The State of the Art in Interplanetary Internet

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ABSTRACT

Developments in space technologies are enabling the realization of deep space scientific missions such as Mars exploration. Interplanetary (IPN) Internet is expected to be the next step in the design and development of deep space networks as the Internet in the space. However, there are significant challenges to be addressed for the realization of this objective. This article captures the current state of the art and open research challenges, and intends to motivate researchers around the world to tackle these challenging problems and help realize the IPN Internet.

INTRODUCTION

Developments in the space technologies are enabling the realization of deep space scientific missions such as Mars exploration. These missions produce significant amounts of scientific data to be delivered to the Earth. In addition, these missions require autonomous space data delivery at high data rates; interactivity among in-space instruments such as satellites, asteroids, robotic spacecrafts, and crewed vehicles; security of operations; and seamless interoperability between in-space entities.

For successful transfer of scientific data and reliable navigational communications, NASA enterprises have outlined significant challenges for development of next-generation space network architectures. The next step in the design and development of deep space networks is expected to be the Internet of the space planetary networks and defined as the interplanetary (IPN) Internet [1].

The IPN Internet is envisioned to provide communication services for scientific data delivery and navigation services for the explorer spacecrafts and orbiters of the future deep space missions [2]. However, there are significant challenges posed by the deep space networking paradigm that need to be addressed for this objective:

- Extremely long and variable propagation delays
- Asymmetrical forward and reverse link capacities
- High link error rates for radio frequency (RF) communication channels
- Intermittent link connectivity
- Lack of fixed communication infrastructure
- Effects of planetary distances on the signal strength and protocol design
- Power, mass, size, and cost constraints for communication hardware and protocol design
- Backward compatibility requirement due to high costs involved in the deployment and launching processes

Many researchers and several international research organizations are currently engaged in addressing these challenges and developing the required technologies for realization of IPN Internet. In this article we present a survey of the proposed architectures and communication protocols and algorithms for deep space networks and Interplanetary Internet. Our objective is to provide better understanding of the current research issues in this field.

INTERPLANETARY INTERNET ARCHITECTURE

A common infrastructure for interplanetary networking and distributed communication technologies are needed to support scientific research and possible commercial applications in the near future. Since the Internet is truly horizontal and has a diverse set of open interoperable standards, building the space Internet on top of Internet technologies could enable any space mission to "plug in" with high quality of service and cost savings. Therefore, most network architectures proposed for deep space exploration are based on Internet technologies.

A general infrastructure is introduced in [3] for the NASA space Internet, which contains a *backbone network*, an *access network*, an *inter-spacecraft network*, and a *proximity network*. The space Internet is described as a *network of Internets* [4], with a specialized deep space backbone network of long-haul wireless links interconnecting these local Internets. Internet or Internet-related protocols are used to form local networks with low-delay relatively low-noise environments

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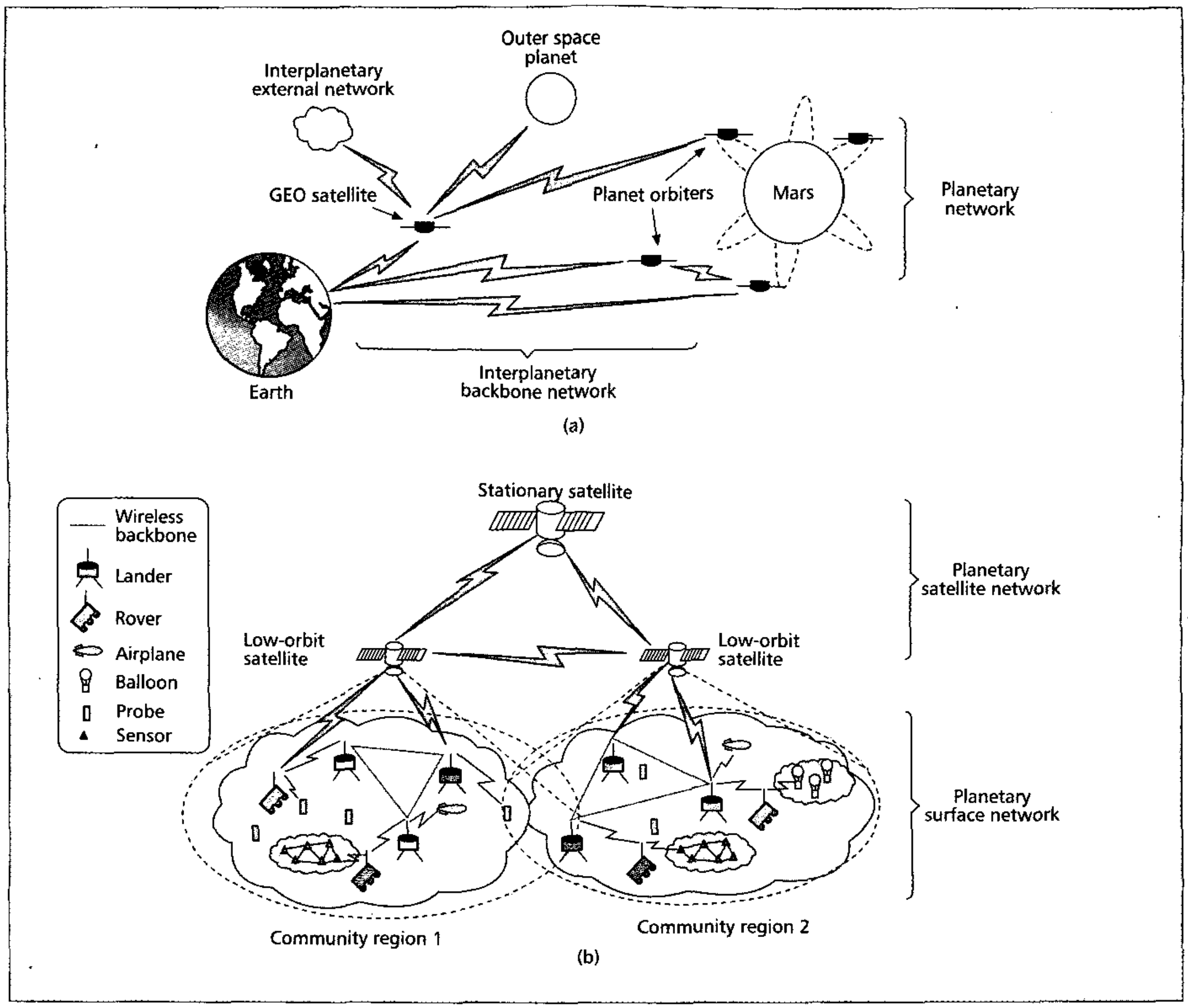

