State of the Art and Innovative Communications and Networking Solutions for a Reliable and Efficient Interplanetary Internet

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Abstract — **In the last few years deep space exploration missions are undergoing a significant transformation as are the expectations of their scientific investigators and the public who participate in these experiences. National Aeronautics and Space Administration (NASA) and European Space Agency (ESA), recently, decided pursuing a mission to study Jupiter and its moons, and another to visit the largest moons of Saturn. Those missions need new communication and networking infrastructures able to support space exploration, to connect scientists and their instruments, and also to involve the public via common web interfaces. A possible solution is represented by the so called InterPlaNetary (IPN) Internet that introduces new challenges in the field of deep space communications.**

In that framework, the paper proposes a description of the challenging scenario, surveys its technical problems and envisages possible advanced communications and networking solutions starting from the analysis of a specific IPN architecture. In more detail, we study the network performance changes due to the nodes' movements from the communications and the networking viewpoint. It represents the main contribution of the paper and opens the doors to future advanced solutions suited to be employed in the IPN Internet.

Index Terms* — *Interplanetary Networks Architecture,, Delay Tolerant Network, Advanced IPN Node, Multicast, Link Selection.

I. INTRODUCTION

Nowadays the early exploration missions, sponsored by both NASA and ESA, are giving way to a new data-intensive era of long duration observational outposts, landed vehicles, sample returns, and multi-spacecraft fleets and constellations. These missions and the future ones will require a robust, efficient and flexible communication infrastructure able to connect earth mission centres with space elements (*Mission Applications*), scientists with remote instruments (*Scientific Applications*) and engage the public by giving them traditional Internet visibility into the space missions (*Public Applications*). This new connection capability matches the vision of the InterPlaNetary (IPN) Internet. In this view, the IPN Internet means orders of magnitude increases in data rates and highly automated communications between remote planets and Earth.

In synthesis, the purposes of this paper are:

- to survey the Interplanetary communication scenario, its characteristics, problems and existing/innovative solutions;
- to analyze a possible IPN network infrastructure, proposed in the following Section;
- to test some networking solutions applied to the Interplanetary network.

Starting from a preliminary study reported in [1] in this paper we aim to highlight the problems that compromise communications among planets, such as huge delays, limited bandwidth availability and link blackouts. In that environment, a set of partially unexplored technical solutions, aimed at connecting the IPN network reliably and efficiently, represents the starting point of the research [2]. In more detail, in this work a study of a IPN network architecture has been proposed and the extremely complex situation in which communication and networking systems operate is shown. In particular the enormous delays and the scarce available resources may compromise a communication process over that network significantly.

Furthermore, together with the study introduced previously, the paper also analyzes the possible exploitation of networking solutions, which plays a crucial role: the Multicast Transmissions [3] and the Link Selection [4]. In the former case, the necessity is due to the scarce resource availability: in case of multiple destinations of the same information, the minimization of the number of traffic flows is strictly needed. For example, if a Mission Control Centre needs to upgrade the software onboard of several IPN nodes (e.g., rovers over planets or orbiting satellites) just one traffic flows will be sent from Earth. Analogously, if a planetary image, acquired by a rover, should simultaneously reach two different ground stations on the Earth, just one copy of that image will be sent from the rover through the IPN network.

The latter considered solution, the link selection, is a network control approach, based on the employment of the Delay Tolerant Networking (DTN) paradigm [5], which allows selecting the best available IPN channel to forward the traffic flows. It is aimed at maximizing the network performance because it permits the exploitation of the best link currently available for a given IPN node that sends data traffic.

All the previously mentioned purposes of the paper are pursued in this work starting from the ongoing research activity of the authors [1].

The remainder of this paper is structured as follows. Section II introduces the general IPN network architecture and describes the network analysed in this work. Section III illustrates the essentials research challenges of the IPN environment and surveys the state of the art in the field. The simulative IPN network study concerning bandwidth availabilities, delays and link blackouts is presented in Section IV. Section V proposes an overview of possible technological communications and networking solutions for the future IPN Internet. Section VI proposes a functional architecture suited to be employed in the IPN scenario and, in particular, analyses the Multicast Transmission and Link Selection necessities with an introductive performance investigation carried out by *ns-2* simulation. Conclusions are drawn, finally, in Section VII.

II. SCENARIO

An interesting overview of IPN network architectures is reported in [2] and it is briefly synthesized in this section. As depicted in Figure 1, an interplanetary network can be split into three different sub-networks:

- IPN Backbone Network;
- IPN External Networks;
- PlaNetary (PN) Networks.

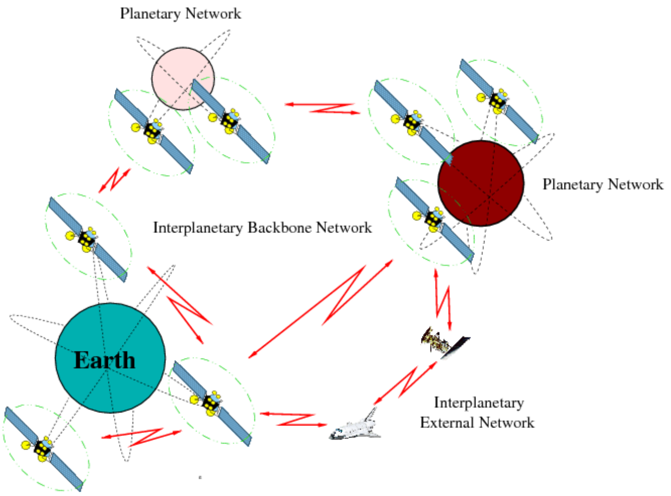

Figure 1. IPN Network.

The *IPN Backbone Network* provides a common infrastructure for communications among Earth, planets, moons, space probes and rovers through spacecrafts (e.g. satellites or orbiters), which operate as network nodes allowing transmissions over deep space channels.

The *IPN External Network* consists of nodes that are spacecrafts flying in deep space between planets, space probes, and orbiting space stations. Nodes of the IPN External Network have both long and short-haul communication capabilities. The former are employed if the nodes are at long distance from the other IPN nodes, the latter are employed at nodes flying in proximity of other ones.

The *PN Network*, depicted in Figure 2, is composed of the *PN Satellite Network* and the *PN Surface Network*. The former includes links among surface nodes, orbiting satellites and IPN Backbone Nodes, providing a relay service between surface network and backbone network and between two or more parts of the surface network. The latter provides the communication links among surface elements, such as rovers and sensor nodes which may have the communication capability towards satellites. It also provides a wireless backbone over the planet employed by surface elements that cannot communicate with satellites directly.

