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The Sky is NOT the Limit Anymore: Future Architecture of the Interplanetary Internet

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INTRODUCTION

Space exploration is not only feeding human curiosity, but also allows for scientific advancement in environmental research, and in finding natural resources [1]. Although media exposure reached its peak during the Apollo programs, space research remains a very active domain, with new exploration and observation missions every year.

Following the Apollo program, public and private organizations launched a wide variety of exploration missions with increasingly complex communication constrains. In 1977, NASA launched Voyagers 1 and 2 [2] to explore Jupiter, Saturn, Uranus, and Neptune. In September 2007, Voyager 1 crossed the termination shock at 84 AU, which is more than twice the distance to Pluto. The Voyager interstellar mission (VIM), an extension to the 1977 Voyager mission, will explore the outermost edge of the Sun's domain and beyond. Regarding nearby planets, NASA launched several exploration rovers in 2004 and 2012, followed by the InSight lander in 2019. Currently, six active satellites orbit around Mars, with primary purpose of studying the atmosphere, relay data for other missions, or test key technologies for interplanetary exploration [2]. Private companies are also starting to take part in space exploration. SpaceX and Blue Origin were founded to reduce the cost and increase the safety of the space flight, and aim for near-future Mars exploration. Finally, in 2018, Luxembourg became the first country to legislate for asteroid exploration and mining, opening the way for a whole new space industry. However, each mission operates independently, has its own dedicated architecture, uses point-to-point communication, and is dependent on operator-specific resources. In this paper, we propose an interoperable infrastructure in a similar fashion to the Internet at stellar scale to simplify the communication for upcoming space missions.

In recent years, space exploration managed to attract a lot of media attention, resulting in a clear regain of interest of the public for space exploration. As a consequence, space agencies started to plan several ambitious missions for the 22nd century, both manned and unmanned. These missions require increasing communication capabilities, proportional to their complexity. Such missions require a reliable, scalable, and easy to deploy common communication infrastructure to transmit scientific data from the outer space to the earth and back. The advantages of such strategy are manifold.

1) *Interoperability*: It significantly reduces the cost of communication and facilitates interagency cooperation. Future missions would benefit from sharing resources.
2) *Security*: Organizations can work together toward a reliable and secure infrastructure.
3) *Increased bandwidth*: Future missions will require a higher bandwidth to provide increasing amounts of data to the general audience.
4) *Scalability*: Since space exploration is an incremental process, it is more efficient to progressively scale up the network instead of deploying all the resources at once.
5) *Colonies*: Several organizations envision definitive Mars colonies. Interconnecting both planets'

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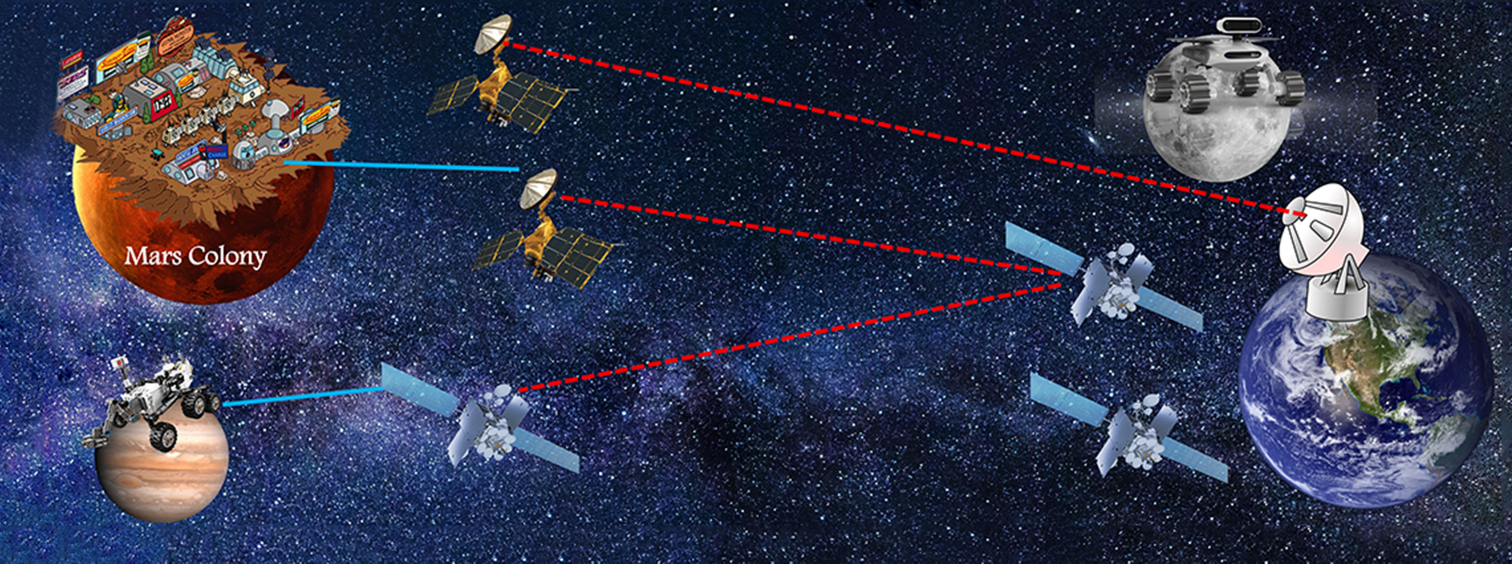


networks would facilitate the expansion of human knowledge.

