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A Roadmap Toward a Unified Space Communication Architecture

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ABSTRACT In recent years, the number of space exploration missions has multiplied. Such an increase raises the question of effective communication between the multitude of human-made objects spread across our solar system. An efficient and scalable communication architecture presents multiple challenges, including the distance between planetary entities, their motion and potential obstruction, the limited available payload on satellites, and the high mission cost. This paper brings together recent relevant specifications, standards, mission demonstrations, and the most recent proposals to develop a unified architecture for deep-space internetworked communication. After characterizing the transmission medium and its unique challenges, we explore the available communication technologies and frameworks to establish a reliable communication architecture across the solar system. We then draw an evolutive roadmap for establishing a scalable communication architecture. This roadmap builds upon the mission-centric communication architectures in the upcoming years towards a fully interconnected network or InterPlanetary Internet (IPN). We finally discuss the tools available to develop such an architecture in the short, medium, and long terms. The resulting architecture cross-supports space agencies on the solar system-scale while significantly decreasing space communication costs. Through this analysis, we derive the critical research questions remaining for creating the IPN regarding the considerable challenges of space communication.

INDEX TERMS Space communication, deep space, Interplanetary Internet, IPN network architecture, interplanetary network, interplanetary network infrastructure.

I. INTRODUCTION

Recent years have seen a resurgence of interest in space exploration, and multiple recent missions have attracted significant media attention. Figure 1 presents several examples of such recent missions. In the upcoming years, both space agencies and private companies intend to pursue this interest through ambitious missions. Space exploration missions, both past and future, require sophisticated communication capabilities to address their specialized needs. However, establishing mission-specific communication architectures is costly and provides little reusability for future missions. In 2021, multiple major space agencies have been contributing to space exploration. These include NASA,[1] European Space Agency (ESA),[2] Canadian Space Agency (CSA),[3] Japanese Aerospace Exploration Agency (JAXA),[4] Chinese National Space Agency (CNSA),[5] and the Russian Federal Space Agency (Roscosmos),[6] as well as a multitude of smaller space agencies and private companies. The lack of common communication architecture between these agencies leads to an increased workload to connect successive missions, higher mission costs, and ultimately, a decrease in inter-agency collaboration.

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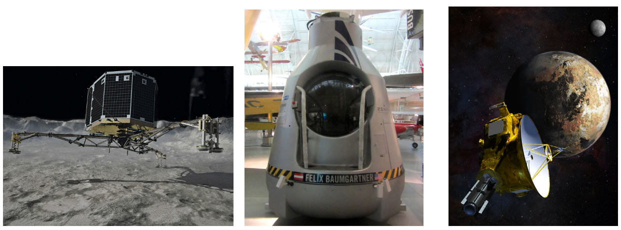
[1]National Aeronautics and Space Administration: https://www.nasa.gov/
[2]European Space Agency: https://www.esa.int/
[3]asc-csa.gc.ca/eng
[4]https://global.jaxa.jp/
[5]http://www.cnsa.gov.cn/
[6]en.roscosmos.ru

TABLE 1. List of acronyms.

Acronym	Definition
IPN	Interplanetary Network
NASA	National Aeronautics and Space Administration
JAXA	Japan Aerospace Exploration Agency
CNSA	Chinese National Space Agency
CSA	Canadian Space Agency
Roscosmos	Russian Federal Space Agency
SNR	Signal to noise ratio
MOC	Mission Operation Center
JPL	Jet Propulsion Laboratory
DSN	Deep Space Network
RF	Radio Frequency
FSO	Free Space Optic
LCRD	Laser Communication Relay Demonstration
LLCD	Lunar Laser Communications Demonstration
LDAEE	Lunar Atmosphere and Dust Environment Explorer
GEO	Geostationary Earth Orbit
MEO	Medium Earth Orbit
LEO	Low Earth Orbit
JWST	James Webb Space Telescope
DTN	Delay Tolerant/Disruption Network
CLP/A	Convergence layer Protocol/Agent
BPA	Bundle Protocol Agent
BP	Bundling Protocol
LTP	Licklider transmission protocol
CCSDS	Consultative Committee for Space Data Systems
V/UHF	Very/Ultra High Frequency



(a) (b) (c)

FIGURE 1. Recent missions with high media coverage. (a) Philae landing on Rosetta.[7] (b) The Stratos capsule.[8] (c) New Horizon reaching Pluto.[9]

In this survey, we integrate the relevant specifications, standards, demonstrations, and proposals to develop a joint space communication architecture. By interconnecting the Earth's Internet with other stellar networks, such an architecture would serve as the basis for an InterPlanetary Network (IPN)[10] [1], [2].

Space communication presents different constraints to Earth communication. In space, nodes are often associated with stellar objects that are separated by extensive distances. These stellar objects are in perpetual motion, leading to variable communication capabilities. Moreover, the solar radiation interference adds a significant amount of noise to radio communication channels. As a result, the communication channel suffers significant and unpredictable latency, frequent interruption of line-of-sight due to obstruction, and low signal-to-noise ratio (SNR) of the received signals. Therefore, the IPN architecture requires a new set of protocols and technologies that are tolerant to long delays and disruptions. Delay/Disruption Tolerant Network (DTN) [3]–[5] is an new architecture, often referred to as a protocol suite, to extend the internetworking capabilities into space-like environments, and enable inter-heterogeneous network communications. DTN-based internetworking can operate in presence of long latency and discontinuous connectivity. In DTN protocol stack, Bundle Protocol Agent (BPA) [6] constructs a store-and-forward overlay network that provides custody-based, message-oriented transmission. BPA stores and carries data units (i.e., bundles) until a solid connection exists to the receiving IPN node. After that, BPA invokes the convergence layer adapter (CLA) [6] that selects a transport protocol. This protocol is selected according to the environment, whether in outer space or on Earth, and the reliability of transmission. DTN protocol stack supports multiple transport protocols, among which are Licklider Transmission Protocol (LTP) [7], [8], Transmission Control Protocol (TCP), Stream Control Protocol (SCTP), or UDP.

The IPN architecture should rely primarily on standard, modular, and reusable components. By combining major space agencies' and companies' efforts, this architecture can be progressively deployed over time, leveraging successive missions to link any significant regions of interest in the solar system. We present a roadmap for the major steps towards deploying a fully interconnected, solar system-wide IPN. This roadmap concludes the international consensus on a recommended approach for transitioning the participating agencies towards a future **network centric** era of space mission operations. The roadmap starts by presenting a mission-specific communication model, then transforming it agency-specific in the short term, with future scalability as a primary goal. As such, medium and long-term architectures can build upon this base infrastructure to deploy a planet- and solar system-wide IPN. Finally, we provide recommendations to concretely deploy such an architecture given the state of current enabling technologies.

This survey's contribution is threefold:

- **Investigating IPN Feasibility.** We compile the relevant specifications, standards, and demonstrations towards the development of an interplanetary network (IPN).
- **Developing the IPN Roadmap.** We study the inter-agency cross-support and joint efforts to develop a joint communication architecture. We also investigate the requirements of each milestone and provide development recommendations.
- **Future direction.** We analyze the needs by highlighting the components and functions needed to develop an efficient IPN architecture.

The rest of this article is organized as follows. Section II presents an overview of the challenges, components, and

[7] NASA/Public Domain

[8] User:FlugKerl2/Wikimedia Commons/CC BY-SA 4.0

[9] DLR/CC BY-SA 3.0

[10] In the following sections, we use interplanetary internet/network or interplanetary networked communication, or solar system internetworking model interchangeably.

requirements of the IPN. Section III analyzes the characteristics of space communication mediums and the orbital parameters. An evolutionary IPN architecture and the involved protocol stack are discussed in sections IV. Section V illustrates the roadmap towards the network-centric IPN architecture. Section VI provides recommendations towards the IPN deployment. Finally, we conclude and highlight some potential research directions in VII.

II. InterPlanetary NETWORK (IPN) OVERVIEW

Space exploration and scientific missions require the transmission of large volumes of scientific data between the Earth and outer space. As such, they need a reliable, scalable, and easy to deploy communication architecture in a challenging transmission environment. In this section, we first define the requirements of a common communication architecture, before identifying the challenges of maintaining communications in deep space. Finally, we sketch the fundamental elements of an IPN architecture that fulfills such requirements and addresses the challenges.

A. REQUIREMENTS

A unified space communication architecture such as the IPN should present the following features:

- **Interoperability**: A typical architecture results in more efficient utilization of combined agencies' resources. It facilitates the inter-organization support, allows the missions to utilize the shared resources through standards, services, radio frequencies, international space operations, and cross support [9]. Interoperability leads to lower design costs, boosted communication, higher opportunities for scientific innovation, and reduced mission risk [10].
- **Reliability**: The expansion of communication systems raises the chance of failure significantly. The IPN provides redundancy and failover methods, enabling organizations to focus their effort on reliability.
- **Bandwidth**: New Horizon's high-resolution pictures of Pluto were a considerable success, regaining the public interest in space exploration. Future missions require higher bandwidth to continue providing data to the general audience to keep this interest going. Moreover, potential planetary colonies require higher bandwidth on both uplink and downlink to address human communication needs. By multiplying the number and capacity of available links, the IPN addresses the ever-increasing need for bandwidth.
- **Scalability**: Space exploration is an incremental process. New milestones for space exploration require upgrading the communication resources. It is not feasible to anticipate all future missions and deploy all the required resources at once. As such, the IPN will progressively scale up to connect new regions and networks.
- **Handover**: The IPN provides connectivity in an environment with highly variable yet predictable connectivity. The handover between the satellites needs to be automated to ensure continuous data flow between spacecraft and mission operations centers. Satellites must include efficient pointing assembly, pointing, acquisition, and tracking (PAT) that ensure accurate pointing while reducing the communication payload's size, weight and power consumption [11], [12].

