are already being carried out, they remain mostly isolated endeavors, with limited collaboration in terms of communication integration. An interoperable framework, akin to the one that enabled the global Internet, will be essential to realize the interplanetary vision introduced in Section 2.3. Encouragingly, organizations like the Consultative Committee for Space Data Systems (CCSDS) and the Internet Engineering Task Force (IETF) are actively working on standardization efforts. The Interagency Operations Advisory Group (IOAG) also supports cross-border agency collaborations. However, significant sociopolitical challenges threaten the progress of such cooperative efforts.

The geopolitical landscape is increasingly polarized, reminiscent of the Cold War-era space race, with nations competing in ambitious space initiatives like lunar exploration. Restrictive interactions between Western and Asian countries create barriers to coordinated efforts in defining and adopting communication standards. Simultaneously, the dominance of highly concentrated private companies like SpaceX further complicates the landscape. While these entities demonstrate extraordinary advancements in communication services (e.g., Starlink) and future Mars missions, their proprietary protocols, and closed systems limit the participation of smaller stakeholders, including academic institutions and emerging space nations. This lack of inclusivity could hinder the development of a collaborative, interoperable IPN framework, ultimately stalling progress toward a unified and successful interplanetary vision.

Outlook

Interplanetary Networking (IPN) is set to revolutionize humanity's interaction with and exploration of the cosmos. However, its full potential hinges on overcoming significant technical, architectural, and sociopolitical challenges—all stemming from the fundamental need to integrate time dynamics into a traditionally synchronous networking Internet paradigm.

First, tackling the challenges of light propagation delays, apparent positions, and spacecraft constraints is essential for accurately defining and understanding IPN topologies. Second, achieving reliable communication across vast interplanetary distances demands innovative temporal models and robust decision-making algorithms to tackle the fundamental constraints of delay and disruptions. Third, the debate between BP-centric and IP-centric architectures underscores the trade-offs between adopting specialized protocols for reliably managing time dynamics and adapting existing IP stacks to address these challenges. Finally, achieving a truly interoperable framework akin to the Earth-based Internet demands coordinated efforts among international agencies, private sector leaders, and academic institutions while navigating a complex sociopolitical landscape.

If humanity aspires to become an interplanetary species, we must first unify under a shared networking vision—one that adheres to a standard communication protocol founded on a profound understanding of the elusive concept of time.

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Juan A. Fraire is a researcher at INRIA (France) and a guest professor at CONICET-UNC (Argentina) and Saarland University (Germany). Core topics of his interest are near-Earth and deep-space networking and informatics, adding up to more than 100 published papers in international journals and leading conferences. Juan is the co-founder and chair of the Space-Terrestrial Internetworking Workshop (STINT) and participates in diverse joint projects with space agencies (e.g., NASA, ESA, CONAE) and companies in the space sector (e.g., D3TN, Skyloom).