Concerning the *Mission Applications*, a first example is the reporting to the mission centre of astronauts' health and spacecrafts status telemetries. Another space mission application is the Command and Control of in-situ elements from Earth or from proximity spacecrafts.

Concerning *Scientific Applications*, a new approach is the so called "Virtual Presence". This type of application is intended to send great volumes of information about a monitored remote planet in order to allow scientists, or in-situ robots and astronauts to interact with high-fidelity models of the monitored area.

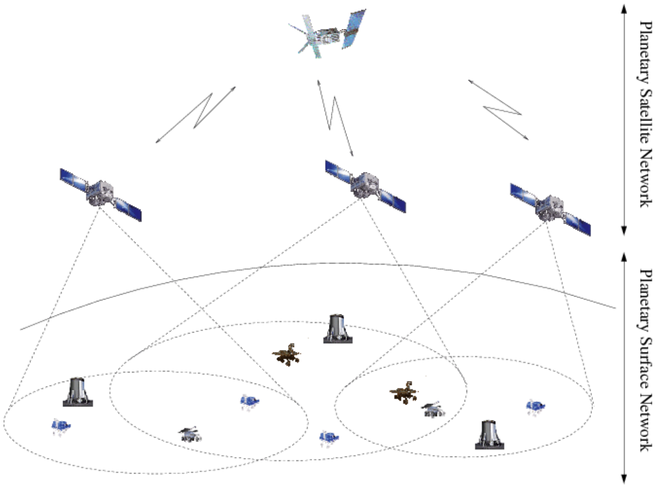

Figure 2. PN Network.

The prospective applications of a space mission, and its related communications network, can be extended beyond the mere space missions' management or the scientific applications. People surfing the Internet today access websites in extreme locations (e.g., Antarctica) and in the future they may be able to access servers on space to request data directly. This concerns the *Public Applications*. New technologies will enable communications to web servers on International Space Stations, space probes and crafts, on the Moon and other planets of the solar system.

In this paper, we utilize the previous mentioned network subdivision to define a specific IPN internet architecture able to provide connectivity between the Earth and two different PlaNetary networks. In more details, as shown in Figure 3, two PN networks are employed over a remote planet (e.g., Mars) and over the Moon. In both cases, the Surface PN network is composed of two landers (MS1 and MS2 over the remote planet and LS1 and LS2 over the Moon), able to transmit information such as images, sensed data (e.g., temperature, humidity etc.), towards the PN Satellite Network. PN satellite networks are structured with four orbiting satellites (MO1, MO2, MO3 and MO4) in the case of the remote planet and two orbiting satellites around the Moon (LO1 and LO2). Over Earth, the PN surface network is composed of six surface nodes. They are typically the destination of the information sent from remote planets and, simultaneously, the source of possible control messages transmitted towards the IPN nodes (e.g., from Mission Control Centres). In detail, Earth Surface nodes are the ones of the well-known DSN - Deep Space Network (ES1, ES2 and ES3) and other possible nodes, such as Space Science Research Centres, distributed over the planet (ET1, ET2 ET3 and ET4). Concerning the PN Satellite Network, three Geostationary satellites (GEO1, GEO2 and GEO3) have been included in the architecture. They are supposed spaced of 120° so allowing the maximum coverage of Earth surface.

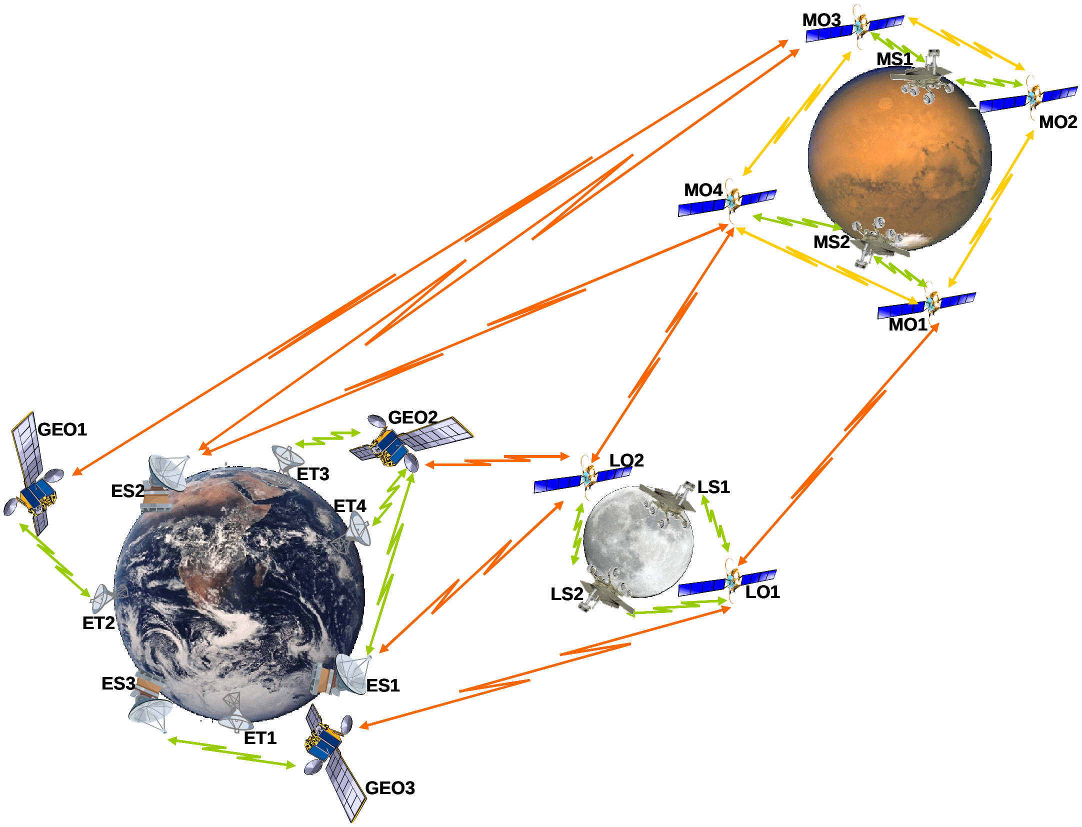

Figure 3. Example of IPN Network Architecture.