Such features enable seamless, cross-agency communication across the entire solar system, improving both international and interplanetary collaboration while lowering the overall communication cost.

B. CHALLENGES

In order to provide the requirements mentioned above, the IPN faces a variety of new constraints, defined as follows [2], [13]:

- **Distance between planets:** The huge interplanetary distances cause extremely long propagation delays and high path attenuation between nodes. This attenuation leads to lower SNR.
- **Planetary motion and solar obstruction:** Planetary motion causes extremely variable propagation delays and intermittent connectivity. Interplanetary links also experience disruption and cause error-prone communication due to the solar conjunction and interference.
- **Low embeddable payload**: satellites can carry a limited payload which leads to constraints on power, mass, size, and cost for communication hardware and protocol design. These constraints limit the bandwidth on the reverse link, causing asymmetry of ratios up to 1000:1.
- **High cost and relative inaccessibility**: The spacecraft have to cruise huge distances in deep space to reach the destination celestial body. The launch date, thus, is restricted by the favorable conjunctions to avoid disconnections. Therefore, an IPN architecture should focus on backward compatibility and scalability to reuse the existing infrastructure and minimize the time and cost of deployment.

These constraints lead to significant challenges: extraordinarily long and variable propagation delays, asymmetric data rates, error-prone links, intermittent link connectivity, and lack of backward compatibility. The IPN architecture needs to address these challenges to withstand the harsh constraints of deep space communication and successfully deliver the scientific data.

C. IPN ARCHITECTURE

The IPN interconnects the terrestrial networks with deep space stations scattered around the solar system. A typical IPN architecture consists of the backbone network, the IPN Access networks, and the planetary/Proximity networks. The backbone network operates in deep space and interconnects planetary access networks. The planetary access network is an interface between the backbone and the nodes of the proximity network. The planetary or proximity network interconnects the surface nodes, e.g., the planet's landers, Earth mission operation centers (MOCs), and other terrestrial nodes. With these networks, the IPN extends the Earth's internet to include other regions of interest (planets, moons) and provides communication among the satellites and planetary surface elements [2] within a given area. Currently, only a tiny portion of the necessary infrastructure is available. On Earth, NASA and the Jet Propulsion Laboratory (JPL) have developed technologies [14] such as the DSN (Deep Space Network), that provide the base for long-distance space communication. Several other initiatives aim to interconnect Earth with specific stellar objects [15], [16].

However, a few research works directly target the establishment of the IPN. Bhasin *et al.* [17], Bhasin and Hayden [18] propose an integrated and evolutive communication architecture that maximizes data delivery, copes with the high data volumes, and provides high communication bandwidth. Alhilal *et al.* [19] propose an evolutionary architecture that adapts the milestones of future space exploration missions, near term, mid term, and long term. Their proposed architecture supports forthcoming scientific missions and space exploration projects with minimum cost and time. Based on these studies, we consider the following components as the base of an IPN architecture:

- **Communication Nodes.** Communication nodes are the base elements that allow the transmission of data within the IPN. They include all communicating entities (e.g., rovers, DSN, spacecraft, satellites).
- **Point-to-point Links and Interfaces.** The essential links that connect Earth with the remote planets. These links are crucial to providing an end-to-end data-passing capability. They include high data rate backbone links and inter-nodal links (e.g., between the backbone and access networks).
- **Layered/Integrated Communications Architecture.** This architecture extends the traditional internet protocol data routing capabilities to enable networking between Earth and outer space nodes. The resulting architecture provides autonomous end-to-end data routing capabilities, considering the nodes' continually changing properties and point-to-point links.

The works mentioned above envision the IPN architecture based only on technical requirements and expectations. Although there have been many inter-agency initiatives towards IPN, these initiatives are dispersed, and a tiny practical implementation has been done. In particular, there is a lack of a clear roadmap towards creating a single, unified IPN. This survey assembles the relevant specifications, standards, demonstrations, and proposals to present a comprehensive roadmap towards a unified interplanetary communication architecture. Furthermore, it surveys the existing deep space communication solutions, addresses a timely issue needed in future space systems, and simplifies the content to readers from different specialty levels.

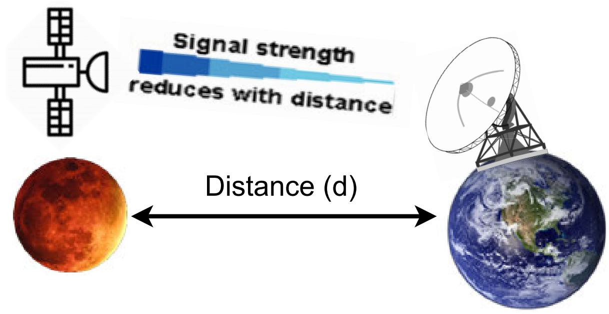
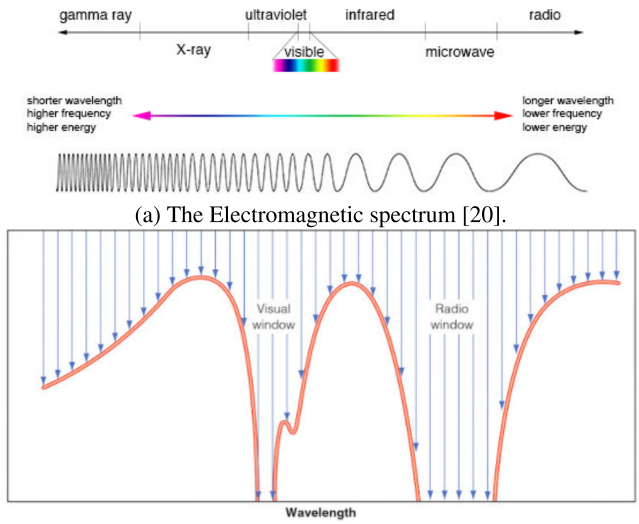


FIGURE 2. Free space path loss.



(a) The Electromagnetic spectrum [20].

(b) Blocked and passed radiations in the Earth's atmosphere (atmospheric windows) [20]. Only visible light and radio frequencies can propagate in the atmosphere without distortion or absorption.

FIGURE 3. Reachability of electromagnetic radiations from outer space to the Earth's surface.

III. DATA TRANSMISSION IN SPACE

Following a bottom-up approach, we first focus on transmitting data over the different communication media available in space. Thus, we first characterize the space medium before discussing the major orbital parameters for point-to-point communication in space.

A. CHARACTERISTICS OF THE SPACE MEDIUM

Due to the diversity of the propagation mediums in a Space-to-Earth communication context, a signal can experience many impairments:

- **Attenuation** is a function of frequency. Therefore, for high frequencies, the signal may experience distortion for large distances. It is, therefore, crucial to amplify high frequency signals.
- **Free Space Loss** is the primary factor for signal loss which is calculated by the following formula [21]–[23]:

$$L_s = (\frac{\lambda}{4\pi d})^2, \quad \lambda = c/f \tag{1}$$

where d is the distance of the link, λ the wavelength, c the speed of light and f the signal frequency. This formula is derived from the ratio between the transmit power (P_t) and the receive power (P_r).

$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi fd)^2}{c^2} \tag{2}$$

Given that the transmit gain in a particular direction is G_t, let a receiving antenna located at a distance d, whose gain is G_r and the effective area is $A_r = G_r \frac{\lambda^2}{4\pi}$, see Figure 2. As such, the receive power is computed by:

$$P_r = A_r \rho = P_t G_t G_r (\frac{\lambda^2}{4\pi})^2 \tag{3}$$

- **Noise** can be thermal, inter-modulating, crosstalk, or impulse noise and mix with a transmitted signal. A key element of the telecommunications-link performance is the received power signal-to-noise ratio (SNR) [24], which is given by:

$$SNR = \frac{P_t G_t A_r}{4\pi d^2 N} = \frac{P_t G_t G_r}{kBT_s (4\pi d/\lambda)^2} \tag{4}$$

  where T_s is the receive system-noise temperature, k is a Boltzman's constant, and B is the bandwidth. A different formula to calculate the received signal from a deep-space spacecraft and SNR has been used in [25], which is modeled based on the modulation and coding rate to receive the signal.
- **Delay.** There are four major sources of delay [26], [27]: Processing, storage, transmission, and propagation. In the context of space communication, the long distances and constant motion of stellar objects lead to large and variable propagation delays that overwhelm the other latency components.
- **Atmospheric Absorption.** On Earth, peak attenuation occurs in the presence of water vapor around 22 GHz and oxygen around 60GHz. Other planets have a different atmospheric composition and therefore different absorption to take into account [28].