In this paper, we propose an evolutionary architecture for an interplanetary (IPN) Internet [3]. Such an architecture interconnects networks from various organizations to form a unified network. To address future space exploration missions requirements, we design three intercompatible architectures, each of which corresponds to a given exploration milestone: *near-term* (current missions), *mid-term* (human colony on Mars), and *long-term* architectures (manned and unmanned colonization of the complete solar system). We support these architectures with the most effective technologies for long, dynamic, and autonomous usage. Our contribution is threefold.

- Proposition of a bottom-up scalable and integrated architecture for future IPN Internet, taking into account the incoming milestones of space exploration.
- Analysis of the implications of this architecture over the path (Jupiter $\rightarrow$ Mars $\rightarrow$ Earth).
- Preliminary evaluation of the architecture.

The remainder of this paper is organized as follows. “RELATED WORK” outlines the related work toward an IPN Internet architecture. We then introduce the existing architectures in “TOWARD AN IPN INTERNET.” Afterward, we propose our architecture, demonstrate the data flow, and discuss further implementation notes. Finally, we support our findings with a preliminary evaluation of the performance in “PRELIMINARY EVALUATION OF THE ARCHITECTURE”.

RELATED WORK

The earliest works in space communication are concurrent to space exploration itself. The ideas of mutualization and reutilization emerged as early as in 1982 [4]. In this section, we present the key studies related to our proposed architecture.

Many studies propose novel infrastructures for the next milestone of the space exploration: Earth–Mars deep space communications. Wan and Zhan [5] propose a structure of satellite orbits based on several two-dimensional planes to optimize the point-to-point physical wireless link capacity. Gladden et al. [6] discuss the current infrastructure and its limitations. The authors consider the necessary predecessor technologies to implement a delay and disruption tolerant network (DTN) with automated *in situ* communication scheduling. These pending technologies enable such a network to be scalable by assimilating spacecraft from a wider cast of participating organizations in the next decades. At NASA, Bhasin et al. [7] describe an architecture to support higher data volumes for Mars exploration alongside the spectrum (X, Ka-band). While proposing a scalable communication architecture to maximize data delivery ($> 100\,\mathrm{Mb}$), they also define the requirements for such architectures: the *architecture elements and interfaces*, *layered/integrated communication architecture*, and the *Communication nodes* (rovers, satellites, spacecrafts etc.).

Regarding the curr1ently deployed architecture, Mars orbiters operate as relays, receiving data from a lander on Mars surface and sending them to a single destination: Earth. The ground operators on Earth inform these orbiters the identity of the asset they communicate prior. The ground station then processes, depackages, resorts, and delivers the data to its final destination [6]. More recently, NASA experimented with satellites acting as bent-pipe relays to land the InSight mission. These relays allowed to keep a line of sight communication with Earth during the critical steps of the landing, resulting in an end-to-end delivery delay of 8 min. Without these satellites, NASA would have had to wait for the Mars relay orbiter (MRO) to complete its revolution around Mars to transmit data, three hours later [8].

Due to the long distances, space communication introduces unshrinkable latencies. Fraire et al. [9] investigate the DTN technologies. They prove that DTN features could become a valuable means to achieve data delivery in future interstellar networks. Project Loon [10] uses TS-SDN for interoperation and coordination of aerospace networks. Finally, Jet Propulsion Laboratory (JPL) deployed the first DTN gateway located 25 million kilometers from the Earth during the "deep impact network experiment (DINET)" [11]. The currently operating architectures are limited and cannot be scaled up to the intended future missions. Moreover, many solutions are purely mathematical [5] without considering the concrete implementation, namely the hardware, the spectrum, the communication protocols, and the prospective technologies highlighted in [6]. These aspects need to be complemented by the use of technologies adapted to IPN conditions, such as DTN [9], [11]. In this paper, we provide a holistic view to a long-term, scalable, and evolutive architecture. This architecture can unfold over time to adapt to the space exploration missions from near-term to long-term future. It covers the milestones of solar system exploration through three inter-compatible architectures, which we refer to as *near-term* (current missions), *mid-term* (human colony on Mars), and *long-term* (manned and unmanned colonization of the complete solar system). Our evolutive IPN architecture not only takes into consideration the time frame of the future exploration and science missions but also NASA's requirements [7]. Moreover, we move further to shed the light on the most effective technologies to embed on IPN nodes toward a long-term architecture.

TOWARD AN IPN INTERNET

Proposing any interplanet network demands studying the supportive architectures, the challenges enforced in the environment, and the potential technologies to overcome the challenges.

SATELLITE AND SPACE COMMUNICATION NETWORKS

The current satellite infrastructure can be broken down into space segment and ground segment. Nowadays, satellites are distributed over three orbits [12]: *geostationary Earth orbit (GEO)*, *medium Earth orbit*, and *low Earth orbit*. The combination of these satellites covers the whole surface of the Earth; thanks to the inter-satellite links. The current space communication architecture operated by NASA embraces three operational networks [13]: first, the *deep space network (DSN)* is composed of three equidistant ground stations to provide continuous coverage of GEO orbits, and unmanned spacecraft orbiting other planets of our solar system, second, the *near Earth network* consists of both NASA and commercial ground stations, and finally, the *space network (SN)* is a constellation of geosynchronous relays, tracking and data relay satellite system (TDRSS), and ground stations.

This infrastructure is very convenient for an IPN Internet and can be used as an access network between the Earth and other planets. Establishing colonies demands such constellations on the host planet to provide full surface coverage and interconnect with the other planets' Internet.