Figure 1. *a) The IPN Internet architecture; b) the planetary network architecture.*

such as around Earth, within a free-flying spacecraft, on and around another planet. A new overlay protocol concept called *bundling* [5] is employed to tie together a set of heterogeneous Internets, performing any required additional functions the local protocols typically cannot do.

To build a general space Internet architecture that combines different challenging parts, our view of the IPN Internet is depicted in Fig. 1a. It includes the *IPN backbone network*, *IPN external networks*, and *planetary networks*.

IPN backbone network: It provides a common infrastructure for communication among the Earth, outer space planets, moons, satellite, intermediate relay stations, and so on. It includes the data links between elements with long-haul capabilities.

IPN external network: It consists of spacecrafts flying in groups in deep space between planets, clusters of sensor nodes, and groups of space stations.

Planetary network: The expanded view of the planetary network shown in Fig. 1a is illustrated in Fig. 1b, which is composed of a *planetary satellite network* and a *planetary surface network*. This architecture can be implemented at any outer space planet, providing interconnection and cooperation among the satellites and surface elements on a planet.

- **Planetary satellite network**: It is composed of multilayer satellites circling the planets as shown in Fig. 1b and provides the following services: intermediary caching and relay service between the Earth and the planet, relay service between the in situ mission elements, and location management of planetary surface networks.
- **Planetary surface network**: It provides the communication links between high power surface elements, such as rovers and landers, as shown in Fig. 1b, that have the capability to connect with satellites. They also provide a power-stable wireless backbone in the planet. Moreover, a planetary surface network includes surface elements that cannot communicate with satellites directly. These elements are often organized in clusters and spread out in an ad

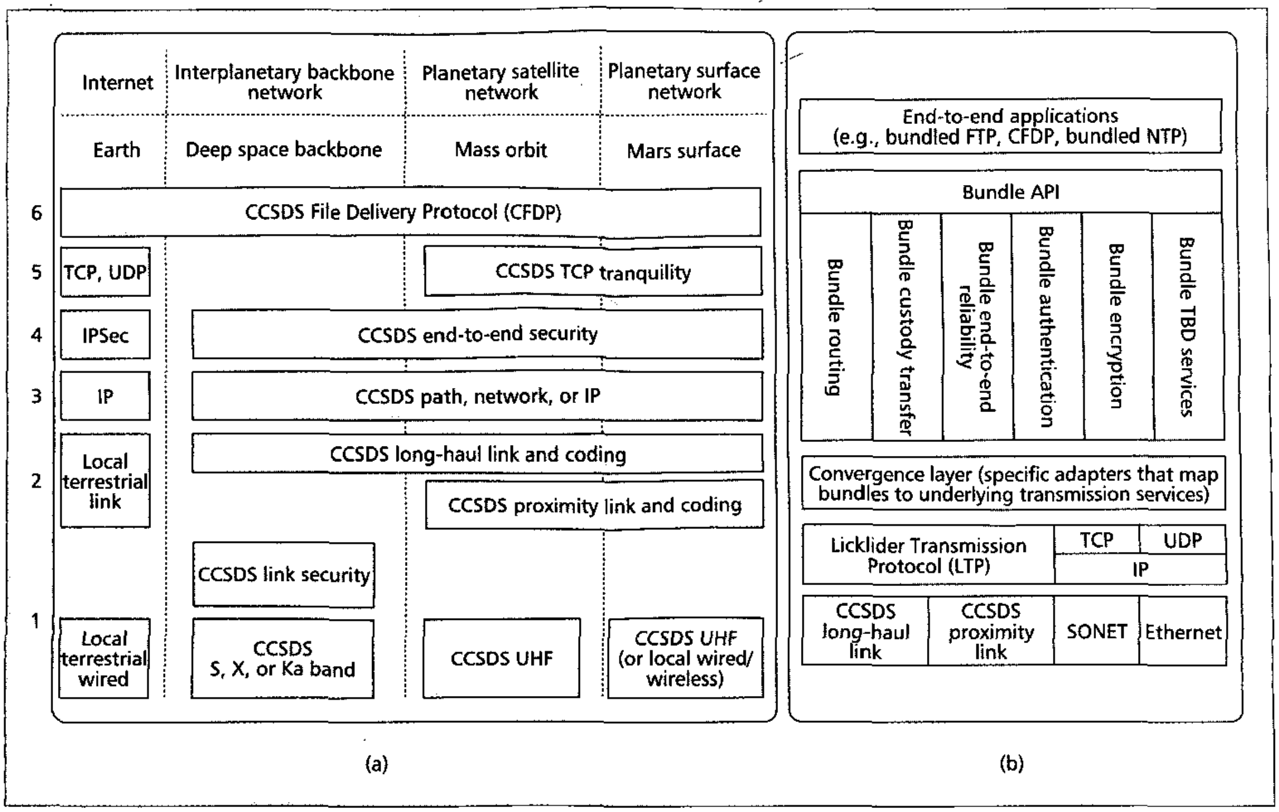

Figure 2. *a) The Mars communication protocol stack; b) the bundling architecture [4].*

hoc manner (e.g., sensor nodes and balloons), as illustrated in Fig. 1b.