Figure 3 represents the different electromagnetic radiations: radio (RF), infrared (IR), visible (FSO), ultraviolet, x-ray, and gamma ray. Most of the electromagnetic radiations emitted by outer space don't reach the Earth's surface except for very few wavelengths. These wavelength include the visible spectrum, also called **free space optic (FSO)**, **radio frequencies (RF)**, and some ultraviolet wavelengths, as shown in Figure 3b. These bands are called atmospheric windows [20], [29], [30]. Although Earth's atmosphere blocks other bands such as gamma rays, infrared, or X-rays, they might still be options to transmit information in the planet's outer space (without passing the atmosphere) and through the atmosphere of other planets.

The lower power consumption, lower mass, higher range, and higher bandwidth of FSO compared to RF make optical communication the promising technology to serve as a communication medium in Interplanetary networks [31]–[33].

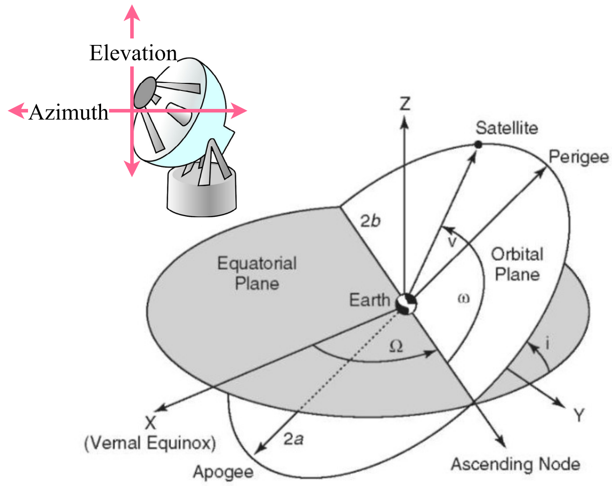


FIGURE 4. Satellite orbital parameters [37].

In practice, NASA Laser Communication Relay Demonstration (LCRD) mission [34] continues the legacy of the Lunar Laser Communications Demonstration (LLCD) [35], using FSO. This latter mission flew aboard a moon-orbiting spacecraft called Lunar Atmosphere and Dust Environment Explorer (LDAEE)[11] [36], in 2013. Compared to traditional communications systems on spacecraft, LLCD used half the mass, 25 percent less power, and transmitted six times as much data per second. LCRD is a joint project between Goddard Space Flight Center,[12] JPL, and MIT Lincoln Laboratory.[13] The project is currently under validation and is expected to be launched in early 2021 from Cape Canaveral Air Force Station in Florida as a hosted payload on the STPSat-6 satellite aboard a United Launch Alliance Atlas V rocket. LCRD will demonstrate the robust capabilities of laser communications, which can provide significant benefits to missions, including bandwidth increases of 10 to 100 times more than radiofrequency systems [34].

B. ORBITAL AND ANTENNA PARAMETERS

The technologies mentioned in the preceding paragraph require line-of-sight communication. However, ensuring line-of-sight is a delicate process since communication nodes in space, particularly satellites, constantly move relative to one another.

In this section, we describe the most important orbital parameters to define Earth-orbiting satellite characteristics. As illustrated in Figure 4, **Apogee** and **perigee** refer to the distance from the Earth to the satellite. Apogee is the farthest point from the Earth, while perigee is the closest point to the Earth. **Ascending Node** is the point where the orbit crosses the equatorial plane, going from south to north. **Descending Node** is the point where the orbit crosses the equatorial plane,

[11] nasa.gov/mission_pages/ladee/main/index.html
[12] https://www.nasa.gov/goddard
[13] Massachusetts Institute of Technology Lincoln Laboratory: ll.mit.edu

going from north to south. **Line of Nodes** is the line joining the ascending and descending nodes through the center of the Earth. **Inclination angle *i*** is the angle of the orbital plane with respect to the equatorial plane. **Eccentricity e** identifies the shape of the orbit, Elliptical in the case of $0 < e < 1$ and Circular in the case of $e = 0$ depending on the orbital velocity and direction of motion imparted to the satellite on insertion into the orbit. When $i = 0$, the orbital plane is identical to the equatorial plane, but when i near 90^o and $e = 0$, it is referred to as a polar orbit. **True anomaly** ν **or** θ is the angular parameter which defines the angle. It lies between the direction of the perigee and the satellite's current position. **Argument of perigee** ω is the angle, taken positively from 0° to 360° in the direction of the satellite's motion, between the direction of the ascending node and the direction of the perigee [37]–[39].

From the ground station's perspective, the satellite's position within its orbit is defined by elevation angles, the angle between the center of the satellite beam and the surface (Azimuth). The coverage area is defined as a region of the Earth where the satellite is seen with a minimum predefined elevation angle.

This section presents the typical techniques and considerations for point-to-point communication in space. However, due to the constant motion of stellar objects and the attenuation of certain transmission media, line-of-sight point-to-point communication is not always possible. As a result, it is critical to enable data forwarding between multiple nodes through an interconnected network such as the IPN.

IV. InterPlanetary NETWORK (IPN) ARCHITECTURE

The Interplanetary Internet is achieved by adequately utilizing the planetary satellites and networks, carefully planning the protocol stack to implement solar-wide DTN architecture, and progressively scaling it. Such architecture helps to minimize latency and connection interruption while reliably enabling data transmission across the solar system. This section first reviews the current satellite and terrestrial infrastructure that can support an IPN architecture before investigating how Delay Tolerant Networks (DTN) can enable reliable data transmission in space communication. Finally, we describe the protocol stack the IPN leverages to achieve end-to-end transmission over point-to-point links with different characteristics.

A. SPACE COMMUNICATION AND NAVIGATION NETWORKS

Figure 5 presents the current satellite infrastructure. This infrastructure encompasses two main segments [38]: the space segment and the ground (or Earth) segment. The two segments are connected via radio frequencies (RF), the only electromagnetic radiation to propagate in the atmosphere with minimum absorption and distortion. The **Space Segment** includes the orbiting satellites and the ground stations that provide the satellite's operational control in orbit. The **Ground Segment** consists of the Earth's surface terminals that employ the Space Segment's communications capabilities. A full constellation of satellites is required to cover the surface of the Earth. Nowadays, satellites are distributed over three orbits [41]–[43]:

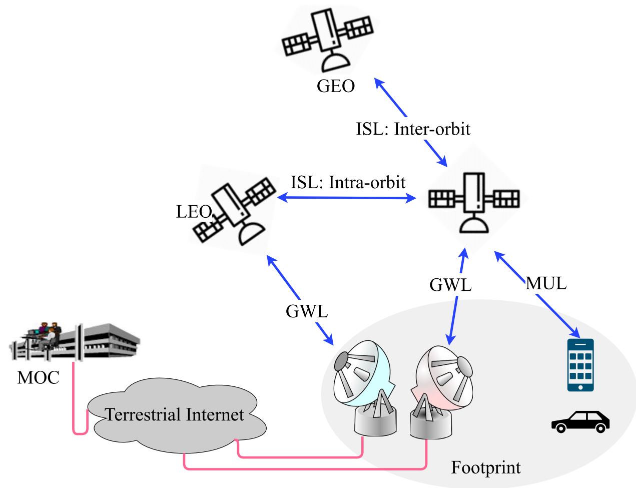


FIGURE 5. Inter satellite links (ISL) and Satellite-Surface communications [40].

- **Geostationary Earth Orbit (GEO)** is synchronized with the Earth rotation and has a 24-hour view of a particular area. GEO satellites orbit the Earth's surface along the equator at an altitude of 35,863 km.
- **Medium Earth Orbit (MEO)** is an Earth-centred orbit with an altitude between 8,000 km and 18,000 km. MEO satellite is only visible for 2-8 hours for a specific area.
- **Low Earth Orbit (LEO)** is closer to the Earth, at an altitude of 500-1500 km. As a result, the LEO satellite is only visible for a short time (15-20 minutes each pass) for a given area.

The combination of these satellites covers the whole surface of Earth thanks to Inter-Satellite Links (ISL). These links can either connect two satellites on the same orbits or different orbits [40]. The LEO and Geo orbits satellites are interconnected using ISLs via Gateway and Mobile User Links (GWL and MUL). Many antennas can reside in a satellite's footprint, as illustrated in Figure 5. The current space communication architecture of NASA, ESA, CSA, JAXA, CNSA, and Roscosmos, primarily embraces three operational networks. These networks collectively provide communication services to supported missions using both space and ground-based assets [44]:

- **Deep Space Antennas.** NASA's deep space network (DSN)[14] comprises three equidistant ground stations to provide continuous coverage of GEO orbits and uncrewed spacecraft orbiting other planets of the solar system [46], [47]. ESA's deep-space antenna is consolidated into seven stations, three of which are technically sophisticated 35 m-diameter [48].