IPN CHALLENGES

Most of the nodes involved in an IPN Internet are revolving around other stellar objects: planets revolve around the Sun with long distances, satellites orbit planets at a relatively close range. This motion poses many challenges to the interplanetary communication[14]–[16].

1. *Extremely long and variable propagation delays*: 3–20 min from Mars to Earth, 4–7 h from Pluto to Earth, depending on their relative positions.
2. *Intermittent link connectivity*: the Sun or other planets may temporarily obscure a given link between two stellar objects. For instance, the Earth to Mars line of sight is regularly obstructed by the Sun when they reach the opposite position in their orbits [17].
3. *Low and asymmetric bandwidth*: the limited payload of the satellites severely impacts their transmission power compared to Earth's transmission relays.
4. *Absence of fixed infrastructure*: Nodes are in constant motion that leads to time-varying connectivity. Instances of connectivity are planned and scheduled rather than opportunistic.

An IPN Internet architecture must address these constraints to optimize the few resources available in the system. Contrary to other opportunistic networks, the motion of the nodes in the solar system follows regular patterns that can be precalculated. As such, the sender can request a graph of contacts to deliver the data to its next destination.

DELAY TOLERANT NETWORKS

The end-to-end latency in an IPN Internet can reach up to a day, and jitter is measured in hours. As such, conventional Internet architectures based on the Transport Control Protocol/Internet Protocol (TCP/IP) stack are not applicable. Delay-tolerant architectures and protocols are designed to withstand the extreme constrains of the system. Fraire et al. [9] prove that DTN protocols can be conveniently combined with the infrastructure of interstellar relay systems to avoid retransmission of data on long distances and, thus, achieve lower end-to-end latency while reducing the relay buffer requirements. Therefore, we consider the DTN architecture and protocols to be the building blocks of our IPN network. The first concepts of DTN were originally proposed to cope with the characteristics of deep space communication (long delays, discontinuous network connectivity) before being extended to other domains. The DTN nodes provide store-and-forward capabilities to handle the eventual link unavailability. The DTN architectures insert an overlay network protocol called *bundling protocol (BP)*, which provides end-to-end transmission between heterogeneous links [18]. This overlay complies with existing Internet infrastructures. At each point of the network, BP employs the transport protocol adapted to the transmission conditions. The BP, therefore, operates over TCP, UDP, and Licklider transport protocol (LTP) [14] to provide a point-to-point transmission protocol for intermittent links. Such characteristics make BP particularly adapted for interplanetary transmission, where the traditional TCP/IP paradigm cannot be applied.

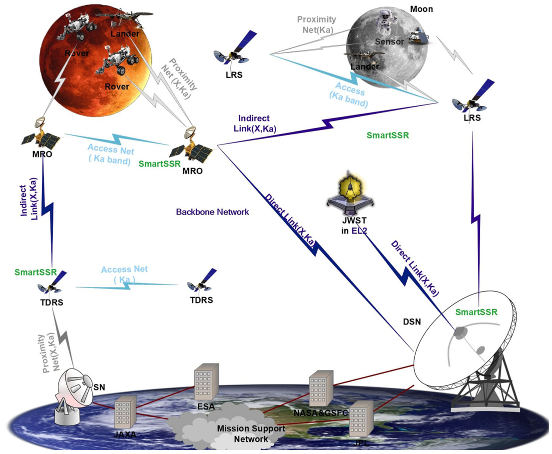


Figure 1.
IPN near-term Architecture. Reusing the existing infrastructure with minimal addition.

ARCHITECTURE AND COMMUNICATION INFRASTRUCTURE FOR FUTURE IPN

Deploying and operating a long-term architecture is extremely intricate and demand a lot of time. In addition, the architecture should withstand the harsh constraints of deep space communication. Given these constraints, an incremental and evolutionary architecture is required. As such, we define an evolutionary architecture that consists of three intercompatible subarchitectures, each of which is corresponding to different milestones in space exploration.

IPN NEAR-TERM COMMUNICATION ARCHITECTURE

We propose an IPN near-term communication architecture for the current missions targeting Mars and the Moon. Both are accessible within a reasonable amount of time and several organizations are already planning manned missions within the next ten years. This architecture reuses a maximum number of available technologies to interconnect the Earth, Mars, and the Moon in a short time frame. Figure 1 illustrates the IPN near-term architecture. We separate this architecture in two subsystems: the physical layer, that we will call *spectrum*, and the upper layers, referred to as *network*. The *spectrum subsystem* provides two bands in the microwave spectrum for data: Ka (26.5–40 GHz) and X (8–12.4 GHz). These bands provide higher data rates than the conventional RF bands. The Ka-band allows for the communication in the backbone network and for intersatellite communication due to its higher frequency (thus, higher data rates). X and Ka together allow for the communication from satellites to the surface of the planet. In our architecture, we switch between both bands depending on the weather, as the Ka-band suffers from attenuation in the presence of humidity.