In summary, the entire IPN Internet architecture shown in Fig. 1a and b is decomposed into different subnetworks. Each subnetwork faces different challenges and has its own design requirements. Therefore, a common protocol stack is needed to integrate the differently challenging parts together and extend the terrestrial Internet into its IPN counterpart. Meanwhile, it also leaves space to develop protocols adaptive to the peculiar circumstances in each subnetwork.

Communication Protocol Suite

As the IPN Internet consists of heterogeneous network architectures as shown in Fig. 1a, each of these components may have to run a different set of protocols that best fits the environment [5]. In this section we explore the current and proposed protocol suites to realize communication in the IPN Internet.

The Current CCSDS Space/ Ground Protocol Stack

The current space/ground protocol stack is proposed by the Consultative Committee for Space Data Systems (CCSDS) for space communications [4]. It is used for Mars explorations [4], and its functionalities are mapped to the generic layers of the current space/ground protocol stack: space wireless frequency and modulation (layer 1), space channel coding and space link (layer 2), space networking (layer 3), space end-to-end security (layer 4), space end-to-end reliability (layer 5), and space file transfer (layer 6), as shown in Fig. 2a.

Although the current protocol stack seems viable, there is also a need to make the protocol stack adaptable to different environmental changes, allowing integration of highly optimized regional network protocols. For example, the protocols used for the Earth and Mars are different, as shown in Fig. 2a. As a result, a proposed protocol stack [5] for future space exploration is described. There is ongoing research on making the stack adaptable with the perceived capabilities.

A Delay-Tolerant Networking Protocol Stack

The ability to integrate highly optimized regional network protocols is the objective of the future space/ground protocol stack developed by the Delay-Tolerant Networking Research Group (DTNRG) [5]. The protocol stack relies on a middleware layer called the *bundle layer* [4, 5] that resides between the application and the lower layers. The bundle layer resolves intermittent connectivity, long and variable delay, asymmetrical data rates, and high error rates by using a store-and-forward mechanism similar to email. It sends a bundle of message fragments to the next-hop node with per-hop error control, which increases the probability of data transmission. The DTN future space/ground protocol stack with the bundle layer is illustrated in Fig. 2b.

The bundle layer consists of many services such as bundle routing, bundle custody transfer, bundle end-to-end reliability, bundle authentication, and bundle encryption, which are currently underway and should be ready by the middle of this decade [4, 5].

Physical Layer Technologies

The physical layer is mainly responsible for frequency selection, carrier frequency generation, signal detection, modulation, and data encryption. Most of the significant challenges for the realization of the IPN Internet exist due to the physical layer issues.

The IPN Backbone Network

Wireless communication systems depend on radiated RF energy, which is subject to spreading loss. This problem leads to significant signal power degradation over very long distance deep space links. In addition to this, the signal-to-noise ratio (SNR) requirement to reliably decipher the received symbols amplifies the problem. One possible approach is to increase the radiated signal power via high-power amplifiers such as traveling wave tubes (TWTs) or klystrons, which can boost output power up to several thousand watts. However, this comes at the expense of increased antenna size and cost, and power problems for remote deep space nodes.

NASA's deep space network (DSN) is designed to operate in the S- and X-bands (2 GHz and 8 GHz, respectively) with 70 m antennas used for spacecraft telemetry, tracking, and command for deep space missions. The new 34 m antennas being designed to operate at the Ka-band (32 GHz) will improve the data rate over currently achievable X-band frequencies [6]. On the other hand, despite their current technological immaturity, due to much higher data rates, and reduced mass, size, and power requirements, optical communication technologies will also be employed to achieve high data rates in the IPN Internet backbone links [2, 7]. However, the deployment of optical communication technologies for the IPN Internet still remains largely unexplored.

On top of the RF backbone technology, carrier frequency selection and RF modulation schemes for different space missions have been recommended by the CCSDS [8]. Furthermore, several channel coding schemes have been studied and recommended by the CCSDS for the deep space channel, including basic convolutional, punctured convolutional, concatenated, and turbo codes to be used based on the performance requirements of the specific space mission [8]. However, due to their high coding gain, compliance with CCSDS recommendations, and reduced receiver complexity, turbo codes are mostly studied as a channel coding scheme at the physical layer of the deep space channel.

The Planetary Network

The most important challenge in the design of physical layer technologies for the communication nodes in planetary surface networks is their physical limitations (e.g., size, mass, and power constraints). Therefore, for planetary satellite and surface networks, novel physical layer technologies need to be developed such as small volume, mass, and low-power RF receivers and transmitters operating over the UHF, X-band, and Ka-band frequency regimes; and low-power infrared for planetary surface communications.

Open Research Issues

Open research issues in the physical layer technologies are summarized as follows:

- **Signal power loss**: Powerful and size-, mass, and cost-efficient antennas and power amplifiers need to be developed to minimize the effects of the spreading loss.
- **Optical communications**: Optical communication technologies should be researched for possible application to the IPN backbone network.
- **Hardware design**: Low-power low-cost transceiver and antennas need to be designed for planetary networks.
- **Modulation schemes**: Simple low-power modulation schemes need to be developed for the communication nodes in planetary surface networks.