Each orbiting satellite of the IPN network has been also considered as a node of the Backbone Network. No External Networks have been considered in this architecture. All details concerning the link: available data rate, propagation delays, network movement and the consequent link blackouts, will be the object of investigation in Section IV where the simulative study of the IPN network architecture has been proposed.

III. CHALLENGES AND STATE OF THE ART

a) Challenges

From the communications viewpoint, the main problems of the IPN scenario concern: extremely long and variable propagation delays (e.g., 3-20 minutes for Mars to Earth); asymmetrical forward and reverse link capacities; high error probability; intermittent link connectivity (due to satellites, spacecraft and space probes eclipses and common link failures due to disturbances); absence of fixed communication infrastructure; attenuation of the transmitted signals due to distances; power, mass and size of communications hardware and costs, of both in terms of hardware and protocols' complexity; backward compatibility requirement due to high cost involved in deployment and launching procedures. These problems strongly compromise the reliability and the efficiency of a communications process over an IPN network and, as a consequence, the reduction of the impact of them on the communications represents the research challenge of the considered environment.

b) State of the Art

In this Sub-Section the State of the Art in the field has been surveyed and it constitutes the starting point for the solutions proposed and investigated in the following.

b1) Satellite Constellations

An important element of the IPN network architecture is the planetary satellite constellation. Generally, satellite constellations are needed instead of a single satellite, because the latter can cover only a limited portion of the Earth and only a limited number of planets [6]. On the other hand, satellite constellations can provide: simultaneous multiple coverage, continuous global coverage, continuous regional coverage or low revisit interval. Constellation design is generally a very difficult problem because each orbit has an infinite number of choices for the six orbital parameters, so for many satellites, the problem is of exceedingly high dimensionality. This is one of the primary reasons why the art of constellation design is presently suffering from a deep technology development delay. In order to solve this complex problem, satellite constellation designers adopt very limiting assumptions preventing the discovery and development of new, useful solutions. For instance, the assumption of circular orbits (e.g. Walker constellations), while simplifying the problem from one side, strongly limits the varieties of potential configurations.

b2) Physical Layers

Another hot topic in relation to IPN network concerns the physical layers. Novel physical layers are currently under investigation by considering power efficient modulation and coding schemes, the exploitation of Extremely High Frequency (EHF) bands and the employment of Ultra Wideband (UWB) communications technologies for satellite and IPN links.

In particular, the utilization of EHF bands allows obtaining a good trade-off between antenna size, bandwidth availability and path loss, [7]. They can be fully exploited in space communications and may represent an answer to the saturation of lower frequency bands, the growth of data-rate requests and the reduction of mass and size of equipment.

Ultra Wideband (UWB) communications for satellite and IPN links is another topic under investigation. The performance studies in the literature [8] concerning UWB signals over satellite links with the constraints on the received power on the Earth surface shows that, in the mentioned conditions, it is possible to achieve a data rate of 236 Mb/s.

b3) Networking Aspects

Concerning networking, traditional TCP/IP systems are not suitable for the IPN networks where transmissions are affected by very large delays and possible lack of connectivity. This does lead to exploit the DTN networking paradigm [5] in the IPN context.

As regards Transport Layer protocols, in [2] it emerges clearly that windows-based mechanisms used by the current TCP protocols, both for wired and wireless networks, achieve very poor performance in deep space communication networks, because of extremely high propagation delays. Also the TCP extensions for the space segment, such as the Space Communications Protocol Standards - Transport Protocol (SCPS-TP) developed by Consultative Committee for Space Data Systems (CCSDS), have not demonstrated to be satisfactory enough. The introduction of a bundling approach has allowed reliable transport over intermittent links. Nevertheless, a transport layer protocol, specifically tailored for IPN communication, is needed. In [9], the Licklider Transmission Protocol (LTP) is introduced for transmission of the bundles between bundling nodes. To achieve efficient routing, new mechanisms are needed. In more detail, the DTN architecture provides a framework for routing and forwarding at the bundle layer for unicast, anycast, and multicast messages that need to be exploited and enhanced. As explained in [2], also possible Data Link Layer solutions suited to be employed in the IPN Internet exist. Nevertheless, this area is vastly unexplored and open to extensive research efforts to develop innovative solutions coherent with the requirements of the IPN Internet.

b4) Network Controls

Another important topic concerning IPN networks is the reconfigurable protocol stack, which is aimed at using information from other protocol layers, and automating the communication process in extreme environments such as the IPN one. It is the principle of cross-layer design, which is envisaged again in [2] as a necessary solution for highly challenging environments. In this perspective, future extension of this work want to explicitly fill the control gap in the currently employed communications and networking solutions applied to IPN networks.

IV. IPN NETWORK ARCHITECTURE STUDY

The design of the system architecture of an IPN network concerns the definition of the number and type of required satellites and ground stations and their location/trajectory. The design of the system architecture is driven by:

- the minimization of number of events of link blackouts;
- the minimization of average duration of link blackouts;
- the minimization of point-to-point link propagation delay;
- the maximization of number of alternative routes .

The causes of blackouts can be: link obscuration between planets, situations of solar conjunctions or out of coverage. The analysis of the proposed architecture (described in Section II) has been carried out for a sample period of 24 hours and in this analysis only the former cause has occurred. It is evident that the complete study of all the events that occur in an IPN mission requires a prohibitively long sample period (many years) which should include all the possible geometric configurations of the architecture. However, in order to set up a significant and feasible simulation scenario, this 24 hours sample period has been selected so that the most important events regarding link blackouts are included.

The architecture considered in this paper is an example of a possible realization of IPN Internet with planetary networks on Earth, Moon and Mars. The proposed example represents an interesting benchmark for the comparison with more complex system architectures. Furthermore, this system architecture is here analyzed so that the performance evaluation of link parameters (i.e. availability, delay and path loss) can be used for the simulation of network protocols (as introduced in Section VI) employing *ns-2* simulator.

It is worth noting that no cable connections between ground stations have been considered and landers can only communicate with the relative planetary network of orbiters.

Furthermore, the lunar lander LS1 is positioned on the dark side of the Moon, and hence, it could not communicate directly with the Earth without using a Lunar relay orbiter. Lunar orbiters has the further task to relay the communications between Mars and Earth when direct communication is not possible.

The average blackout duration for a selected set of IPN links between external nodes is summarized in Table I.

TABLE I AVERAGE BLACKOUT DURATION FOR A SELECTION OF IPN LINKS.