The *network subsystem* contains three subnetworks (see Figure 1): The *proximity network* contains the interelement links relatively close to the planet or the Moon and the surface networks. The *access network* consists of satellites orbiting the planet or the Moon interconnected with each other. In our architecture, there are three access networks formed by the satellites orbiting each planet and the Moon. The *backbone network* interconnects the three access networks with the DSN stations on Earth. This network provides two kinds of links for interconnection: direct links and indirect links. Direct links connect Mars and lunar relay satellites directly to the DSN on Earth. Indirect links go from Mars and lunar relay satellites to Earth relay satellites where the data are then directed to DSN antennas. We propose to launch four lunar relay satellites (LRS) and four MROs. Three relay satellites are operating, whereas the fourth remains as a spare. On the Earth, we reuse TDRS satellites, currently operating in geostationary orbit, to serve as relay of the data arriving on the indirect links. Each node along the path has SmartSSR technology to support DTN functionality. Therefore, it is installed on DSN, relay satellites (LRS, MRO, TDRS), and even in the proximity networks: Landers, Robots, Rovers (data collectors), SN and mission centers (data destination). SmartSSR is a solid-state recorder developed by the Applied Physics Laboratory. Its small mass and size combined with its relative low cost make it easy to massively install on the payload module of any spacecraft. These features make the SmartSSR an optimal choice to provide DTN capabilities. It features JPL's DTN ION implementation and uses the space file system (SpaceFS) to manage spacecraft data. The SpaceFS is adapted to meet the special requirements of space operational environment [19].

Figure 2 outlines the data transmission process from the mission center on the Earth to a Mars rover. BP functions as an overlay over TCP between the mission center and the DSN antennas, and over LTP in second trunk (DSN antennas → Mars Orbiter → Mars Rover). On the latter, we utilize the microwave band Ka and LTP to

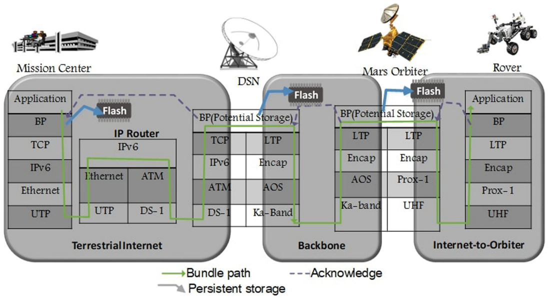


Figure 2.
End-to-end data transfer using DTN. In near-term architecture, the DSN directly connects to the Mars Orbiter, which relays the bundle to the rover using BP over LTP.

transmit the data over the long distance – high latency – between the Earth and Mars. The green continuous line depicts the data path from the mission center to the Rover. The purple dashed lines show the hop-to-hop acknowledgments between two neighboring elements gained from custodian transfer property, a property of DTN functionality supported through utilizing SmartSSR hardware. Currently, Mars and Moon's orbiters use the Proximity-1 data link protocol to communicate with the surface elements and the advanced orbiting systems space data link protocol for communication between orbiters and the DSN antennas on Earth.

IPN MID-TERM COMMUNICATION ARCHITECTURE

For our mid-term architecture, we consider the human colonization of Mars and the further side of the moon, which will further lead to the long-term goal of colonizing the whole solar system. As such, we expect an ever-increasing demand to exchange huge amounts of data in both directions. The lower power consumption, lower mass, higher range, and higher bandwidth of optical communication compared with RF make it an auspicious technology to serve as a communication medium in IPN [20]. Therefore, we propose using an onboard optical module for spacecrafts and optical communication terminals (OCT) on the planet's surface to support two-way communication with high data rates. This design allows us to considerably reduce the bandwidth asymmetry. These technologies require less power and considerably reduce the payload. They are also able to reach longer distances and provide higher data rates, 10–100× higher than that of the RF.

Figure 3 illustrates the IPN mid-term architecture that interconnects the Earth with Mars and other planets. In this architecture, we upgrade the transmission spectrum from microwave (X, Ka) to an optical communication, or so-called Free-space optical communication (FSO). The optical communication is an emerging technology in which data is modulated onto a laser for transmission. The laser beam is significantly narrower than a RF beam and, thus, promises to deliver more power and achieve higher data rates. In outer space, the communication range of FSO is on the order of thousands of kilometers. Optical telescopes, therefore, play a pivotal role as beam expanders to bridge interplanetary distances of millions of kilometers. To this purpose, each spacecraft carries a small (a dozen cm) Cassegrain reflector, a 22 cm aperture, 4 W laser and contains an isolation and pointing assembly for operating in the presence of spacecraft vibrational disturbance, and a photon-counting camera to enable the acquisition, tracking, and signal reception.

The planet's ground optical terminals contain photon-counting ground detectors that can be integrated with large aperture ground collecting apertures (telescopes) for detecting the faint downlink signal from deep space. The ground OCT contains six small (a dozen cm) refractive telescopes for the transmitter and a single bigger reflective telescope as a receiver. The latter is connected via optical fibers to the destination. The operating constellations in this architecture are optical TDRS around Earth, geostationary Mars orbiters (GMOs) and geostationary planet orbiter. They provide relay services between nodes at the surface of the outer planet, in-between planets and between the access network from other planets. The optical deep space network substitutes the DSN ground stations by supporting two communication technologies: RF microwaves (X and Ka-band) and optical (Lasercom). This hybrid results in installing optical mirrors in the inner 8 m of a standard DSN 34 m beam waveguide antenna. The RF communication is kept in order to maintain the operation in all weather conditions.

IPN LONG-TERM COMMUNICATION ARCHITECTURE

The optical communication in the space is based on line of sight (LOS), which may experience obstruction or conjunction. For instance, Earth and Mars can be obscured from each other by the Sun. This obstruction lasts for two weeks every 26 months. Moreover, LOS communication in space attenuates because of free-space loss that increases with distances. Therefore, communication between the Earth and further planets experiences much more attenuation than communication between the Earth and Mars. If we consider transmission between the Earth and Pluto, the signal travels 38.44 AU = 5766 million km (0.52 AU for Earth to Mars) in space and needs 5.4 h to reach its destination.