Due to its high coding gain, compliance with CCSDS recommendations, and reduced receiver complexity, Turbo codes are mostly studied as a channel coding scheme at the physical layer of the deep space channel.

Data Link Layer Issues

The data link layer is mainly responsible for the multiplexing of data streams, data frame detection, medium access, and error control. It performs transmission of the upper-layer protocol data units over the physical space channel.

Medium Access Control

Medium access control is required in the data link layer to accommodate multiple nodes sharing the same transmission medium by utilizing network resources with maximum efficiency and minimum contention. We explore the issues pertaining to MAC separately for the IPN backbone network and planetary networks.

The IPN Backbone Network — The challenges posed by the IPN backbone link for the MAC layer protocols can be summarized as follows:

Very long propagation delay: The IPN backbone links have extremely high propagation delays.

Physical design change constraints: The MAC protocols should be designed such that minimum physical or hardware changes are necessary at the controllers in space.

Topological changes: Due to possibly frequent topology changes, MAC protocols need to accommodate reconfigurability and dynamic access control mechanisms.

Power constraint: The limitation in power requires stringent use of memory, processing, and communication powers, which require power-efficient MAC designs.

Extensive performance evaluation is yet to be performed to assess the suitability and performance of the fundamental fixed channel assignment based MAC schemes including frequency-division multiple access (FDMA), time-division multiple access (TDMA), and code-division multiple access (CDMA) and their variants in the IPN Internet. On the other hand, *In order to further strengthen the ARQ mechanism over the InterPlaNetary Backbone links with very long propagation delay, the virtual channels are protected by Reed Solomon forward error correction codes.*

the link layer for the deep space long-haul links has been addressed thus far by the *packet telecommand* and *packet telemetry* standards [8] established by the CCSDS. Packet telecommand incorporates the *virtual channelization* method, which is responsible for the MAC layer functionalities. Virtual channelization allows various sources to be virtually granted exclusive access to the physical channel by assigning them transmission capacity on a frame-by-frame basis.

Planetary Networks — For planetary networks, the MAC protocols proposed for satellite communications can be used at planetary satellite networks with proper modifications and improvements. The MAC layer issues for the planetary surface network, on the other hand, could be addressed by incorporating the existing MAC protocols for mobile ad hoc networks and wireless sensor networks [2]. However, these solutions need proper modifications and improvements to address the heterogeneous networking environments of the planetary networks.

The Proximity-1 link layer protocol [8] is currently being developed by the CCSDS as a bidirectional data link layer protocol specifically designed for short-range communications between surface vehicles and planetary orbiters in the planetary satellite network. The MAC sublayer of Proximity-1, which is one of five protocol sublayers, is responsible for the establishment and termination of each communication session and for any operational changes in the physical layer configuration [8]. Although the protocol specification includes some procedures for contention management of multiple orbiters, further research is required to obtain a concrete solution that addresses the medium access problems of planetary networks in the IPN Internet.

Error Control

Another important function of the data link layer is the error control of transmission data. Typical error control mechanisms fall into two classes: Automatic Repeat Request (ARQ) and forward error correction (FEC). Here, we explore the currently proposed error control techniques and their shortcomings for IPN backbone and planetary networks.

The IPN Backbone Network — All NASA missions, including Earth orbit and deep space, design their RF systems to provide 10^{-5} or better bit error rate (BER) after physical link coding [9]. Hence, the data link layer and its error control/correction capabilities play a crucial role in the overall performance of deep space communications for both data and multimedia traffic delivery.

On top of the channel coding mechanisms standardized by the CCSDS [8], the packet telecommand standard of the CCSDS seeks to achieve link-layer reliability by providing a *Go-Back*-n frame retransmission protocol, known as the *Command Operation Procedure* (COP) [4]. However, COP is mainly designed to address short-range communication links. In [8] the *advance orbiting systems* recommendation by CCSDS includes a *space link ARQ protocol* (SLAP) for handling link layer issues of space missions. SLAP performs ARQ link layer protocol over created virtual channels. However, in order to further strengthen the ARQ mechanism over IPN backbone links with very long propagation delay, the virtual channels are protected by Reed Solomon FEC codes.

PlaNetary Networks — Due to the similarities between planetary satellite network links and terrestrial satellite channels, the FEC schemes proposed for terrestrial satellite links can be applied to planetary satellite networks.

As planetary surface networks are composed of several mobile and static wireless ad hoc and sensor networks, the error control solutions proposed for terrestrial wireless, wireless sensor, and ad hoc networks are possible candidates for this environment. In this respect, ARQ is a viable option due to its low-delay access links. However, ARQ alone may lead to significant communication inefficiency in the presence of high link errors due to harsh space environments and atmospheric effects. Furthermore, the scarcity of power resources at remote communication nodes such as sensors, landers, and rovers require specifically tailored FEC schemes that have high energy efficiency as well as powerful correcting capability. Hence, hybrid ARQ schemes with simple encoding techniques that enable easy decoding might be preferred as energy-efficient solutions for planetary surface networks.

Open Research Issues

The key open research issues for the link layer problems can be summarized as follows:

MAC for the IPN backbone network: New MAC protocols should be devised that can accommodate extremely-long-delay IPN backbone links as well as high link errors.

MAC for planetary networks: New and preferably adaptive MAC protocols need to be developed in order to maintain seamless communication for reliable data and time-sensitive multimedia flows throughout the planetary surface and satellite networks.

Error control schemes: New and very fast FEC schemes, new adaptive error control schemes, and hybrid ARQ mechanisms need to be researched to achieve unified efficient error control in planetary networks and planetary surface networks, respectively.