[14]https://eyes.nasa.gov/dsn/dsn.html

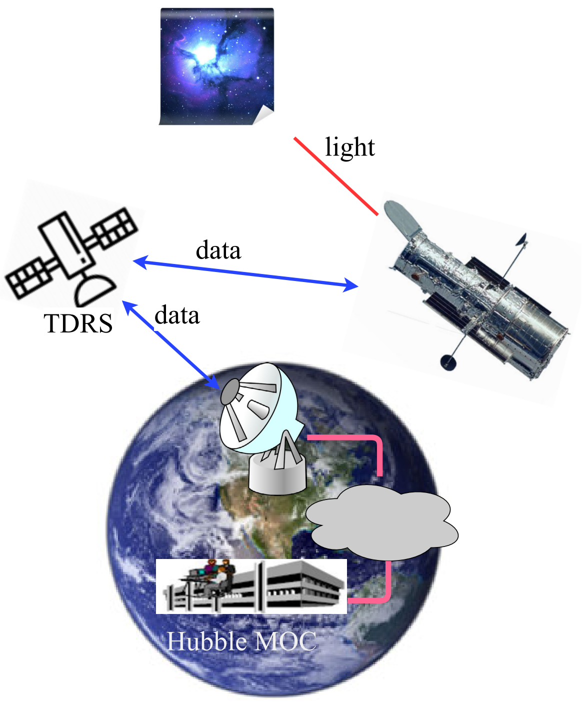


FIGURE 6. The data path of Hubble observations. Hubble observes the light in deep space, relays it to Tracking and Data Relay Satellite (TDRS), and then to Hubble mission operation center (MOC) [45].

CNSA's five-hundred-meter aperture spherical radio telescope (FAST) is a radio telescope of a 500 m diameter dish constructed in a natural depression in Guizhou, southwest China.[15] FAST is the world's largest filled-aperture radio telescope [49] and the second-largest single-dish aperture, after the sparsely-filled RATAN-600[16] of Roscosmos.

- The **Near Earth Network** consists of ground stations of NASA, ESA, JAXA, CNSA, CSA, and private companies. It integrates systems providing space communications and tracking services to orbital and suborbital missions.
- Finally, the **Space Network** is a constellation of geosynchronous relays and associated ground stations. NASA's Tracking and Data Relay Satellite System (TDRSS) relays the Hubble telescope's observations to the telescope operation center, as shown in Figure 6. Several satellites are evenly distributed in geostationary orbit all around the world to provide a global view such as India INSAT, JAXA Geostationary Meteorological Satellite (GMS), and ESA Meteosat,[17] as shown in Figure 7.

ESA's tracking station network is interlinked with NASA's DSN through a long-term cross-support agreement with NASA. Both agencies routinely support each other's communication needs [48]. JWST, a successor to the Hubble Space Telescope, is an inter-agency mission and based on a partnership between the three agencies, NASA, ESA, and CSA [51]. JWST [52] is aimed to investigate the origins of the universe by observing infrared light from the youngest galaxies and possibly the first stars. The three agencies have continuous communications with JWST through their deep space antennas. However, despite these collaborative efforts, NASA, ESA, JAXA, and CNSA, and other agencies' networks remain currently deployed in parallel with minimal interaction. The first step towards an extended and unified deep-space communication architecture would be to chain relays near Earth, in the solar system, and in deep space. Chaining relays requires the deployment of more advanced routing and forwarding technologies that are resilient to the long and variable delays in space.

[15]http://www.spaceflightfans.cn/28219.html
[16]https://www.sao.ru/hq/CG/cold/part2.htm
[17]esa.int/Education/3._The_geostationary_orbit

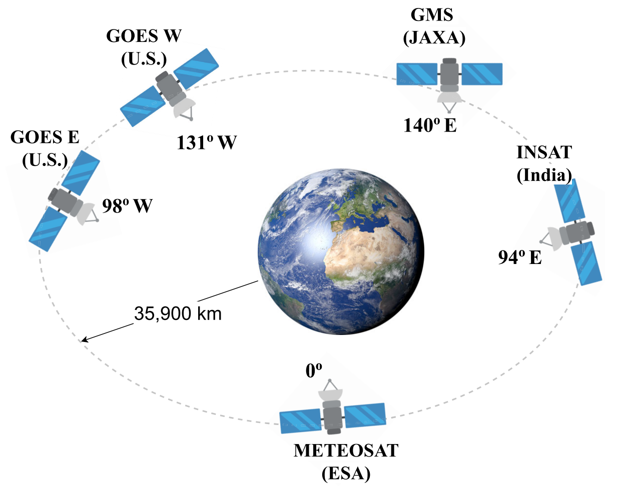


FIGURE 7. A global view of some of the world-wide geosynchronous satellites [50].

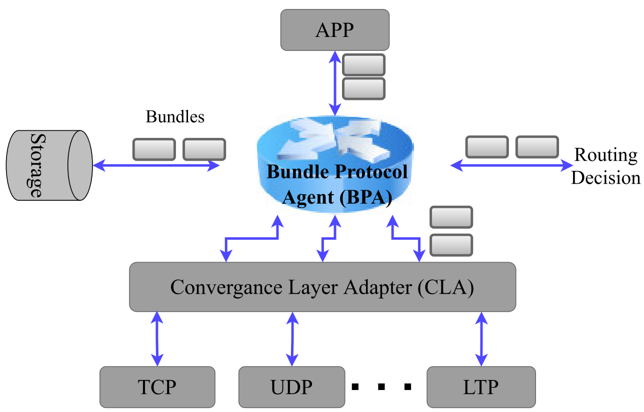


FIGURE 8. Overview implementation of bundle forwarder interaction with CLA and underlying protocols [53].

B. DELAY TOLERANT NETWORKS (DTN)

As summarized in Sections IV and III, deep space communication is subject to long delays and intermittent network connectivity due to the planetary and spacecraft motion. The

DTN architecture was proposed to cope with such challenges. The DTN architecture involves an overlay layer that is inserted into the existing protocol stacks. This layer contains BPA to integrate dissimilar networks (interplanetary network and planetary network) and ensure the interoperability between such heterogeneous networks. In reality, this architecture's implementation is done in the Relay Nodes or **DTN Gateways**. These nodes provide asynchronous messaging using store-and-forward to aggregate messages into bundles and forward them when the link with the next hope becomes available.

Bundling Protocol Agent (BPA) is the main component in DTN to establish a store-and-forward overlay layer. BPA interconnects heterogeneous networks and allows their nodes to exchange data bundles. BPA invokes services from the underlying **Convergence Layer Protocol (CLP)**. In turn, CLP takes on the responsibility to send and receive the bundles by utilizing the services of the 'native' protocol stack that is supported within the environment in which the node is functionally located [54], as seen in Figure 8. **CLPs** are a collection of protocol-specific convergence layer adapters (CLAs) that provide the functions necessary to carry bundles on each of the corresponding protocols. They are classified as TCP-based CLP or so-called TCPCL [55], SCTP-based CLP [56], UDP-based CLP [57], LTP-based CLP [58] and SpaceWire CLP [59]. TCPCL and UDPCL are mainly designed to operate in terrestrial networks, while the others are designed to operate efficiently in highly stressed environments like deep-space communication.

The DTN suite also contains network management [60], security, routing, and quality-of-service capabilities, which are similar to the capabilities provided by the terrestrial Internet suite. The benefits of employing DTN architecture and suite are [61]:

- **Autonomous Operations and Situational Awareness:** The DTN store-and-forward mechanism significantly reduces the scheduling and planning of the links. Its automatic operation addresses the outages when handovers and poor atmospheric conditions are present.
- **Interoperability and Reuse:** A standardized DTN protocol suite enables cross support across the international space community and expands the enabling levels of space communications and navigation interoperability. Thus, it allows future missions to reuse any space agency or private company's space assets.
- **Efficient and Robust Space Links:** By having multiple network paths and potential communication hops, the Store-and-forward mechanism provides the communications protocol the capability to store the Bundle PDUs for arbitrary lengths of time until the DTN node looks up the next hop. It then queues the data on its outbound link. Custody transfer services also ensure end-to-end reliability on a hop to hop basis. Overall, they make efficient use of the bandwidth and increase the goodput (i.e., the percentage of useful data).
- **Security:** CCSDS Streamlined Bundle Security Protocol (SBSP) [62] provides the DTN architecture with security services allowing the Bundle Protocol agent authenticates the transmitting entity (hop-to-hop security). It also provides confidentiality and integrity for the data (end-to-end security). For instance, a Lander BP agent at Mars encrypts the bundles, and the BP agent of Lander MOC decrypts them and checks the integrity of the data. LTP - Security Extensions [63] provides cryptographic authentication of the bundle PDUs using message authentication code or digital signature.
- **Quality-of-Service:** The DTN protocol suite can prioritize the Bundle PDUs to prioritize the delivery of the most important data and tolerate some latency in the delivery of less important data.

The DTN architecture enables the reliable transmission of the data over continually varying node configurations. However, this architecture alone is insufficient to adapt to the diversity of transmission conditions in the solar system over multiple hops. The IPN leverages multiple protocols to adapt to the conditions on each segment in the end-to-end transmission.