Link	**Average blackout duration**	**Link**	**Average blackout duration**
LO1-GEO1	2286 s	LO1-MO1	2157 s
LO1-GEO2	2496 s	LO1-MO2	2258 s
LO1-GEO3	2170 s	LO1-MO3	1209 s
LO2-GEO1	2453 s	LO1-MO4	1209 s
LO2-GEO2	2410 s	LO2-MO1	2157 s
LO2-GEO3	2156 s	LO2-MO2	2258 s
ES1-LO1	10230 s	LO2-MO3	1209 s
ES1-LO2	8939 s	LO2-MO4	1209 s
ES1-MO1	6797 s	ES1-MO3	17198 s
ES1-MO2	6726 s	ES1-MO4	17199 s

From the values of the average blackout duration, it can be noticed that the DSN Earth station ES1 (Canberra), and hence similarly ES2 (Goldstone) and ES3 (Madrid), shows a long blackout duration of the links to the Lunar or Martian orbiters. However, this is overcome by using alternative links through three GEO satellites.

Another important aspect of the system architecture is the propagation delay. The mean value of the propagation delay is shown in Table II for a selection of IPN links. The propagation delay can be as long as 20 minutes in the case of Mars-Earth connection. However, since the shortest path from Mars to Earth (i.e. the MSx-MOy-ESz path) is not always available, in many cases the total end-to-end delay can be much higher.

TABLE II AVERAGE PROPAGATION DELAY FOR A SELECTION OF IPN LINKS.

Link	Average propagation delay	Link	Average propagation delay
LO1-GEO1	1.25 s	LO1-MO1	1210 s
LO1-GEO2	1.25 s	LO1-MO2	1210 s
LO1-GEO3	1.25 s	LO1-MO3	1210 s
LO2-GEO1	1.25 s	LO1-MO4	1210 s
LO2-GEO2	1.25 s	LO2-MO1	1210 s
LO2-GEO3	1.25 s	LO2-MO2	1210 s
ES1-LO1	1.3 s	LO2-MO3	1210 s
ES1-LO2	1.3 s	LO2-MO4	1210 s
ES1-MO1	1210 s	ES1-MO3	1210 s
ES1-MO2	1210 s	ES1-MO4	1210 s

The data rate of each link has been computed on the basis of the DVB-S2 standard and with realistic values of transmission power and antenna size [10]. The performance of the DVB-S2 standard in terms of Bit Error Rate (BER) versus Signal to Noise Ratio (SNR) E_s/N_0 follows a threshold behavior which is due to the adopted modulation and coding schemes. In fact when the SNR is lower than the required E_s/N_0 the BER is very large, while when the SNR is larger than the required E_s/N_0 the performance of the system is quasi error free ($BER=10^{-10}$) [11]. Therefore, a constant data rate has been considered. It has been computed in each link for the maximum distance (worst case) by using the lowest modulation index and code rate (i.e. QPSK 1/4) with a packet length of 64,800 bits. However, since the DVB-S2 standard foresees adaptive coding and modulation schemes and the propagation losses are highly variable, another possible approach is to consider variable data rates on the basis of the selected modulation and coding scheme for every set of propagation losses.

TABLE III DATA RATE FOR A SELECTION OF IPN LINKS.

Link	Forward link data rate	Reverse link data rate
LOx-GEOx	100 kbps	100 kbps
LOx-MOx	1 kbps	1 kbps
ESx-GEOx	10000 kbps	10000 kbps
ESx-LOx	1000 kbps	100 kbps
ESx-MOx	10 kbps	1 kbps

The parameters reported in Table I, II and III have been also employed in the performed simulations described in the following Sections.

V. COMMUNICATIONS AND NETWORKING SOLUTIONS: A GENERAL OVERVIEW

a) Topological Solutions

The first important topic to be addressed in an efficient and reliable IPN network, which suffers the problem previously described, is the design of a system of space systems such that the durations of the link unavailability and the propagation delay (i.e., the path length) are minimized. Therefore, the research, currently ongoing and object of future extension of this paper, concerns the optimization of the architecture, defining the number and type of the required satellites and ground stations and their location [6, 12]. The envisaged optimization will consider a combination of the average duration of the link unavailability and the average propagation delay and it will deal with the orbital parameters of each satellite included in the IPN architecture. In general it is possible to design a planetary satellite constellation network and a set of ground stations such that the availability of communication links is ensured, but this implies very high costs. As a consequence, a constraint on the maximum number of satellites will be fixed and the performance of the architecture in terms of link availability and propagation delay will be optimized. A new type of satellite constellations that can be used in the system optimization process is represented by the Flower Constellations set. The name Flower Constellation (FC) has been chosen because of the compatible orbit relative trajectories in the Earth-Centered Earth-Fixed (ECEF) reference frame, resemble flower petals. A FC is a set of spacecrafts characterized by the same repeating space track, a property obtained through a suitable phasing scheme [12]. The FC approach provides great flexibility and interesting dynamics. In particular, the FCs can be designed to offer dual compatibility, hence providing synchronization with both the Earth and the target planet (e.g. Mars). This synchronization can be exploited in such a way that the link availability is maximized and the propagation delay is minimized.

b) Communications and Networking.

The second scientific topic to address in the considered IPN environment, concerns advanced physical layers, networking layers and control procedures suited for application in the IPN scenario. It is worth noting that the IPN nodes will not be based on traditional Internet Protocols, but on innovative optimized protocols, though compatible with the former ones. This point has been highlighted since the origin of the IPN Internet when, at the beginning of this decade, the first short-lived IRTF “Interplanetary Internet” group was founded by Vint Cerf and a couple of internet-drafts were proposed. In particular, at the turn of 2002 and 2003 the IPN problem scope widens to “Delay Tolerant Networking” (proposed by Kevin Fall, mainly) and the concept of bundle, briefly described below in Section VI.a, was created.

The IPN nodes will include adaptive functions that will allow employing them in each part of the considered network whatever channel conditions are experienced.

TCP/IP systems are poorly suited for adoption in networks where links operate intermittently and over extremely long propagation delay. This analysis leads to propose a network architecture based on an independent middleware, the Bundle Layer, which is the key element of the Delay/Disrupt Tolerant Network (DTN) paradigm [5, 9]. This architecture uses an overlay protocol, which allows storing packets, between the application and the locally optimized protocol stacks. The overlay protocol serves to bridge different stacks at the boundaries between environments (e.g., PN Network and IPN Backbone) providing a general-purpose application-level gateway. It is the networking paradigm considered. However, it is not sufficient to offer reliable and efficient transmission over the IPN Internet because of the dynamics of the considered environment. A more insightful approach is needed for the join optimization of the bundle overlay layer and the other layers.