Cross-layer optimization: Interactions between the link layer and physical, network, transport layers should be exploited to the fullest while developing MAC protocols and error control techniques as well as network and transport layer solutions. Furthermore, the optimal packet size for the data link layer should be investigated to minimize overhead and maximize link utilization in the IPN Internet.

Network Layer Issues

In the IPN Internet architecture as shown in Fig. 1a and b, end-to-end communication includes identifying the communicating endpoints, as well as the routing in the IPN backbone network, planetary networks, and IPN external networks. While the existing routing protocols for mobile ad hoc and sensor networks can be applied to IPN external networks, there are significant challenges that necessitate specifically tailored solutions for routing in other parts of the IPN Internet. In the following sections, the design issues of naming and addressing in the IPN Internet, and routing in the IPN backbone network and planetary networks are explored.

NAMING AND ADDRESSING

In today's Internet, addressing is used for routing purposes. The matching of global unique destination addresses in a router's local forwarding table gives the next-hop address. Naming is applied to make the addressing easier for humans. Naming/addressing translation is done through domain name server (DNS) services. *Tiered naming and addressing* [5] is proposed to address the challenges in employing DNS in the IPN Internet with long delay links. A *name tuple* identifies a communicating entity and comprises two variable-length portions: {`region ID`, `entity ID`}. The `region ID` identifies the entity's region and is known by all regions in the IPN Internet. The `entity ID` is a name local to the entity's region and is treated as opaque data outside this region. The resultant *late binding* avoids having a universal name-to-address binding space and preserves a significant amount of autonomy within each region.

Tiered naming and addressing enables new regions with new naming and addressing systems to be added with no impact on previously deployed nodes, and keeps DNS translation efficient in the IPN Internet. It is suggested in [5] that the names be directly used to identify objects. For addressing in the IPN Internet, the objective is to make it as compatible as possible with existing IP technologies. Therefore, Internet address space is used in [8] to identify the objects.

To support end-to-end communication in the IPN Internet, the expected new universal addressing scheme should perform the following functions:

- Locate the elements in a hierarchical way in the IPN Internet architecture; support efficient routing through different subnetworks and under node movement.
- Allow the IPN Internet to expand while maintaining the addressability of previously deployed elements.
- Allocate and retrieve addresses dynamically.

THE IPN BACKBONE NETWORK

The IPN backbone network in Fig. 1a provides data delivery across interplanetary distances to support deep space exploration.

Challenges and Related Work — The main challenges that affect network layer design in the IPN backbone network are as follows:

Long and variable delay: In networks with extremely long propagation delays, routing protocols most severely affected are the distributed algorithms that require timely dissemination of state to avoid route inconsistency. The movement of nodes in the IPN backbone network adds to delay variation.

Intermittent connectivity: Intermittent links cause several challenging problems: determining the predicted time and duration of intermittent links and the degree of uncertainty of these estimates, obtaining knowledge of the state of pending messages, scheduling their transmission when the link becomes available, and abandoning the wait for a predicted link.

Space Communication Protocol Standards — Network Protocol (SCPS-NP) by CCSDS [8] is proposed as a scalable network protocol for in-space routing through space networks. To allow designers to accommodate differences from one mission to another, SCPS-NP employs a scalable bit-efficient header using a technique called *capability-driven header construction* to reduce the transmission overhead. The format of the packet header is based exclusively on the protocol's capabilities required for each particular datagram. Routing tables can be configured either statically, centrally, or locally. In addition, a *selectable routing* method is used for datagrams with different priorities. However, a detailed routing algorithm is lacking in SCPS-NP to deal with the above-mentioned challenges in the IPN backbone network.

The IPN Internet can be regarded as a special type of the DTN discussed earlier. To deal with the intermittent property of IPN backbone links, the *tiered routing* mechanism [5] uses both current and expected connectivity information. Specifically, routes through the IPN backbone network comprise a sequence of *contacts* that indicate the duration, endpoints, and forwarding capacity of a link in the topology graph. A future network topology consisting of contacts is estimated. If an episode of connectivity does not occur as expected, rerouting is conducted accordingly.

Open Research Issues — Despite some protocols proposed for routing in the IPN backbone network, the following research issues need further exploration:

Distribution of topology information: One-hop link state information and a distance-vector type of aggregation beyond one hop can be maintained to obtain a probabilistic view of the overall topology. Moreover, the trajectory and velocity information of backbone nodes can be distributed to help make routing decisions.

Path calculation: Optimal path selection and transmission are difficult due to the temporal nature of the topology graph and the nonnegligible link transit time. Hop-by-hop routing is expected using incomplete topology information and probabilistic estimation.

PLANETARY NETWORKS

Routing in planetary networks is necessary to achieve end-to-end communication between Earth and outer space planets. It also integrates local planetary components to realize autonomous communication and control.

Challenges and Related Work — The challenges for routing in the planetary network are:

Extreme power constraints: Space elements mainly depend on rechargeable batteries using solar energy. Therefore, power availability is of overriding importance.

In networks with extremely long propagation delays, routing protocols most severely affected are the distributed algorithms that require timely dissemination of state to avoid route inconsistency.

Because of the extreme long delay from the Earth control center to outer-space planets, autonomous control and local coordination is required to maintain network connectivity, make timely local decision based on the temporal conditions.

Frequent network partitioning: The network can be partitioned due to environmental factors, such as meteoroid showers, high electro-magnetic radiation, sand storms, and node malfunction.

In respect to data delivery in a network experiencing frequent partitioning due to sporadic or constant disconnection, a number of research efforts have arisen recently. *Epidemic routing* [10] relies on *carriers* to carry messages between disconnected portions of the network through node mobility. The *MULE architecture* [11] adds an intermediate layer of mobile nodes to the existing relationship between sensors and access points used in typical sensor network designs. MULEs collect data from fixed sensor nodes and later transfer to access points in a store-and-forward manner. These ideas can be leveraged in planetary surface networks for routing during periods of disconnection.