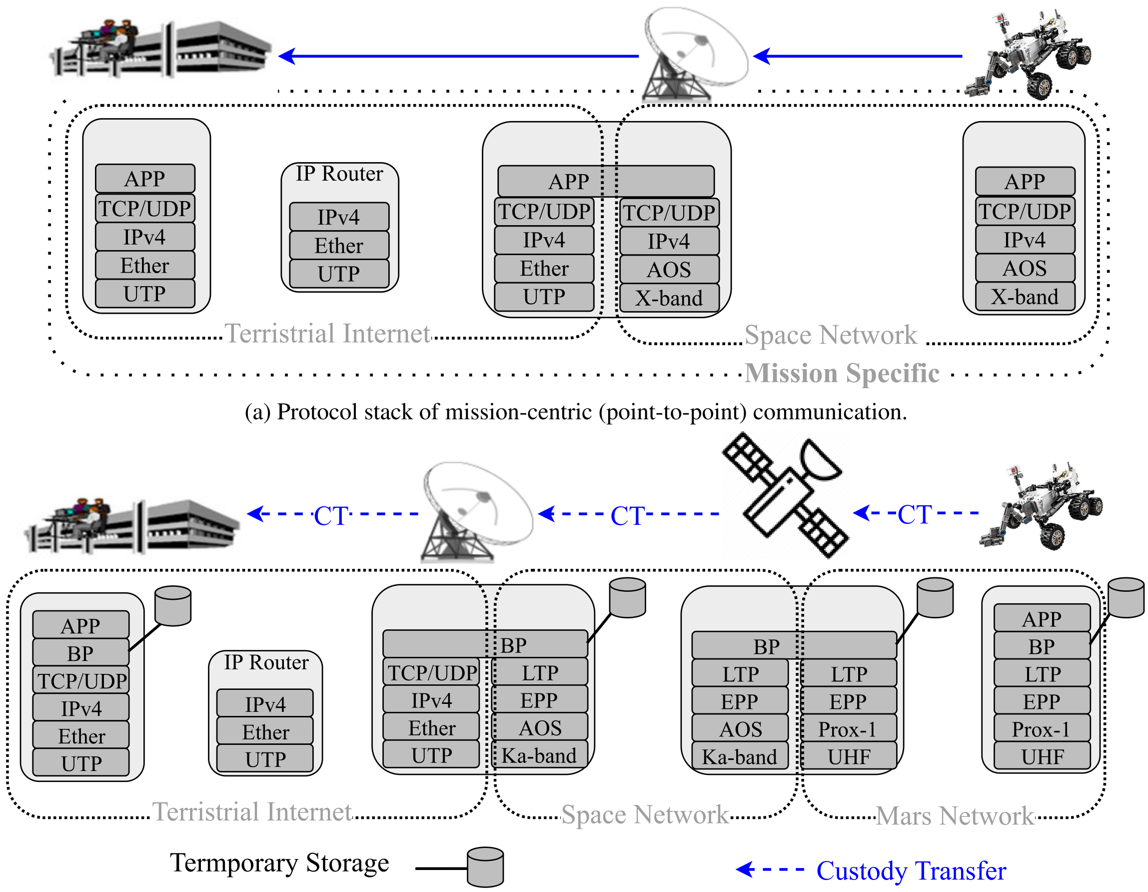
C. IPN PROTOCOL STACK

In this section, we consider the case of communication on the return path between a Mars lander and its MOC on Earth, going through eventual intermediate nodes. Figure 9 represents how such communication happens in the case of traditional, mission-centric communication (Figure 9a), and in the IPN (Figure 9b).

In mission-centric communication (Figure 9a), each mission relies on a specific point-to-point link between Earth's DSN and a given element (rover, lander, satellite) in the solar system. Once reaching Earth, data is forwarded to the MOC through the traditional IP protocol stack. However, such point-to-point communication architecture fails to cross-support other agencies ' missions or even successive missions within the same agency.

Recently, agencies have started to employ DTN architecture to provide relay communications. While very effective, such relay operations are still highly idiosyncratic, with store-and-forward and application-layer functions directly above the link layer (i.e., non-functional network layer). They also lack the scalability with more complex scenarios and yield low and extreme asymmetric bandwidth [64].

The IPN introduces the idea of network-centric communication, where agencies cross-support future missions, leveraging DTN. Figure 9b illustrates how the transmission of data from a Mars lander to the Earth MOC happens within the IPN. DTN implements a functional network layer using bundling protocol agents (BPAs). BPA invokes the services of CLA to forward the bundle to the next DTN node [65]. The forwarding process transforms the bundle from the inbound network-compatible transport protocol to the outbound network-compatible one. As such, the IPN architecture



(a) Protocol stack of mission-centric (point-to-point) communication.

(b) The protocol stack of network-centric communication. Lander data are transferred reliably using custody transfer to the lander MOC on Earth

FIGURE 9. Protocol stack and data flow of mission-centric vs IPN network-centric communications.

achieves end-to-end data delivery across multiple hops over multiple paths, involving multiple spacecraft. Given the scenario mentioned above, a Mars lander transmits scientific data to Lander MOC on Earth (Mars lander → intermediate nodes → lander MOC). The transmission will take place over several wired and wireless links that account for the Earth's atmosphere and Mars' atmosphere. BPA allows the DTN nodes to temporarily store the bundles using embedded storage and forward them upon link availability. To deliver the bundles, BPA delegates the transmission to LTP (space compatible) in outer space and the terrestrial transport protocol (e.g., TCP and UDP) on the Earth's surface. Each DTN node transmits the data reliably on a hop-to-hop basis using the custody transfer.

End-points can send the scientific data as files using CCSDS File Delivery Protocol (CFDP). CFDP is an IPN compatible file transfer protocol in the application layer. Before transmission, the sender end-point can perform lossless data compression or lossy image compression to reduce the data volume, transmission time, used channel bandwidth, and storage requirements. Table 3 defines the protocols and media to achieve end-to-end data delivery. They are classified and ordered in a top-down design to match the protocol stack.

V. IPN ROADMAP AND EVOLUTION

Establishing the IPN architecture mentioned above requires the deployment of the underlying network infrastructure and operations. Inter-agency cooperation is critical for cost-effective deployment and efficient usage of limited resources. The Interagency Operations Advisory Group (IOAG) was established to support interoperability among the space community internationally. Its chattered group, the Space Internetworking Strategy Group (SISG), reached a consensus on developing a future network-centric era of space mission operations [66]. The underlying architecture and operation form the Solar System Internetwork (SSI) architecture. SSI provides the network capability to connect various participants via various media and equipment, such as radio, wired, or optical communications devices. The functional network layer is prescribed by protocol specifications established by the IETF[18] and the CCSDS.[19] Overall, the SSI paves the way for deploying applications in space akin to terrestrial internet applications, e.g., reliable transfer of files and messages.

[18] Internet Engineering Task Force (IETF): ietf.org
[19] Consultative Committee for Space Data Systems (CCSDS): ccsds.org

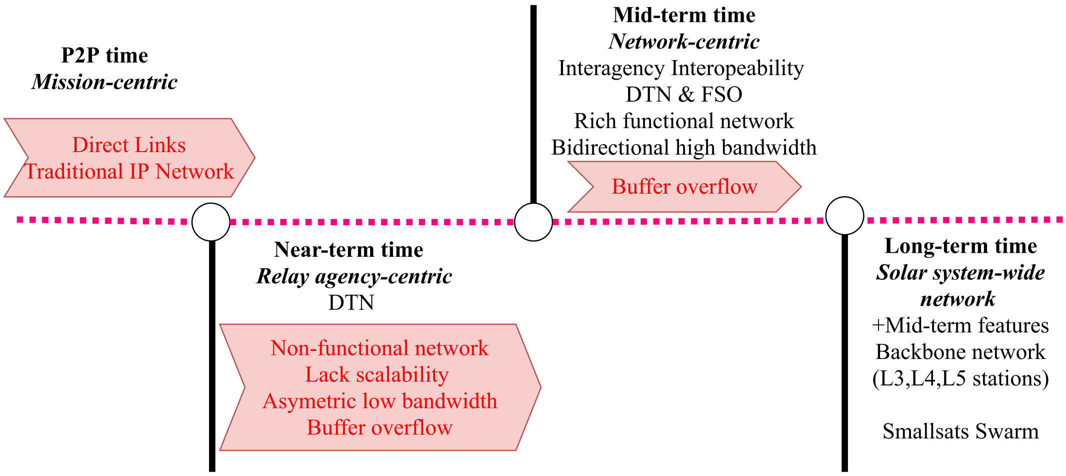


FIGURE 10. Roadmap to IPN. Transition from mission-centric (point-to-point) to network-centric communications, passing through agency-centric communications. In addition to mid-term features, Long-term IPN architecture involves stationing spacecraft at Lagrange points to cover the solar system. The latter deploys swarms of miniaturized satellites.

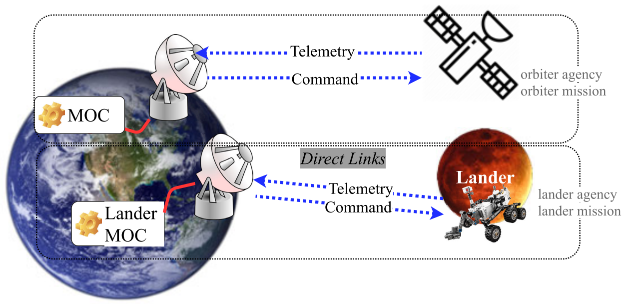
The SSI deployment will occur incrementally, following three primary stages [12]:

1) **Mission-centric Communications Model:** A space agency manages a mission that has a single spacecraft. The latter communicates only with a single mission operation center (MOC), using downlink (telemetry) encapsulated in CCSDS telemetry frames or uplink (commands) encapsulated in CCSDS telecommand frames. The spacecraft communicates directly with one or more DSN antennas. The data are selected and retransmitted manually during the contact between the spacecraft and the Earth station.
2) **Agency-centric Communications Model:** The elements of a space agency might be utilized to support multiple missions. The elements include spacecraft and landers. An agency can also use the Earth station of another space agency.
3) **Complex Mission Communications Model:** This model ensures many features: 1) Interoperability: Missions are operated by multiple space agencies utilizing different elements and managed by different MOCs. They may also use multiple space agencies' ground stations, 2) Failover: A mission can have multiple spacecraft that collaborate autonomously towards its objective, and 3) Data Relay in Space: A spacecraft relays data to/from the MOCs via different routes. Scientific data routing becomes similar to packet switching on the internet and ensures data delivery in both directions with no distinction between uplink or downlink traffic.