We propose operating spacecrafts in Sun–Earth's Lagrangian points to address these problems. Figure 4 shows the positions of the five Lagrangian Points L1, L2, L3, L4, and L5. At each point, the gravitational forces of two large bodies (Sun–Earth for instance) cancel the centrifugal force. A spacecraft can, therefore, occupy the point and move around the Sun without the need for external intervention. These points are commonly used for observation missions and are envisioned as relays for

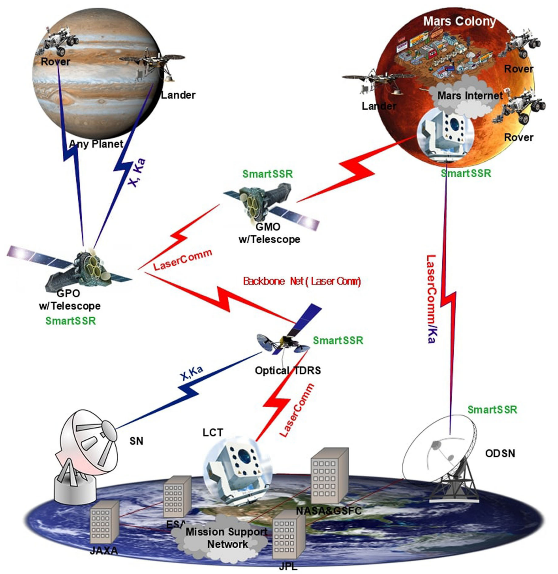


Figure 3.
IPN mid-term Communication Infrastructure. We start to deploy Lasercom for long distance links, and extend the architecture to other planets.

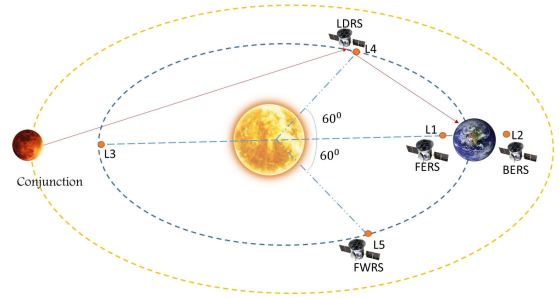


Figure 4.
Spacecrafts placement at Sun–Earth Lagrangian points. When the Mars–Earth LOS is obscured, data can go through the LDRS or FWRS to avoid service interruption.

space colonization. In our architecture, we employ these points to operate spacecraft as repeaters. These repeaters bridge the long distances, relay the data between the planets, and provide alternative paths for the routing in the space. More specifically, we propose to operate spacecraft in points L4, lead relay spacecraft (LDRS), and L5, follow relay spacecraft (FWRS), to address obstruction and conjunction, and L1, front end relay spacecraft (FERS), and L2, back end relay spacecraft, to tackle attenuation. In addition, this will fragment the tremendously long path to amplify the weak signals.

AUTONOMOUS OPERATION

Currently, space communication systems are mission-specific and point-to-point. Moreover, they are dependent on operator-specific resources. Our approach aims at reducing the dependency on resource scheduling provided by Earth operators and interconnect the planets. To do so, our architecture provides autonomous operation on each spacecraft to autonomously deliver the data in space.

To this end, we employ DTN alongside with allowing the communication terminal of the satellite to control the antenna pointing, transmit power and data rates, and provide synchronization capabilities between the sender or the receiver. The next step is to provide interactive links between the nodes that can be created and broken on demand at any time in the whole IPN network.

These on-demand features require specific hardware for pointing and focusing transmission. We propose to use coarse pointing assembly (CPA) and fine pointing assembly (FPA) [21] to orient the antenna and the beam. Pointing synchronization between the sender and the receiver is very crucial to provide autonomous operation of the communication links. Therefore, we incorporate the following two subsystems.

LOCALIZATION SUBSYSTEM

The HORIZONS system [22] provides the solar system's spatiotemporal data and the accurate ephemerides for solar system objects. These ephemerides provide the sender spacecraft's optical communication terminal (OCT) with spatiotemporal information about the receiver spacecraft's OCT location at a given time. The sender's OCT locates the receiver's OCT by feeding the reference position and the new position to the position controller and feeding the reference velocity and the current velocity in the velocity controller. It then estimates the distance to its partner and adjusts the transmission power accordingly. The orbits of all of the planets are within a few degrees of the same plane that makes the solar system disc-shaped; therefore, the localization process is achieved by adjusting both the azimuth (the horizontal orientation of the sender's OCT in relation to Sun's equator) and the elevation (the vertical tilt of the sender's OCT) angles of the pointing assembly. The expected localization accuracy is Azimuth < 1 arcSecond, Elevation < 1 arcSecond, where 1 arcSecond $\approx 4.85\,\mu$rad [23]. Likewise, the expected angular accuracy is $< 5\,\mu$rad. The angular disturbance can only reach a few hundreds of nanoradians to stabilize the laser beam in the presence of spacecraft base motion disturbances and vibrations. To achieve this accuracy, a pointing and vibration control platform (PVCP) can be employed. The PVCP integrates the pointing with vibration isolation to reduce the disturbance and, thus, improves the pointing control accuracy [24], [25].