Since space exploration missions may be carried out on different parts of a planet, the planetary surface network may be divided into several physically disconnected subnetworks where each belongs to a community region as shown in Fig. 1b. One possible way to resume the connection between partitioned domains is through the satellite connections. This calls for the use of satellites in the planetary satellite network to assist surface communications and node reconfigurations. Support for surface network topology maintenance is lacking in the routing protocols proposed in terrestrial satellite IP networks.

Because of the extremely long delay from the Earth control center to outer space planets, autonomous control and local coordination is required to maintain network connectivity and make timely local decisions based on the temporal conditions. The *Sensor Web* project [12] poses an interesting approach to realize coordination and information sharing among multiple sensor nodes. Different from sensor networks, a sensor web allows information gathered by one sensor to be shared and used by other sensors, so sensor webs can react and modify their behavior on the basis of collected data. Sensor webs can be used together with orbital spacecrafts to adaptively adjust the monitoring spatial scales between those of a lander to those of an orbital platform. Therefore, the *sensor web* is a very promising concept that can be exported to planetary networks.

Open Research Issues — The following are some of the key issues to realize autonomous and reconfigurable planetary networks.

Routing support from satellites: In order to support end-to-end routing between the Earth and outer space planets, as well as between community regions within planetary surface networks, network integration of routing protocols through the satellites and protocol support from the satellites need to be investigated.

Topology maintenance and Reconfiguration: The frequent network partitioning in a planetary surface network calls for network reconfiguration mechanisms to reconstruct network topology.

Power efficiency: Power availability at each node and overall network power efficiency should be considered in routing decisions.

Transport Layer Issues

Transport layer functionalities are necessary for both reliable transfer of scientific data and timely delivery of multimedia information in the IPN Internet. Among the architectural elements of the IPN Internet, the IPN backbone network poses the most challenging problems for reliable data and multimedia transport in the IPN Internet as outlined below:

Very long propagation delays: The end-to-end round-trip time (RTT) for the Mars–Earth communication network varies from 8.5 to 40 min according to the orbital location of the planets. Similarly, the end-to-end RTT from Jupiter and Pluto to Earth vary between approximately 81.6 to 133.3 min and between 593.3 to 1044.4 min, respectively.

High link error rates: The raw BERs on the IPN backbone links are on the order of 10^{-1}.

Blackouts: Periodic link outages may occur due to orbital obscuration with loss of line of sight because of moving planetary bodies or spacecraft.

Bandwidth asymmetry: Asymmetry in the bandwidth capacities of the forward and reverse channels is typically on the order of 1000:1 in spacecraft missions.

The existing transport layer protocols proposed for terrestrial, satellite, wireless, and ad hoc networks with appropriate modifications and improvements can be applied to IPN external networks and planetary networks as shown in Fig. 1a. However, the above challenges posed by the IPN backbone network need new specifically tailored transport layer solutions.

Reliable Data Transport in the IPN Backbone Network

Related Work — The challenges posed by the IPN backbone links need to be addressed in order to meet the communication requirements of deep space missions and realize the IPN Internet. However, the existing reliable transport protocols have been shown to achieve very poor performance in deep space communication networks. The dominant factor in this performance degradation is the extremely high propagation delay in deep space links. This is solely due to the window-based mechanism used by the current TCP protocols. Although there are transport protocol solutions proposed for satellite links [13], these solutions cannot be directly applied to the IPN backbone network because of the extremely high propagation delay and the other challenges mentioned above.

Space Communications Protocol Standards-Transport Protocol (SCPS-TP) [8] is a set of TCP extensions developed by the CCSDS. SCPS-TP mechanisms are basically a combination of existing TCP protocols with some modifications and extensions to address link errors, bandwidth asymmetry, and link outages, which are shown to be inadequate to addres the challenges in the IPN backbone network. The CCSDS File Delivery Protocol (CFDP) [8] has also been developed for reliable file transport over space links. In [5], as mentioned before, the bundling approach, which performs a custody-based *store-*

and-forward approach, is introduced to address the intermittent connectivity, large and variable delays, and high BERs. Although this approach achieves reliable transport over intermittent links, it still requires a specifically tailored transport protocol for high-performance bundle transport between two IPN Internet nodes.

In [14] a reliable transport protocol, TP-Planet, for the IPN backbone network is introduced. Two novel algorithms, Initial State and Steady State, constitute the structure of TP-Planet. Initial State replaces the inefficient slow start algorithm in order to capture link resources in a very fast controlled manner. In Steady State a new congestion detection and control mechanism is deployed to minimize erroneous congestion decisions due to high link errors. TP-Planet deploys a newly developed end-to-end rate-based additive-increase multiplicative-decrease (AIMD) congestion control, whose AIMD parameters are adjusted to compensate for throughput degradation. In order to reduce the effects of blackout conditions on throughput performance, TP-Planet incorporates a Blackout State procedure into protocol operation. Bandwidth asymmetry is addressed by the adoption of delayed selective acknowledgment (SACK) options. It is shown in [14] via simulation experiments that TP-Planet significantly improves the throughput performance and addresses the challenges in the IPN backbone network.

Multimedia Transport in the IPN Backbone Network

Audio and visual information including planet images are one part of the aggregated traffic in the IPN backbone network. Control of multimedia traffic is an important problem, because uncontrolled multimedia traffic not only can congest the network, but can also cause unfairness and starvation for other data traffic.