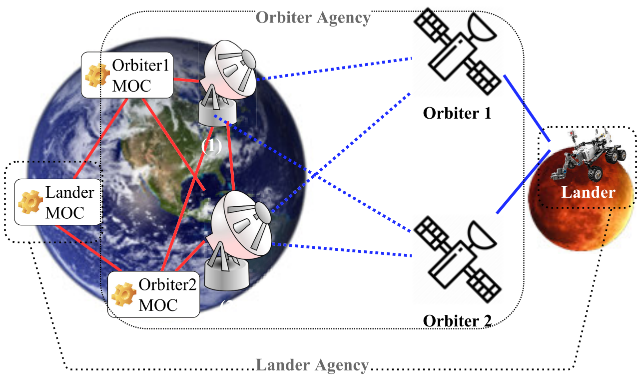
Given these stages, we present a roadmap for the IPN architecture evolution in Figure 10. This roadmap starts with near-term agency-centric communication to a long-term, fully interconnected solar system-wide communication network, going through mid-term network-centric and inter-agency communication architecture. At the time of writing this article, agencies have started deploying the near-term architecture to enable intra-agency relay communications. This architecture is developed using DTN with store-and-forward capabilities and application-layer functions. Application-layer functions are implemented directly above the link layer, without a functional network layer. As a result, data routing requires sequencing and scheduling before transmission at the MOC and cannot be performed dynamically on intermediate nodes.

Therefore, it fails to scale efficiently to more complex scenarios and introduces low asymmetric bandwidth [64]. Moreover, such short-term architecture is characterized by intra-agency relay communication. On the other hand, the mid-term architecture brings inter-agency cross-support (interoperability) and leads to fully network-centric communication architecture.

This architecture is developed over DTN with a rich functional network layer. Data routing is automated and occurs across multiple hops over multiple paths, involving DTN nodes from different agencies (e.g., spacecraft, ground stations). The communicating parties use optical communication (FSO), which increases the data rate in both directions (forward and return links). Finally, this architecture can be extended by stationing swarms of spacecraft or small satellites at Lagrange points. IPN architecture can cover the entire solar system with such swarms and enable solar system-wide exploration and communications. Figure 12 illustrates a snapshot of long-term solar system-wide IPN, where the backbone network interconnects the spacecraft deployed at the Lagrange points. Lagrange points are where all the gravitational forces acting between two objects cancel each other out and can be used by spacecraft to hover [19], [61]. These spacecraft operate as relay stations that relay data from satellites orbiting a planet to the Earth's DSN. DSN receives the weak signals efficiently from deep space (i.e., spacecraft



(a) Point-to-point communication in mission-centric approach



(b) Network-centric inter-agency communication. Orbiter 1,2 MOCs interconnect Lander with MOCs across multiple hops. The lander sends data through any orbiter to any available ground station.

FIGURE 11. Transition from mission standalone functionality to networked communication.

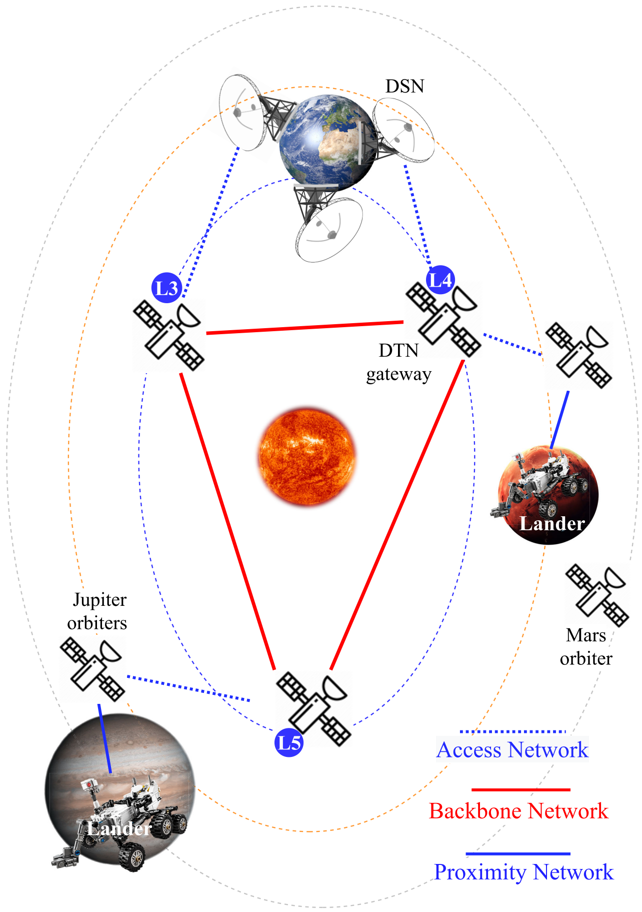


FIGURE 12. Future interplanetary network. A backbone network of spacecraft located at Lagrange points (L3, L4, L5) interconnect the planets' access networks of their orbiters with the Earth's DSN. The planet's launders make the proximity network which uses orbiters network to relay the launder's data.

at Lagrange points) through direct links on Earth. Moreover, the spacecraft in the backbone network, the orbiters in the access network, and the Earth's DSN operate as DTN routers. As such, they support multiple transport protocols that correspond to the inbound network and the outbound network.

The IPN architecture will evolve incrementally to cover the entire solar system ultimately. Figure 11 illustrates the transition from mission-dependent functionality to a network-centric communication architecture, corresponding to the protocol stack represented in Figure 9. Agencies have been launching spacecraft to deploy the core architecture and internally support future missions. Standardizing the network layer enables inter-agency cross-support in future missions. At this level, data routing operates similarly to the terrestrial internet, involving multiple hops over multiple paths via relay spacecraft. The benefits also include signal regeneration at the relays, switching Data Link layers to suit the local environment, and the ability to make routing decisions both in space and on the ground [10].

Such an architecture will enable efficient communication between multiple nodes scattered in space. In the next section, we display a concrete application of interplanetary DTN communication and the appropriate protocols for each point-to-point link.

VI. IPN RECOMMENDATIONS

IPN is envisioned as a unified architecture, providing common communication and navigation services for scientific data delivery which will serve most future deep space missions. Bhasin *et al.* [67], Bhasin and Hayden [17], [68] developed the needs and requirements from NASA's perspective. As such, the **Architectural Development Process** should go through steps:

A. PLACE THE INFRASTRUCTURE COMPONENTS

There are mainly three types of elements in IPN infrastructure: backbone elements, access elements, and proximity elements (on the planet. i.e., rovers, sensors, robots, humans). The best practice is to deploy these elements incrementally, from the closest to the farthest. This practice ensures minimal errors, precise and safe deployment, and at a low cost:

1) **Place the backbone network elements.** Such a placement allows space agencies to have a better control over the next step of deployment.
2) **Launch and deploy the access network elements.** The backbone elements facilitate the tracking and

controlling of this stage, where the feedback received using DSN is used to adjust this deployment. Once deployed, the backbone spacecraft can facilitate the deployment of access network satellite to remote planet orbit. The placement process requires commands to flow in both uplinks and downlinks. The uplink command flows through DSN-to-backbone links and then backbone-to-access network links. The downlink telemetry flows through access-to-backbone links and backbone-to-DSN links.

3) **Place proximity elements.** The entry, descent, and landing of proximity a element (e.g., a planet's surface lander, rover, or robot)would be controlled autonomously once the access networks are in place and operating efficiently. The spacecraft that carry these elements communicate with the nodes in the access network to provide telemetry and receive commands. The telemetry (downlink) flows from the carrier spacecraft to the Earth's DSN through a spacecraft in access and backbone network. The command flows on the reverse link (uplink), driving the placement process. This process was demonstrated in the entry, descent, and landing process of Mars Curiosity Rover.[20] The process was as simple as just sending special signal tones to each stage of the emplacement.

B. INTEGRATE THE COMMUNICATION ARCHITECTURE

As a fundamental component of the IPN architecture, the communication architecture must function over feasible communication media and dynamic links. On top of that, a reliable internetworking architecture must be established.