VI. THE IPN NODE FUNCTIONAL ARCHITECTURE

Starting from the general overview proposed previously, in this paper a functional architecture suited to be employed in IPN networks has been proposed. In this Section, moreover, the introductive performance investigation of some features of the proposed node (Multicast Transmission and Link Selection) have been included.

The envisaged IPN Node architecture is reported in Figure 4. It includes the Bundle Layer and a Higher Convergence Layer that act as bridge between two different portions: a standard stack (e.g., the TCP/IP one) used to connect common network devices to the IPN Node and the space protocol stack suited to be employed in the IPN environment. The Higher Convergence Layer will allow managing traffic flows both sent by standard and DTN-compatible hosts. It acts as adaptation layer and realizes the backward compatibility with common protocol stacks. After the adaptation phase all packets become bundles (the transmission unit of DTNs) and they are sent though specific transport and network layers designed for the space portion of the IPN network. The IPN Node transport and network protocols parameters will be adaptively optimized starting from the employed channel conditions. Data Link and Physical Layers have been again differentiated into two families: Long and Short-haul. In the former case, the lower layers solutions will be specialized for very long distance channels (e.g., between satellites of the IPN backbone). In the latter case, solutions are suited to be used in short distance channels (e.g., between spacecrafts and proximity satellites of the IPN network or between PN satellites and planet surfaces). The Lower Convergence Layer acts as selector between the Long or Short-haul layers in dependence on the position of the IPN network elements. Long and Short-haul protocols, opportunely designed for the IPN environment, allow implementing possible adaptive functionalities of the lower layers.

In the following, each layer of the IPN node has been briefly described and some considerations concerning the related open research issues have been included.

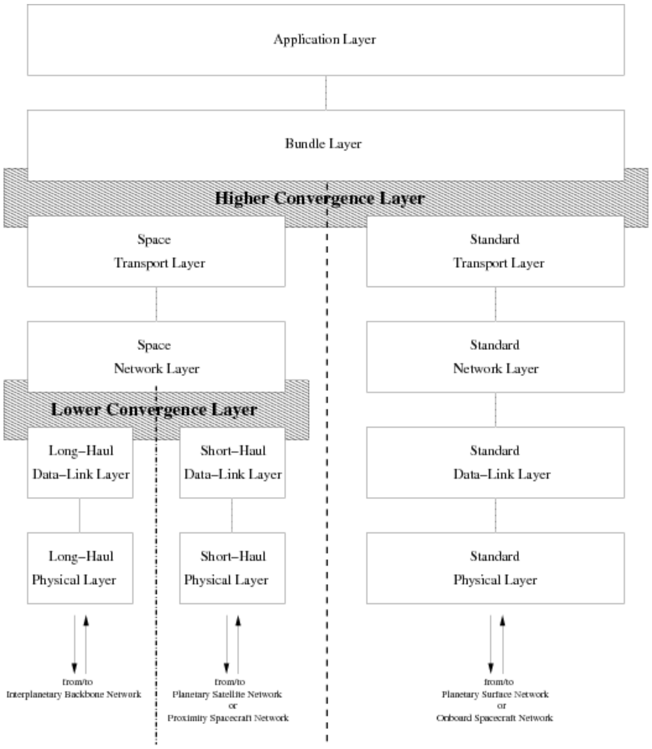

Figure 4. IPN Node Protocol Stack

a) Bundle Layer

To match the IPN environment requirements, the Bundle Layer needs to be extended. In more detail, its current specification does not include error detection mechanisms of bundles. It opens the doors to the employment of application layer coding, both in terms of source coding and error detection and recovery approaches. Other important open issues related to the Bundle Layer will be taken into account: the bundle size optimization and the related problem of fragmentation; the study and the design of common bundle layer routing approaches for the IPN environment; the Quality of Service (QoS) concept, whose meaning in the IPN network differs from the common one, together with new QoS mechanisms suited to be exploited in the considered environment.

b) Transport and Network Layers

The performance issues of the space transport and network layers represent another important research topic of the IPN node design [2]. In terms of recovery procedures and congestion control schemes, new transport protocol will be developed. For example, Additive Increase/Multiplicative Decrease concepts, able to cope with blackout events by taking advantage of probing packets will be taken into account to realize the transport layer. In turn, in the case of unavailable or strongly asymmetric return links, the transport protocol’s reliability will be ensured by using appropriate strategies based on erasure codes. The problem of congestion events occurring at deep space IPN Node will be also solved by considering call admission and flow control schemes together with effective storage routing strategies.

The IPN Node protocol stack will also support the point-multipoint applications. Multicast/broadcast transmissions will allow reaching several IPN nodes, so optimizing the resource utilization. This requires the introduction of Multicast

Transmission approaches whose possible enhancements will be object of future and extensive research.

In this sub-section some preliminary simulation results, carried out by means of *ns-2* simulator, have been provided. Performance analysis has been conducted by implementing in *ns-2* the network topology and its evolution respectively described in Figure 3 an Section IV. In particular, two different files have been used as input for *ns-2* simulator: the former providing bandwidth capacities and propagation delays of different links, while the latter giving information regarding to all the link blackouts. These files are obtained from IPN network simulative studies described in Section IV. It is worth noting that results shown in this sub-section (VI.b) are obtained utilizing the standard version of *ns-2*, where packets delivery is based on the standard internet protocols, while in the remaining sub-sections, the *ns-2* simulator has been upgrated with *ns-DTN* module introducing an *DTN-Agent* with Bundle Protocols functionalities. In more details, in the *network simulator-2* the DTN module is implemented like a transport layer protocol, defining for each DTN node an *Agent* able to manage efficiently the routing and the reliable packets delivery. Moreover, the *DTN-Agent* supports the custody transfer procedure and allows to exchange bundle protocol signaling among the different DTN nodes.

They show the impact of multicast data delivery in deep space exploration missions. In particular, it has been highlighted the advantages that could be obtained utilizing groups oriented applications respect to point-to-point transmissions in the IPN scenario.

It is worth noting that, in the depicted IPN topology, (reported in Figure 3) two different kind of Multicast Connections could be thought: (i) Multicast Forward Connections (MFC), where sources are, for instance, Earth Mission Centers and receivers are the deep space nodes; Multicast Reverse Connections (MRC), for communications from remote planets to Earth. As mentioned in the introduction, the MFC could be used for Mission Applications to provide control information and to upgrade the software implemented in the IPN nodes. While, MRC could be utilized for Scientist and Public Applications to receive planetary images, videos and experimental results acquired by space stations.