POINTING CONTROL SUBSYSTEM

Once the sending spacecraft's OCT adjusts the orientation and the direction of the laser beam, the next phase of pointing starts. The technique here employs the same laser as a beacon and for transmission. The beamwidth is controlled from broad in the acquisition stage (also referred to as coarse pointing), to narrow in the tracking stage (also referred to as fine pointing). The acquisition is achieved by the hardware 2-axis gimbals' pointing and a CPA that allow contact with broad beacon beam. When acquired, the beam focusing phase (fine pointing) progressively narrows the beam while correcting the pointing accuracy up to sufficient level of beam concentration to get maximum received power, and thus, high data rates. This stage uses either the FPA or beam control approach that includes three control components: fast steering mirror, point ahead mirror, and laser beam defocus mechanism.

In short, synchronizing the sender and the receiver requires to incorporate these subsystems to quickly find the partner and reduce the offline time. Afterward, the sender starts sending data as bundles using DTN technology. Custody data transfer ensures end-to-end reliability on the hop-to-hop basis.

DATAFLOW AND BUNDLE DELIVERY

In the light of the long-term architecture as in "IPN LONG-TERM COMMUNICATION ARCHITECTURE," we herein discuss the delivery of the scientific data on the return link (e.g., Mars lander $\rightarrow$ intermediate spacecraft $\rightarrow$ Earth's station). This section demonstrates how to employ a DTN architecture to deliver the data packets on the return link. The packet data unit (PDU), in the context of DTN, is called bundle. In fact, using bundle as PDU guarantees the application of custody data transfer, which in turn guarantees end-to-end reliability on the basis of hop-to-hop custody transfer [6]. We propose to install a SmartSSR on each node (i.e., satellite, spacecraft, lander, and DSN) with the interplanetary overlay network (ION) software v3.7 or higher to support the DTN capabilities, the contact graph routing (CGR) implementation and the consultative committee for space data systems's (CCSDS) schedule-aware bundle routing (SABR). The DTN functions enable the node to store the bundles, carry them until a link to the next hop is available, and then, forward them using CGR or SABR to an endpoint identified by a compressed bundle header encoding (CBHE)-conformant [26] endpoint identifier (EID) through the best route with the best delivery time (BDT). Both CGR and SABR rely on accurate contact plan information, provided in the form of contact plan messages [27]. Each DTN node contains a bundle protocol agent (BPA) to originate, forward and deliver the bundles, and is assigned a number by an authority, from a range allocated by the Space Assigned Number Authority. Each node must be registered using one or more EIDs. Each EID serves as a different DTN application operating at that node [28].

Let us consider that a rover on Mars is sending a file to the NASA mission operation center. The NASA mission centre's EID is identified using the Uniform Resource Identifier (URI) *ipn://10.2*, which conforms to the CBHE, where 10 is the receiving node number, and 2 is the service number for a file transfer application. The service number functions as a demultiplexing token. Assuming that the route shown in Figure 4, where the link between Mars and the Earth is available through LDRS, is used as a relay between Mars and Earth to reamplify the signal and counteract eventual occlusion. This route ensures the BDT, since its contacts are available anytime and features the shortest path of any possible routes. Other possible routes lead to longer forwarding times. These routes include R2 $= [C^{0:100}_{MarsRover,MarsGMO}, C^{0:1000}_{MarsGMO,LDRS}, C^{0:700}_{LDRS,FERS}, C^{0:100}_{FERS,DSN}, C^{0:1}_{DSN,NASA}]$, where C is a contact with the parameters (sender, receiver), (start time: stop time), and a start time equal to 0 means the link is available for transmission anytime, whereas the stop time value is set to any number $\geq$ light seconds required to send the bundles.

We illustrate both the data flow and the process flow in Figure 5, where Mars rover sends the file using CCSDS file delivery protocol (CFDP). The rover's BPA encapsulates the file into bundles, which are stored and forwarded when the link with GMO becomes available. Once it is available, the BPA invokes LTP to transport each bundle as segments. The segments are sent to the GMO using either laser communication or ultra high frequency RF. The GMO then, follows the same logic to forward the bundles to the Earth's LDRS, using laser communication and onboard autonomous operation. The LDRS stores the bundles on persistent storage (Flash NAND in SmartSSR) and carries them until the link to the next hop becomes available. The LDRS communicates with the DSN to forward the bundles using the same protocols and communication medium. The DSN's BPA invokes the underlying convergence layer agent to transform from LTP to TCP, to transport the bundles. The OCT on DSN directs the optics to the control room where the laser is demodulated digital data. These data are finally transferred using unshielded twisted pair cables to the mission center, which is the final destination identified by *ipn:10.2*. After delivering data to the mission control center, the deencapsulation process converts the TCP segments into bundles and delivers them into the CFDP to build the file. For each hop, the receiver's BPA (custodian endpoint) creates and replies with an acknowledgment to confirm data reception. This acknowledgment confirms the delivery on a hop-to-hop basis (dotted lines on Figure 5). The BPA guarantees end-to-end reliability through custody transfers.