1) **Communication medium.** The selection of communication medium is associated with the environment's conditions. The signal attenuates as RF waves spread out over long distances, resulting in decreased data transmission rate. The FSO laser beams, on the other hand, maintain their focus, enabling the signal to travel over longer distances without requiring extra power [69]. However, RF outperforms FSO in atmospheric propagation. Therefore, the hybrid RF/FSO system would be the best communication medium for high data rates in the backbone network and anti-atmospheric absorption in near-Earth networking.
2) **Delay-Tolerant Networking (DTN).** Intermediate nodes between IPN end-points must enable DTN functionality. That includes proximity elements, access and backbone network spacecraft. In addition, they have to have a BPA driver (e.g., ION or DTN2 in Table 2) installed. These elements must function as a DTN node, with custody transfer and store-forward capabilities.
3) **Dynamic Links (Interactive links).** The links between IPN nodes should be established dynamically, similar to the links upon which phone calls are made. The collection of protocols, interfaces, and extensions should make it possible to establish on-demand links dynamically.

[20] https://mars.nasa.gov/msl/mission/communications

C. IDENTIFYING COMMUNICATION NODES

This stage identifies the communication nodes within each region of interest. It defines the required entities to achieve all present/future human/robotic missions (e.g., sensors, spacecraft, aircraft, robots, rovers, humans). These nodes are distributed over regions of interest as nodal groups: the Earth proximity communication nodal group, the Mars proximity communication nodal group, the Moon proximity communication nodal group, any region of interest (e.g., a planet) proximity communication nodal group, and the deep space communications nodal group. The latter are scattered among the outer planets and moons to form the backbone. Each proximity communication nodal group contains geostationary, medium, and low orbit orbiters. For instance, the Earth's nodal group comprises satellites distributed over GEO, MEO, and LEO [18].

D. POINTING, ACQUISITION, AND TRACKING (PAT)

The planets' orbits reside within a few degrees of the solar system plane. The pointing process is achieved by adjusting both azimuth and elevation angles of the pointing assembly in sender and receiver antennas. The pointing process must be accurate in such a tremendously colossal space, especially when using optical communication. Reducing the size, weight, and power of communication resources is a constraint. In addition, the laser signals are subject to the classic inverse distance square loss and encounter photon noise when pointing close to the Sun. As such, a focused narrow beam is necessary to distinguish the transmitted photons.

The narrow beamwidths involved require precise acquisition and tracking as well as beam stabilization techniques [70]. The expected pointing accuracy for Azimuth is < 1 arcSecond, and for Elevation is < 1 arcSecond. Likewise, the expected angular accuracy is < 5 μrad, where 1 arcSecond ≈ 4.85 μrad [71]. The spacecraft must employ vibration mitigation techniques to stabilize the laser beam in the presence of base motion disturbances and vibrations. The angular disturbance can be up to a few hundred nano radians. Pointing and Vibration Control Platform (PVCP), a mitigation technique, integrates pointing with vibration isolation to reduce the disturbance [72], [73]. Interferometric Fiber Optic Gyroscope (IFOG) [74] and Fiber optic Gyro (FOG) [75] are introduced to improve the stabilization system. FOG can effectively extend beacon-aided acquisition beyond Mars [76].

Synchronizing the sender and receiver requires incorporating PAT and stabilization techniques to find the partner and reduce the off-line time quickly. Afterward, the sender starts sending data to the receiver DTN node (e.g., spacecraft, DSN).

In practice, JPL deployed EPOXI spacecraft as the first DTN Gateway located about 15 million miles from the Earth under "The Deep Impact Network Experiment

TABLE 2. BPA Implementations.

Protocol	Description
DTN2 [79]	DTN2 implements primarily BPA defined in RFC 5050 [6]. It is flexible and written primarily in C and supports the standard and LTP convergence layer protocols and Bundle Security protocols. It demonstrates the basic functionality and thus does not operate efficiently.
ION [80]	ION is the NASA/JPL implementation of DTN protocols. It addresses the constrains of communication architecture between the IPN spacecraft and the mission control center (MOC), and supports high-speed, small-footprint deployment of DTN in embedded systems (i.e. ROBOTIC SPACECRAFT), and runs on various Linux platforms, OS/X, FreeBSD, Solaris, VxWorks, and RTEMS.
IBR-DTN [81], [82]	The modular design of IBR-DTN with various interfaces makes it possible to change functionalities by simply inheriting a specific class. As a result, the routing and storage of the bundles can be easily updated to use resources efficiently and inter-operate with other DTN implementations, e.g., DTN2 reference implementation.

(DINET) [77], [78]. During DINET, 300 images were transmitted from the JPL nodes to the spacecraft and automatically returned to test the functionality of DTN. In addition, several other NASA missions have used DTN, such as the Earth Observing mission 1[21] and LLCD. Integrating DTN with NASA's communication networks, including DSN, NEN, and SN, is under development with the Space Communications and Navigation (SCaN) program to support future missions [61].

E. ENABLING TECHNOLOGIES

This section highlights some technologies which substantially accomplish the IPN architecture. We specifically focus on the communication and hardware aspects of a durable infrastructure.

1) DTN BPA IMPLEMENTATION

As a DTN component, the implementation of bundling protocols (BPA) is crucial in developing of the DTN protocol stack. The implementation must support LTP, a point-to-point protocol designed and operated efficiently over links similar to deep space communication links. Three BPA implementations support such functionalities– DTN2[22] from Delay Tolerant Networking Research Group (DTNRG) [79], the second, ION,[23] from JPL [80], and IBR-DTN[24] from Technical University of Braunschweig [81]. These implementations are listed and described in table 2.

2) DTN GATEWAYS

In data routing, the intermediate nodes along the paths must operate as DTN Gateways to interconnect two heterogeneous networks. As such, a DTN node must have a DTN driver installed (e.g., ION). In addition to store-forward and capabilities mentioned in section IV-B, the driver supports contact plan-based routing, i.e. Contact Graph Routing (GCR) [83] and/or Schedule-Aware Bundle Routing (SABR) [84]. Each DTN node is identified by an Endpoint Identifier (EID), and a Compressed Bundle Header Encoding (CBHE)-conformant [85] EID. Using a contact plan and the routing algorithm, a DTN node forwards the bundles through the best route having the best delivery time. In contrast to the terrestrial Internet, where routers can discard packets upon buffer overflow, DTN bundles are stored in permanent memory storage and cannot be discarded once custody is accepted. The occupied memory portion must be released as soon as possible to enable other critical space applications to use it; otherwise, memory storage depletion and data overflow would certainly occur [86]. Many techniques are proposed to automate buffer management, either using Reinforcement Learning [87] or priority based message delivery and deletion [88]. Moreover, deploying swarms of cost-effective satellites increases the link availability. DTN nodes thus carry the bundles for a shorter time, and minimize the occurrence of memory overflow. Table 3 summarizes the enabling IPN protocols and standards, and investigates their purpose.

3) ACCURATE POINTING TOOLS

The backbone network must be capable of transmitting higher bandwidth compared to access and proximity networks. FSO is the potential communication medium, especially in deep space that exhibits extremely low humidity and zero atmospheric distortion Focused communication can push the signal further in the space, the issue that requires a transition from coarse-grained pointing to fine-grained pointing. More specifically, it is a process that starts from acquisition and narrows down the beam to achieve higher SNR and minimize the offline time. Coarse Pointing Assembly (CPA) and Fine Pointing Assembly (FPA) [89], [90] assist in synchronizing the receiver's antenna and the sender's laser beam, and 2-axis gimbals to orient an optical payload towards the receiving spacecraft antenna [72], [73]. Moreover, an anti-vibration mechanism is pivotal to maintain accurate pointing, for instance, the usage of FOG [75] to improve the stabilization system.

The IPN concept is still in the incubation stage, so the infrastructure and architecture of IPN should be planned and well-studied before deployment. A considerable amount of common standards and research is required before deployment can occur to make IPN feasible [100].

VII. CONCLUSION AND FUTURE DIRECTIONS

The increasing number of space exploration missions has created an urgent need for a unified communication architecture. Such architecture should be scalable, reliable, and on-demand to address the specific needs of communication in space. This architecture aims to connect and reuse critical elements in space (spacecraft, landers, satellites) with the Earth's internet, forming an Interplanetary Network (IPN). IPN utilizes delay/disruption tolerant networks (DTN) architecture

[21] eospso.nasa.gov/missions/earth-observing-1
[22] https://github.com/delay-tolerant-networking/DTN2
[23] https://sourceforge.net/projects/ion-dtn/
[24] https://gitlab.ibr.cs.tu-bs.de/forward-secure-dtn/ibr-dtn

TABLE 3. IPN Protocols and Concepts, Descriptions and Purposes. The protocols involved in the protocol stack all the paths to Earth DSN, their description, and purpose in current and future missions. The protocols are described herein from top to bottom with respect to the protocol stack layers.