The results highlight how a multicast approach could lead to a most efficient resource management compared with Unicast techniques. For instance, considering a scenario where a terrestrial node (i.e. ES1) sends data to receivers of a multicast group located on two different planets and supposing that four receivers belong to such a multicast group (two scattered on the Moon and the other ones located on Mars) the situation is as follows. Unicast approach foresees four connections between sender and receivers; this means that the same information is sent on the channel four times. Therefore, in this case a Unicast approach increases the accesses to the links needed to forward the same packet. Clearly, such a issue is more manifest when the number of receivers increases. While, a multicast approach always foresees the same number of accesses (i.e. one each planet) regardless of the number of receivers belonging to the same multicast group. These result are depicted in Figure 5 varying the number of multicast receiver for region/planet. The obtained result demonstrates that a multicast approach in IPN networks gives the following advantages: *(i)* it reduces the links utilization, saving radio resources that could be utilized to supply transmission of further services; *(ii)* it optimizes the memorization units size (buffer size) and reduces the signalization due to acknowledgment procedures and routing.

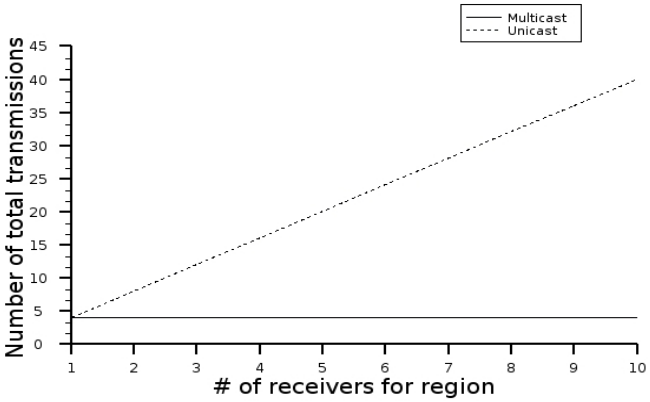

Figure 5. Number of accesses to the links varying the number of receivers per region.

The next results concern how Unicast and Multicast transmissions affect the buffer size (in terms of maximum number of packets that can be memorized) of IPN nodes. We assumed that the buffer size is equal for each IPN node. Figure 6 depicts the obtained results for a MFC connection in term of Packet Delivery Ratio (PDR).

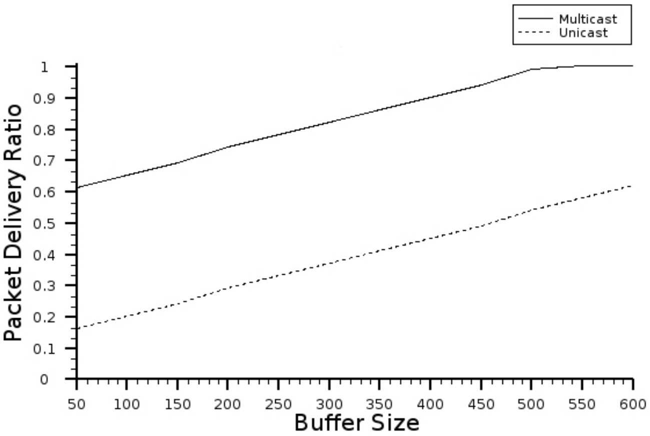

Figure 6. MCF: PDR varying buffer size.

How mentioned above Unicast transmissions foresee that the same information is sent on the channel for all the receivers. From Figure 6 such an issue affects the limits in terms of buffer size more in Unicast approach than in Multicast ones, clearly. On the other hands whether the buffer size is increased then the PDR also increases. From a buffer size equal to 500 packets (i.e. 83,4% of the overall forwarded traffic) there are not loss due to congestion of the buffers, considering multicast transmission.

In this case, the bottlenecks in the nodes MO1 and LO1 are the main reason of packets loss. Therefore, also in this case a Multicast approach improves the performances in IPN network with respect to Unicast transmission. Moreover, it is worth noting that these results have been obtained by considering unreliable traffic only. This means that a packet is removed from the buffer as soon as it is sent on the radio link. In case of reliable Multicast transmissions the propagation delays on the links have to be taken into account; they clearly can get worse the performance showed in Figure 6 in both Unicast and Multicast approach, but affecting Unicast Transmissions significantly.

Future activities are aimed to improve the performance of Multicast Transmission in IPN network implementing DTN paradigm. In particular, the research activity will deal with the following issues: *(i)* definition of procedures for notifications and registration/de-registration of multicast groups; *(ii)* definition of multicast routing protocols that utilize models based on both tree or mesh topologies, in order to minimize the path length between source and destinations and to increase the probability that the bundle is delivered to as many destination nodes as possible; *(iii)* definition of transport and bundle layers suitable to provide end-to-end reliable connections, defining efficient transmission and retransmission procedures. In this context, the storing functionalities for the store-and-forward policies have to be design in order to guarantee data persistence in DTN nodes also for relatively large time slots. For dealing with that, DTN aggregates data into bundles and stores them in persistent storage of different IPN nodes so that in case of loss of connectivity, the bundles could be retransmitted from the closest storage points rather than from the source node. A key Bundle Protocol innovation is known as Custodial Delivery. The memorization functionality in DTN nodes will be considered as a new network resource that has to be administered and protected. Fundamental open issues in the definition of a new protocol stack are related to these topics. At the moment, the Bundle Protocol specifies the procedures for supporting custodial delivery of bundles destined to unicast applications. However, it does not discuss how Custodial Delivery should be provided for bundles destined to multicast groups (multicast bundle). There is a strong motivation for using custodial multicast in IPN to preserve the already-scarce resource of bandwidth during transmission and retransmission procedures [3].

c) Data Link and Physical Layers

Data Link Layers protocols of the IPN node include functionalities concerning the medium access control (MAC) and error control functions. Also in this case, advanced network control features need to be considered and they are aimed at optimizing the utilization of IPN channels. For both Long and Short-haul physical layers, specific solutions will be studied in terms of bandwidth/power efficient modulations and low complexity channel codes with high coding gain. Waveforms design and the exploitation of Ultra WideBand (UWB) systems needs to be considered with the goal to reduce the complexity of the system and the sensitivity to IPN channels' non-linearity [8].