IPN IMPLEMENTATION NOTES

The deployment of an IPN infrastructure takes several years. Afterward, the deployed elements have to operate

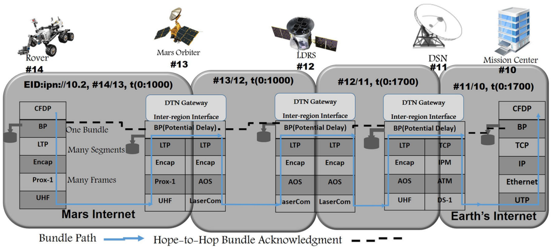


Figure 5.
Mars Rover (#14) to Earth Mission Center (endpoint identifier: *ipn://dest node number.service number*). Data bundles flow through the Mars Geostationary orbiter (#13), which forward them to the Earth LDRS (#12). The LDRS then transmits them to the DSN on Earth (#11), which finally forward the bundle to the Mission Center.

autonomously for decades. Besides, failure is unpredictable and may cause unforeseeable outages. Maintenance requires an extremely long time. Therefore, a comprehensive proposal needs to address these issues. To this end, we propose to integrate *TemporoSpatial software defined network (TS-SDN)* [10], [29] with the "AUTONOMOUS OPERATION," aligned with the spacecraft at the Lagrangian points as in "IPN LONG-TERM COMMUNICATION ARCHITEC TURE." The TS-SDN decouples radio control functions from radio data-plane. It replaces the hardware with the software to reduce deployment costs, limit the number of points of failure, and provides the ability to update the internal mechanisms without physical access to the hardware. TS-SDN controllers use a predefined knowledge, as discussed in "*LOCALIZATION SUBSYSTEM*," to predict the future state of the lower-level network. This setup provides a predictive, time-dynamic and holistic view of the topology that includes both the available wireless links, the approximate accessible time interval of the current and the candidate wireless links, and the future links. We, thus, replace fixing hardware failures with software updates, and drastically reduce the maintenance time from years to hours. It also provides autonomous network topology formation to deliver the data that overcomes any unpredictable problem along the path.

In Figure 6, we demonstrate how TS-SDN architecture works and how its components interact. Given the TS-SDN application is topology management, this application interacts with TS-SDN controllers, namely spectrum management and mobility management through Application Programming Interface (API) or so-called northbound interface. Afterward, the controller interacts with the underlying network elements (satellites, spacecraft, rovers, landers, etc.) through control-to-data-plane interface. This interaction could update the transmit power, the beam width, the RF band used, or any network configuration. Each planet has such architecture deployed; therefore, the TS-SDN controller has the knowledge about the position of each planet and its trajectory plus the relative position and trajectory of the orbiters.

Hardware softwarization and robotic missions, however, require the communication systems to offer maximum reliability with *robust two-way links* for software uploads and updates, virtual interactions and telemetry control. Establishing a bidirectional link requires an efficient pointing technology. When a spacecraft points to another spacecraft, the receiving one should be able to infer the location of the sender from the light signal itself and respond by an uplink laser beacon to guide the transmitter, then redirect the laser beam to the exact location of the receiving telescope. To this end, a spacecraft needs to be provided with multiple transceivers, each of which is provided with telescope to bridge the interplanetary long distances, as discussed in "MID-TERM ARCHITECTURE." In addition, the spacecraft should have many capabilities (i.e, localization, coarse-grain pointing, and fine-grain pointing), and the communication terminal is capable of controlling the antenna pointing, transmit power, laser beam direction, as stated in "AUTONOMOUS OPERATION."

PRELIMINARY EVALUATION OF THE ARCHITECTURE

During the motion of Earth and Mars, the minimum distance between them is $54.6e^6$ km, whereas the maximum is $401e^6$ km, which happens when they are in opposition relative to the Sun. The minimum distance between Earth and Moon is 363 104 km, whereas the maximum is 405 696 km. In the near and mid-term architecture, other planet's satellites communicate directly to TDRS orbiting Earth, so the communication is subject to latency (delay). The speed of light in a vacuum c0 is 299 792 458 m/s and the propagation delay caused by the long distances is $delay = distance/speed$. Therefore, the estimated latency for the minimum, maximum, and average distance of Moon, Mars, and Jupiter are shown in Figure 7(a). Since, the IPN mid-term architecture uses laserCom instead of X-band, we achieve a higher throughput that enables missions to transfer 10X → 100X more data from the planet of interest to Earth but same delay as near-future architecture.

By adding spacecraft LDRS in Lagrangian point L4 for

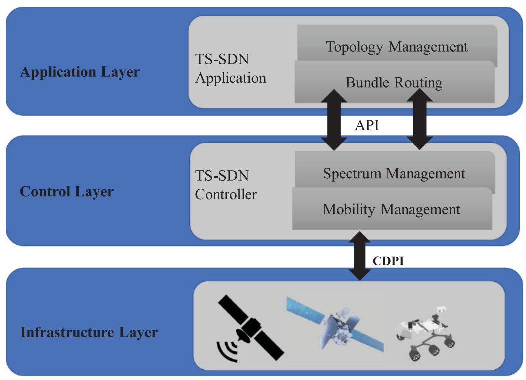
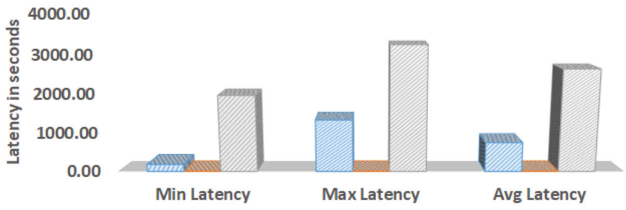
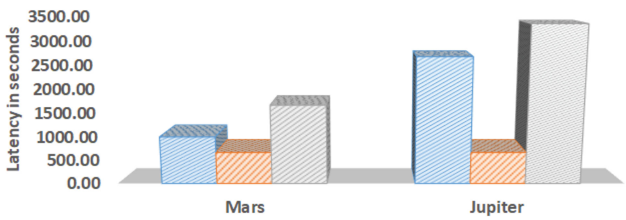


Figure 6.
Abstract overview of SDN architecture.