Protocol	Description	Purpose
Delay Tolerant Networking (**DTN**) [3]–[5]	An end-to-end communication architecture in environments presenting intermittent connectivity, large and variable delays, and high bit error rates	Provides communications for interplanetary communication and connects sender nodes on outer planets to terrestrial receiver nodes through intermediate nodes scattered around the solar system.
Contact Graph Routing (**CGR**) [83]	CGR is a routing protocol that computes efficient bundle forwarding routes between source and destination in DTN	Computes routes between DTN routers in the backbone and access networks
Schedule-Aware Bundle Routing (**SABR**) [84]	SABR is another touting protocol that provides dynamic route computation in environments with stable topology but time-varying, scheduled connectivity	Computes routes between DTN nodes with predictable connectivity (e.g., orbiting nodes).
Lossless Data Compression [91], Image Data Compression [92]	Source coding for data compression is a method utilized in data systems	Reduces the volume of digital data so as to reduce the transmission channel bandwidth, buffering and storage requirement, and data-transmission time
CCSDS File Delivery Protocol (**CFDP**) [93]	CFDP provides file manipulation operations for use in space. It is an international standard for automatic, reliable file transfer in both directions.	Provides file transfer for space-ground/ground-to-ground/ground-space as an end-to-end application.
CCSDS Streamlined Bundle Security Protocol (**SBSP**) [62]	SBSP provides authentication, integrity, and confidentiality for bundles along a path in DTN	Protects space mission data from potential network threats. Requires the presence of SBSP security-aware nodes.
Licklider Transmission Protocol (**LTP**) [7], [8]	LTP provides retransmission-based reliability over intermittent links with extremely long round-trip times and/or frequent interruptions in connectivity [8]	Supports "long-haul" reliable transmission in interplanetary communication.
Licklider Transmission Protocol **- Security Extensions**) [63]	Authentication mechanism that provides cryptographic authentication of the segment for LTP	Authenticates the DTN nodes and the exchanged bundles on a hop-to-hop basis
Convergence Layer Protocol (**CLP**) [53]	Provides the functions necessary to carry bundles on the lower layer transport protocol, i.e., over LTP, UDP, SCTP, TCP, SpaceWire, or TCP	Establishes overlay layer which operates over various hop-to-hop transport protocols, and ensures end-to-end data delivery. For instance, LTP for deep space links, and TCP for terrestrial links
TCP-based CLP (**BP/TCPCL/TCP/IP**) [55]	Carries bundles over TCP/IP in DTN architecture	Carries bundles between terrestrial DTN nodes all the way to mission operation center
Stream Control Transmission Protocol (SCTP) - Convergence Layer protocol (**BP/SCTPCL/SCTP**) [56]	Carry bundles on multiple stream with concurrent multi-path transfer	Carries bundles between terrestrial DTN nodes
UDP-based CLP (**BP/UDPCL/UDP/IP**) [57]	Carries bundles over UDP/IP in DTN architecture	Carries bundles between terrestrial DTN nodes, but for less reliable data such as video streaming
LTP-based CLP (**BP/LTPCL/LTP**) [58]	Carries bundles over LTP/IP	Ensures data exchange between DTN routers in deep space, e.g. orbiters in access network or spacecraft in backbone network.
SpaceWire CLP [59]	Carries bundles over SpaceWire	Carries bundles between DTN nodes in the outer planet's proximity network
Encapsulation Packet Protocol (**Encap or EPP**) [94]	Encapsulates higher-layer protocol data units recognized by CCSDS over applicable ground-to-space, space-to-ground, or space-to-space communications links using Space Data Link Protocols	Supports missions that require cross-support capabilities, and to provide data communications over space links between CCSDS Agencies in such situation
Advanced Orbiting Systems (**AOS**) [95]	Space Data Link Protocol for cross-supported inter-agency missions	Establishes space-to-ground, ground-to-space, or space-to-space communications links for space missions
Proximity-1 Space Link Protocol (**Prox-1**) [96], [97]	A Data Link Protocol for proximity space links which are short-range, bi-directional, fixed or mobile radio links	Allows outer planet's probes, landers to intercommunicate with its orbiting constellations, or orbiting relays
Physical Layer (**Radio Links**) [98]	DTN uses Ku-Band (12-18 GHz) and Ka-band (27-40 GHz) to increase the bandwidth and achieve higher data rates, compared to the previously utilized lower bands, S-band (2-4 GHz), and UHF (300MHz - 3000MHz)	Conveys data from Earth to outer space, and possibly from other planets to outer space, as a countermeasure for atmospheric absorption
Physical Layer (**Optical Links**) [99]	Future missions will use the visible light spectrum $(4 - 7.5x10^{14} Hz)$ to achieve much higher data rate	Provides high data-rate communication primarily in the backbone network, and between the backbone and access networks

to overcome the long delay and discontinuous connectivity of the links between the communicating elements. The IPN architecture would rely on modular and reusable components which enable progressive installation over time. Currently, the communication architecture is agency-centric, lacks scalability, and provides a non-functional network. By combining major space agencies' and companies' efforts and leveraging successive missions, IPN would connect any significant regions of interest in the solar system using a rich functional network. In the long run, swarms of cost-efficient smallsats will strengthen the backbone network, improving the availability of IPN. However, the installation of IPN will require affordable network units (e.g., miniaturized satellites), a solar system-wise positioning system, autonomous operation in deep space, and proper key management in DTN. The article provided some research directions to respond to the need for complementary components and services to operate the IPN efficiently.

With this article, we hope to have provided a comprehensive roadmap towards deep space internetworked communication. We believe this roadmap will assist private space companies and organizations. However, many issues might emerge regarding the reliability, quality of service, time, and cost of IPN deployment. These issues require demonstrations and open up many research opportunities as follows:

A. AFFORDABLE NETWORK UNITS

Miniaturized satellites are of low mass and size, usually under 500 kg (1100 lbs). Their tiny size brings down the launch and construction costs significantly. Cubesats or nano/microsats can be launched as secondary payloads, making them highly affordable. They allow space agencies and private companies to launch large numbers of satellites at once, and thus bridge large distances, decrease the mission cost and achieve better SNR [101]. However, miniaturized satellites come with size, mass, and power constraints, leaving an open research question of how to allow small satellites to communicate from very far distances in the solar system. Space agencies can launch swarms of small satellites to act as autonomous network nodes [102]. Each swarm is capable of forming large synthetic apertures in deep space. Super-high-speed intra-swarm communications could be achieved via omnidirectional optical links. Another study proposes a combined solution of inflatable antenna reflectors and the arrays across multiple CubeSats, where inter-satellite intra-arrays collaboration is enabled [103]. However, the use of swarms or smallsat arrays brings many challenges. 1) Their navigation needs deep-space communications links for command/telemetry and radiometric data for navigation. 2) They may involve near-simultaneous communication and navigation but have a minimal number of ground antenna assets, as well as the available spectrum, to support their links. These challenges also raise other open research questions: 1) What is the best method to track and operate multiple spacecraft simultaneously, including spectrum coordination? 2) How to streamline the access to DSN and the related services [104]?

B. SOLAR SYSTEM POSITIONING SYSTEM (SSPS)

Currently, spacecraft navigate beyond the Earth based on radio instructions from the terrestrial tracking and commanding (TT&C) system [105] on the Earth. The TT&C system acts as the primary means of spacecraft tracking, ranging, monitoring, control, and data transmission. TT&C uses large-diameter antennas (i.e., DSN), small antenna arrays [106], or low noise temperature receiver and weak signal demodulation technologies [107] to establish RF links with deep space planetary spacecraft. However, missions targets are located farther and farther away from Earth, increasing communication times to minutes, even hours, and making the establishment of a solar system-wide positioning system a pressing issue. SSPS would not only guide probes and – possibly crewed spacecraft autonomously, but it would also ensure that astronauts on long-term space missions to Mars, or beyond, have a reliable navigation system with them [108].

C. KEY MANAGEMENT IN DTN

The document [63] defines new security extensions for LTP but does not address key management. IPsec key exchange does not work efficiently in stressed environments, where link delays are in minutes or even hours. Therefore, key management in DTN remains an open research question [63], [109]. Another solution proposes to deploy LTP as a layer on top of UDP, making it possible to use IPsec or other existing security mechanisms. However, the long delays complicate such a solution, making it infeasible [110].

D. RELAY SPACECRAFT AT LAGRANGE POINTS

A Lagrange point is a location in space where the combined gravitational forces of two large bodies, such as Earth and the Sun or Earth and the moon, equal the centrifugal force felt by a small body [111]. The interaction of the forces creates a parking space, where a space agency can station a relay spacecraft and reduce fuel consumption needed to remain in position. The JWST telescope, for instance, will orbit the Sun 1.5 million kilometers (1 million miles) away from the Earth at the second Lagrange point L2. Many research works [19], [112], [113] propose to station relay satellites at the Earth-Sun liberation points. However, the costs and benefits of such a deployment remain an open research question. Stationing relay satellites at Lagrange points requires a rigorous technical analysis in advance. Another research question would be: What are the benefits of stationing extremely inexpensive satellites (e.g., CubeSats) [114]. Alternatively, the ability of the relay satellites to boost the signals from the endpoints of the path, thereby increasing the data rate even when Earth and Mars are not in opposition, would make them cost-effective year-round.

E. AUTONOMOUS OPERATION

The spacecraft may operate as a relay node (i.e., DTN router) in deep space. They also operate as sensors in deep space. Unless it is a technology demonstration mission, the spacecraft will carry instruments to collect scientific data. A science payload is integrated with the spacecraft to register characteristics of phenomena in their immediate vicinity [115]. Simultaneously, they rely on radio instructions from Earth stations to navigate beyond the Earth. The spacecraft typically are constructed to accomplish many different objectives, sometimes simultaneously. There is potential competition for communication resources (including the attitude of the spacecraft itself, given body-fixed antennae) at any time, and resolving those conflicts is even more challenging than configuring the radio.

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