Also space physical layer solutions that exploit Extremely High Frequency (EHF) bands can be taken into account. EHF employment, in particular the W-band [7], represents an answer to the needs of IPN links: the saturation of lower frequency bands, the growth of data-rate request and the reduction of mass and size of equipment. Considering that the main disadvantage of the use of W-band frequencies is the atmospheric attenuation, the benefits of its employment could be fully exploited in deep space channels where the atmosphere is absent. The reduced antenna size due to the use of higher frequencies represents a further advantage of this choice.

Two important factors that should be considered when dealing with the physical layer design are: antenna pointing and energy consumption. The reduction of antenna size has a positive impact on the pointing subsystem. On the other hand, the design of the physical and link layers should constrained in terms of QoS metrics and should be optimized in terms of energy efficiency.

d) Convergence Layers

Convergence Layers, both Higher and Lower, and IPN Network Control approaches concern another group of innovative solutions, envisaged in this work, which needs to be developed. As previously said, the action of the Higher Convergence Layer is to offer a common interface to the transport layers (space and standard). The Lower Convergence Layer will offer a common interface towards data link and physical layers and vice versa and it will offer innovative control functions in terms of selection of the opportune lower layer stack (e.g., vertical handover) by considering the situation in which the IPN Node operates (long- or short-haul network segment).

e) Network Controls

In order to smooth the effect of the intrinsic heterogeneity of the IPN network, adaptive mechanisms [13], based on the cross-layer principle [2], are needed. It means that appropriate solutions are necessary to harmonize each single layer solution and jointly optimize the capabilities of IPN Node layers. For example, the transport and network protocol parameters need to be dynamically tuned in dependence on the channels and network status, which is unpredictable, and on the basis of blackouts, which are predictable due to the knowledge of the IPN Network Elements' orbits (for satellites and orbiters) and trajectories (in the case of spacecrafts and probes).

The same concept holds true for all protocol layers, also with respect to the position of the IPN Node within the IPN topology. Figure 7 reports the envisaged main blocks concerning both data and control planes and synthetically indicates the main envisaged functions of each control component.

The chosen DTN paradigm, and the developed protocol solutions jointly used with novel network control procedures will allow the optimization of the networking and communication mechanisms of the IPN Node so guaranteeing a reliable and efficient communication process over the IPN Internet.

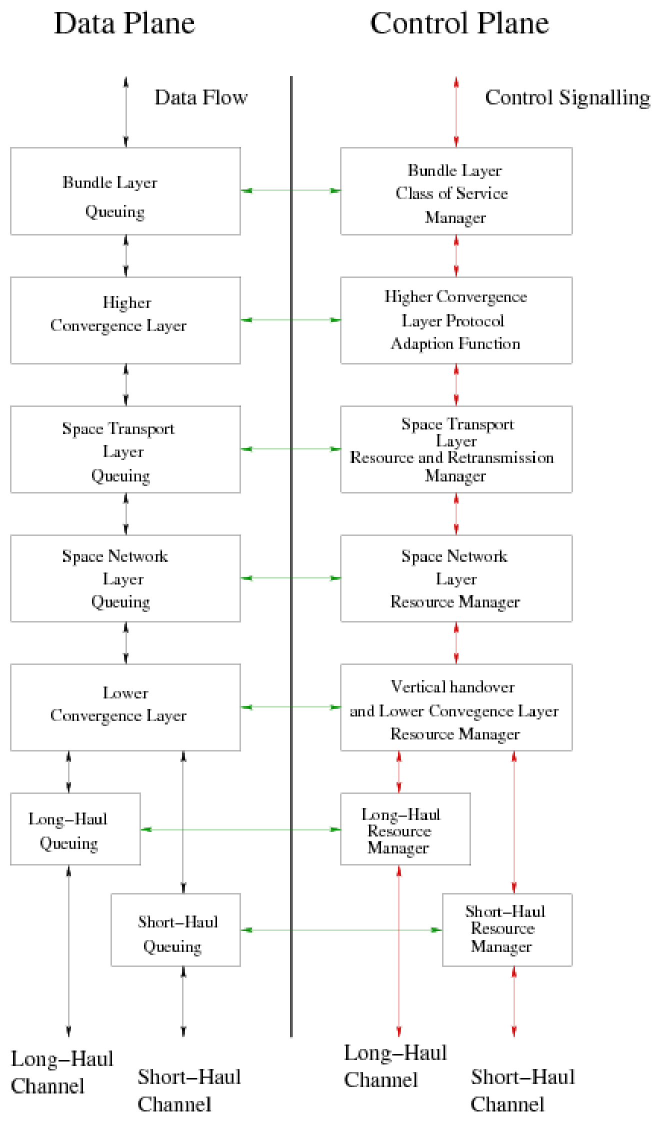

Figure 7. IPN Node Data and Control Planes.

In the set of possible Network Controls, a partially unexplored solution concerns the Link Selection strategies based on the exploitation of the Bundle Layer of the DTN paradigm. In more detail, Link Selection techniques, also called Congestion Aware Routing, have been proposed in [4] where the mathematical framework has been formalised. It has been taken as example in this paper.

In synthesis, the approaches proposed allow selecting a forwarding link, among the available ones, by optimising one or different metrics, simultaneously. In fact, in this paper, the optimization of one metric has been considered: the Bundle Buffer Occupancy (BBO). The Bundle Buffer Occupancy is the ratio between the number of bundles stored in the bundle layer buffer and the maximum size of the buffer itself. The evaluated Link Selection technique is based on its minimization.

As previously introduced, performance analysis has been conducted by taking network topology depicted in Figure 3 as reference and by considering the bandwidth capacities and propagation delays reported in the analysis of Section IV. All the link blackouts, due to IPN node movements, have been also included in the simulations whose results have been reported in the following. Moreover, each node implements a bundle layer buffer size equal to 400 bundles. Constant Bit Rate (CBR) traffic sources are considered: they are kept active for 50 s each hour of simulation and generate data bundles of 64 Kbytes at rate of 1 bundles/s, yielding 512 Kbit/s. Furthermore, in this case, the traffic sources have been set on the planetary regions, and in particular the traffic sources are the nodes MS1 and MS2 from the remote planet, LS1 and LS2 from the Moon. They send data over Earth to ET1, ET2, ET3 and ET4, respectively, which are set as receivers. The simulation duration was of 7200 s (2 hours out of 24, which is the duration of the analysis proposed in Section IV) for each test carried out by *ns-2* simulations.