	Min Latency	Max Latency	Avg Latency
Mars	182.13	1337.59	750.52
Moon	1.21	1.35	1.28
Jupiter	1961.36	3228.91	2625.15

(a)



	Mars	Jupiter
planet->LDRS	1000.69	2668.52
LDRS->Earth	667.13	667.13
path	1667.82	3335.65

(b)

Figure 7.
Latency of communication with Moon, Mars, and Jupiter for near-term and long-term. (a) Latency of direct communication, near/mid-term. (b) Latency using LDRS for long-term.

indirect communication (planet → LDRS → Earth), the overall availability of LOS in long-term architecture is 100%, since it overcomes the blackout of the communication. Communication, thus, follows the alternative path (Mars → LDRS → Earth). The estimated distance of Mars → LDRS path is $300e^6$ km, Jupiter → LDRS is $800e^6$ km, and LDRS → Earth path is $200e^6$ km. Therefore, the average latency for each segment and the whole path are shown in Figure 7(b).

In Figure 8, we estimate the latency of Earth to Mars and Earth to Jupiter communication over ten years for our near-term, mid-term, and long-term architecture. In the near-term architecture, the average latency between Earth and Mars is varying periodically between 182 and 1337 s due to their respective orbits around the Sun. However, once every 26 months, the Earth and Mars are in opposition, and communication is interrupted for 14 days. During this period, the latency reaches up to 14 days or $1.21e^6$ s and decreases linearly with time until conjunction passes. As our near-term architecture only focuses on Mars and the Moon, we assume that no new equipment is deployed on Jupiter. Currently, only one satellite – Juno – orbits around Jupiter with a period of 53 days. Consequently, communication is only possible for a duration of 26.5 days every 53 days. As such, the average latency varies heavily between 2600 s and $2.6e^6$ s. In the mid-term architecture, we assume that Jupiter is now covered by a network of stationary satellites. Communication to Jupiter is, thus, possible most of the time, except in the case of opposition. When planets are in opposition, it becomes possible to use another planet as a relay. When Mars and Earth are in opposition, the latency drops to 5175 s, by using Jupiter as a relay. Similarly, Mars to Earth communication can use Jupiter as a relay in case of conjunction. Nevertheless, the mid-term architecture does not take into account the case of both Jupiter and Mars being in opposition as it happens in 2027, which results in high latency. As stated previously, our long-term architecture uses LDRS at L4. Not only do these satellites allow to keep constant communication with Earth, but they also considerably lower the latency in case of opposition. This latency drops to 1667 s for Mars and 3335 s for Jupiter. The long-term architecture, thus, decreases the maximum latency up to 700 times and allows for communication with Jupiter in less than 2 h year-round.

CONCLUSION

This paper proposes an *evolutionary architecture* for IPN Internet to migrate from mission-centric architectures to a single common, scalable, and reliable architecture.

In this paper, we first propose three intercompatible architectures, each of which corresponds to a given milestone of space exploration, *near-term* (current missions), *mid-term* (human colony on Mars) and *long-term* architectures (manned and unmanned colonization of the complete solar system). We then support this architecture with the prospective technologies that effectively address the IPN challenges, specifically DTN and the communication protocols that fit each environment. We also address the problem of point-to-point communication and provide the hardware and subsystems for multipoint

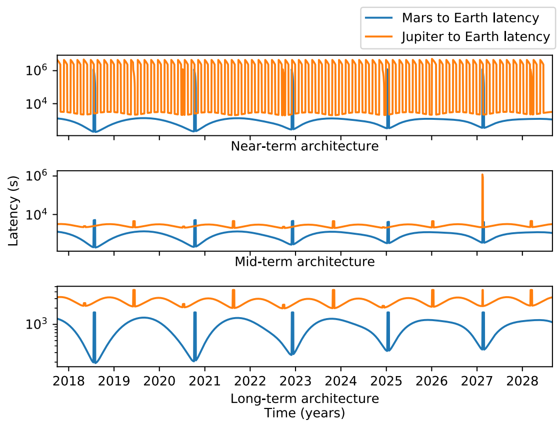


Figure 8.
Predicted latency to Mars and Jupiter for the next ten years for near (top), mid (middle), and long (bottom) term architectures.

communication and *autonomous operation*. Long run of such architecture may cause unpredictible failure. We, thus, propose to extend the usage of *TemporoSpatial software defined network* for efficient, time-less maintenance (e.g., software update). Afterward, we demonstrate the sequence of the protocol stack and the da‘taflow using a case study (send file from Jupiter to Earth through Mars as a relay planet). Finally, we evaluate the latency of this case study.

With this paper, we hope to have provided a novel point of view for future IPN architectures, and set some foundations for an actual implementation within the next decades. In future works, we plan to focus on two concrete aspects of space communication at the core of our architecture. First of all, we plan to develop time-dynamic, predictive communication link modeling, and solar objects’ position and velocity modeling to support TS-SDN and operating links autonomously in deep space. Furthermore, we aim at providing a rigorous technical analysis of the costs and benefits of stationing more inexpensive relay satellites (inspired by CubeSats) at the Earth/Planet-Sun liberation points. This analysis needs to evaluate the performance in terms of boosting the signals and gained data rate.

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