Challenges — In addition to the challenges for reliable data transport in IPN backbone networks described earlier, there are the following additional challenges due to the unique requirements of multimedia transport:

Bounded jitter: Multimedia traffic has strict requirements on bounded variation of the end-to-end delay (i.e., jitter), because it can cause problems in reconstructing multimedia.

Minimum bandwidth: Most multimedia applications require minimum bandwidth in order to maintain minimum perceived media quality.

Smooth traffic: Abrupt and frequent fluctuations in the media rate can cause significant degradation in received media quality.

Error Control: Despite the existing error resilience techniques, compressed video is still highly sensitive to data loss and requires efficient error control mechanisms due to high link errors in the IPN Internet.

Related Work — Many multimedia transport protocols are proposed to control the flow of multimedia traffic in terrestrial networks. These proposed protocols can be categorized mainly into two types of rate control schemes, AIMD-based and equation-based.

AIMD-based rate control schemes are TCP-compatible; that is, they follow TCP behavior to conservatively update the sending rate based on feedback information. However, all of these existing AIMD-based rate control schemes are developed based on the assumption that the propagation delay is relatively short, which does not hold in the IPN backbone network links. Moreover, the AIMD schemes cause abrupt and frequent fluctuations in the media rate in the form of a sawtooth pattern, which is not suitable for most multimedia applications.

Equation-based rate control schemes are proposed to provide relatively smooth congestion control for multimedia traffic by adjusting the transmission rate using the throughput estimate of the corresponding TCP counterpart experiencing the same packet loss rate and RTT. Although the use of the TCP response function for throughput estimate ensures long-term fairness, the steady-state throughput model of a TCP source is highly sensitive to RTT values, which prevents equation-based schemes from achieving high link utilization in the IPN backbone network links with extremely high propagation delay.

RCP-Planet [15] is proposed to address the challenges of the rate control problem for multimedia traffic in the IPN Internet. RCP-Planet consists of two novel algorithms, *Begin State* and *Operational State*. In Begin State, an RCP-Planet source conservatively sets the initial media rate to be the minimum media rate required by the application in order not to inject too many packets into the network. Based on a novel rate probing mechanism, RCP-Planet deploys a new rate control scheme to update the media rate smoothly and conservatively in Operational State. In order to recover packet losses due to link errors and congestion, tornado codes are used for packet-level FEC because of their very low encoding and decoding times. Furthermore, FEC block-level ACKs are used to address bandwidth asymmetry problems. Apart from that, the blackout state is incorporated into RCP-Planet to improve performance in blackout conditions.

Open Research Issues

The open key research issues regarding transport layer problems in the IPN Internet are as follows:

Transport protocols for planetary networks: The performance of the current transport layer solutions for terrestrial satellite, wireless ad hoc, and sensor networks, and the required modifications and improvements should be researched for planetary satellite and surface networks.

Extreme interplanetary distances: Performance of the existing proposed solutions over the links with extreme distances, such as Jupiter and Pluto, that have intermittent connectivity within an RTT period needs to be evaluated, and proper modifications and improvements should be performed if necessary.

End-to-end transport: Extensive performance comparisons between end-to-end solutions and store-and-forward approaches should be performed. Furthermore, possible extensions of the existing proposed solutions and new adaptive transport protocols for end-to-end transport should be further investigated.

Many multimedia transport protocols are proposed to control the flow of multimedia traffic in terrestrial networks. These proposed protocols can be categorized mainly into two types of rate control schemes, AIMD-based and equation-based.

Mission Name	Schedule	Description and Objective
Deep Impact	December 2004	To investigate the interior of the comet, the crater formation process, the resulting crater, and any outgassing from the nucleus, particularly the newly exposed surface.
Mars Reconnaissance Orbiter	July 2005	To study Mars from orbit, perform high-resolution measurements. and possibly serve as a communications relay for later Mars landers until about February 2010.
New Horizons	January 2006	To fly by Pluto and its moon Charon and transmit images and scientific data back to Earth. The mission will continue to return further data from Kuiper Belt Objects.
Dawn	May 2006	Orbit two of the largest asteroids, Ceres and Vesta, in our solar system. The objective is to return a wide range of scientific data from these asteroids.
Kepler	October 2006	Search for terrestrial planets (i.e., similar to Earth) using a telescope equipped with the equivalent of 42 cameras to monitor the stars.
Mars 2007	Late 2007	Orbiters, Netlanders, Scout Missions: The French Space Agency mission to launch a remote sensing orbiter and four small Netlanders to Mars. Also, an Italian Space Agency mission to launch communications orbiter to link the Netlanders and future missions. Scout missions to Mars including returning samples of Mars atmosphere, networks of small landers, orbiting constellations of small craft, and a rover.
Mars 2009	Late 2009	Smart Lander, Long Range Rover, and Communication Satellite to perform many long-duration scientific studies of Mars.

Table 1. *Future interplanetary mission timeline.*

IPN Internet Applications

The IPN Internet will provide communication services for scientific data delivery and navigation services for explorer spacecraft and orbiters of future deep space missions [2]. Many of these future planetary missions, which will be performed by the international space organizations such as NASA and European Space Agency (ESA), have already been scheduled for the next decade. Some of these missions are summarized along with their timelines and objectives in Table 1.

As shown in Table 1, all of these future space missions have a common objective of scientific data acquisition and delivery, which are also the main possible applications of the IPN Internet [1]:

Time-insensitive scientific data delivery: The main objective of the IPN Internet is to realize communication between in-space entities allowing large volumes of scientific data to be collected from planets and moons.

Time-sensitive scientific data delivery: This type of application is required to deliver great volumes of audio and visual information about the local environment to the Earth, in situ controlling robots, and eventually in situ astronauts [1].

Mission status telemetry: The status and health report of the mission, spacecraft, or landed vehicles could be delivered to the mission center or other nodes. This application requires periodic or event-driven unreliable transmission services.