The proposed results concern a macroscopic analysis of the Link Selection method's performance. It looks into performance provided by the whole network and, in this view, two metrics have been considered: Bundle Loss Rate (BLR) and Data Delivery Time (DDT) coherently with [4]. The first is defined as ratio between the number of received and of transmitted bundles. The second accounts for the time interval required to complete the data delivery to destinations. It is possible to observe, in Figure 8, the Bundle Loss Rate (BLR %) performance for each Flow where Flow1 is the data flow between LS1 to ET1, Flow2 is the data flow between LS2 to ET2, Flow3 is the data flow between MS1 to ET3 and Flow4 is the data flow between MS2 to ET4. The BLR measured highlights quite effective results. This means that a Link Selection Control (or Congestion Aware Routing) allows reaching good network performance also in challenging network as the IPN ones. In more detail, Flow1 is privileged with respect to the others. Actually, it is mainly due to the simulated period: in the first 2 hours, out of 24, the link blackouts have penalized Flow4 and, partially, Flow2 and Flow3. Moreover, Flow3 and Flow4 experience very low link capacities over the IPN network due to the very high distance between Mars and Earth.

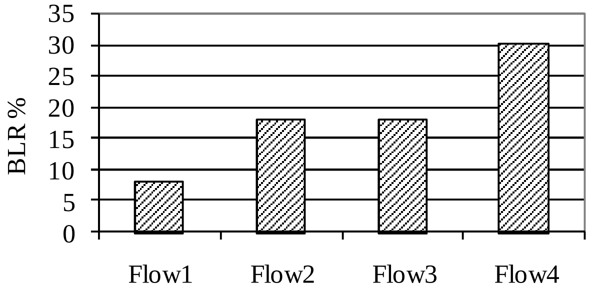

Figure 8. Bundle Loss Rate [%]

On the other hand, as far as Data Delivery Time (DDT) is concerned, it can be observed from Figure 9 that the Link Selection solution offer satisfactory performance. The shown DDT can appear very high but the enormous propagation delays and the very small available link capacities do not allow better performance. It is obvious in particular in case of transmissions from the remote planet (Mars in Figure 3): they require almost the overall time that has been simulates (about two hours). Transmission from the Moon requires about 260 [s] in average.

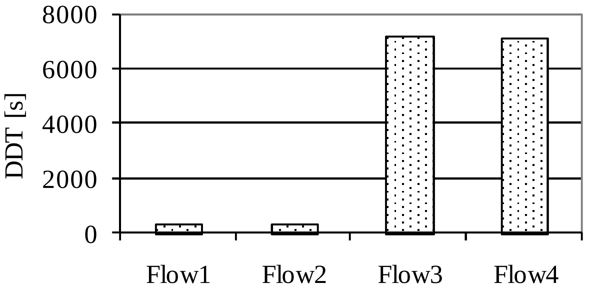

Figure 9. Data Delivery Time [s]

However, from the introductive evaluation proposed, it is worth noting that the proposed control technique have promising performance. This opens the doors to future extensions and investigations that will analyse in-depth the performance of the Link Selection over the considered network architecture.

VII. CONCLUSIONS

From the proposed IPN network analysis and the envisaged IPN node architecture, it appears clear that the technological challenges described in this paper are of great interest on a basic research perspective, and, simultaneously, let the space communications sector be strategically capable to provide future competitive services and solutions. The presented work opens the doors to new communications and networking challenges, which are the ones of the so called InterPlaNetary (IPN) Internet. In particular, the described innovative protocol solutions jointly used with novel network control procedures will allow the optimization of the networking and communication mechanisms of the network's nodes so guaranteeing a reliable and efficient communication process over the IPN Internet.

These solutions will be the object of ongoing and future research that will be developed as extensions of this work, which represents an introductive overview of them.

REFERENCES

[1] G. Araniti, I. Bisio, and M. De Sanctis, "Towards the Reliable and Efficient Interplanetary Internet: a Survey of Possible Advanced Networking and Communications Solutions", First International Conference on Advances in Satellite and Space Communications, SPACOMM 2009, Colmar, France, July 20-25, 2009.

[2] I. Akyildiz, O. E. Akan, C. Chen, J. Fang, and W. Su, "The State of the Art in InterPlaNetary Internet," IEEE Communications Magazine, July 2004 pp. 108–118.

[3] S. Symington, R. C. Durst, and K. Scott, "Custodial Multicast in Delay Tolerant Networks" Consumer Communications and Networking Conference, 2007. CCNC 2007. 4th IEEE Jan. 2007 Page(s):207 - 211.

[4] I. Bisio, T. de Cola, and M. Marchese, "Congestion Aware Routing Strategies for DTN-based Interplanetary Networks," IEEE GLOBECOM 2008, New Orleans, LA, USA, Nov.-Dec. 2008.

[5] V. Cerf, et. al., "Protocol Specification", IETF RFC 4838, experimental, April 2007.

[6] M. Lo, "Satellite-Constellation Design", IEEE Computing in Science and Engineering, vol. 1, no. 1, pp. 58-67, January 1999.

[7] E. Re, M. Ruggeri, V. Dainelli, M. Ferri, , "Millimeter Wave Technology for Moon and Mars Exploration", IEEE Aerospace Conference 2008, Big Sky (MO), 1-8 March 2008.

[8] Y. Kunisawa, H. Ishikawa, H. Iwai, and H. Shinonaga, "Satellite Communications using Ultra Wideband (UWB) Signals," Proceedings of the International Symposium on Advanced Radio Technologies (ISART 2004), March 2-4, 2004.

[9] S. K. Burleigh, M. Ramadas, and S. Farrell, "Licklider Transmission Protocol - Motivation," RFC 5325, Sept. 2008.

[10] G.K. Noreen, et al., "Integrated network architecture for sustained human and robotic exploration," IEEE Aerospace Conference 2005 (Big Sky, Montana), 5-12 March 2005.

[11] Digital Video Broadcasting (DVB), Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications, ETSI EN 302 307, v1.1.2, 2006.

[12] M. De Sanctis, et al., "Flower Constellation of Orbiters for Martian Communication", IEEE Aerospace Conference 2007, Big Sky (MT, USA), March 3-10, 2007.

[13] C. Peoples, G. Parr, B. Scotney, and A. Moore, "A Reconfigurable Context-Aware Protocol Stack for Interplanetary Communication," In proc. IWSSC 2007, Salzburg, Austria, September 2007, pp. 163-167.