Command and control of in situ elements: The closed-loop command and control may involve indirect or multihop communication of remote nodes (the Earth station controls the mission rover on the planet surface) or close proximity nodes (the planetary orbit controls the lander).

Thus far, these communication requirements of deep space missions have been addressed by NASA's Deep Space Network (DSN). However, it is clear that the IPN Internet is expected to extend current space communications capabilities to a point where the boundaries between terrestrial and space communications become transparent. The experiences obtained from the DSN help us to understand the unique challenges posed by deep space communication environments. Nevertheless, new communication technologies and novel networking protocols that address the challenges and open research issues presented earlier are yet to be developed for the realization of next-generation deep space communications and hence the IPN Internet objective.

Conclusions

The vision of future space exploration involves the design and development of next-generation deep space networks, which are expected to be the Internet of the deep space planetary networks and defined as the IPN Internet. However, there are significant challenges for the realization of this vision in several aspects of the communication architecture. In this article these challenges and the current status of research efforts to address them are explored along with their shortcomings. As listed in Table 2, many researchers and several international research organizations are currently engaged in developing the required technologies to realize the IPN Internet. Despite a considerable amount of ongoing research in this direction, there still remain significantly challenging tasks for the research community to address before realization of the IPN Internet. We anticipate that this survey will serve as a building block for researchers around the world to motivate them to solve these challenging problems and help realize the IPN Internet.

Project name	Research area	HTTP location
DTN, IPN	Architecture and protocol design Bundling overlay protocol, postal class of service, security	http://www.dtnrg.org http://www.ipnsig.org
CCSDS	Transport, network, data link and physical layers Security and space file transfer	http://www.ccsds.org
SCPS	File handling (SCPS-FP), retransmission control (SCPS-TP) Data protection (SCPS-SP), networking (SCPS-NP)	http://www.scps.org
OMNI	Operating missions as nodes on the Internet Investigate Internet technologies to enable space operation	http://www.ipinspace.gsfc.nasa.gov
DSN	NASA Deep Space Network Support exploration of the solar system and the universe	http://deepspace.jpl.nasa.gov/dsn
Mars Network; Space Communications; Mobile Router	Constellation of Microsats and MARSats as a Mars "Internet" Space data delivery and distributed communication Enable continuous connectivity using Internet-based protocols for near-planetary observation and sensing spacecraft	http://marsnet.jpl.nasa.gov http://scp.grc.nasa.gov http://www.grc.nasa.gov/www/RT2001/5000/5610ivancic1.html
TDRS	Space network tracking, data, voice and video services to NASA satellites, the shuttle, international space station, etc.	http://tdrs.gsfc.nasa.gov/Tdrsproject/
Sensor Webs	An network of wireless intracommunicating sensor pods Establish a virtual presence throughout the solar system	http://sensorwebs.jpl.nasa.gov
IPN3	A group of spacecraft equipped with gamma-ray burst detectors	http://ssl.berkeley.edu/ipn3
SpI	Space Internet: Architecture and protocol design for Space Internet	http://www.ece.gatech.edu/research/labs/bwn/

■ **Table 2.** *Current research projects.*

Acknowledgment

NASA's VISION: *to improve life here, to extend life to there, to find life beyond.* NASA's MISSION: *to understand and protect our home planet, to explore the Universe and search for life, to inspire the next generation of explorers.* OUR AIM: *to point out the research problems and inspire the researchers worldwide to realize these objectives.*

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Special Issue
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Call for Papers

Scope: Next generation wireless networks are evolving to accommodate a variety of services and traffic types, including data transfer, voice, video and multimedia streaming, while allowing a user to roam within the service area of the network, or between networks without disrupting the quality of service (QoS) provided. Current wireless local area networks can provide only best-effort QoS with limited capabilities regarding mobility. Future wireless access networks must be able to guarantee predefined levels of QoS allowing the services mentioned above to be supported. Furthermore, the QoS parameters should not be exceeded during intra WLAN and WLAN – cellular handoff.

Providing QoS sufficient to support these applications over a WLAN can be a challenging task. WLANs often allow a variable number of users with heterogeneous QoS requirements to share a common radio channel, usually with limited access control, making packet delivery fluctuant and unpredictable. WLAN MAC protocols must be extended to support prioritization and bandwidth reservation in order to enable guaranteed QoS provisioning to users of wireless services. Also, user mobility, as it has been manifested in extensive studies in cellular networks, introduces a new set of QoS parameters which must be considered when designing a local area network.

Wireless Local Area Networks cover single-hop or multi-hop communications which can provide various network services within a limited service area. Research and deployment of these networks has been very rapid in the past few years, leading to the development of a number of wireless local area network technologies, like 802.11 (Wi-Fi), 802.15.3 and HiperLAN. Even though these technologies can provide high speed (broadband) wireless access to IP networks, they have significant limitations, which must be overcome for allowing seamless, scalable and stable QoS for wireless mobile users.

The goal of the special issue in IEEE Network Magazine is to publish original research and review articles which should be comprehensive to all readers, regardless of their specialty. This special issue will cover comprehensively architectures, algorithms and technologies for quality of service (QoS) and resource management in wireless local area networks (WLANs). In particular we are interested in tutorial, survey and original research articles on, but not limited to the following topics:

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- WLAN performance evaluation studies
- Consistent QoS across WLAN and 3G handover
- Service differentiation in WLANs
- QoS accounting & billing for WLAN hotspots.
- QoS provisioning, management and capacity optimization in WLANs.
- Layer 2 mobility management/support in WLANs
- Power control and management for energy-efficient WLANs
- QoS and security in WLANs

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