The Interplanetary Network Node: Architecture and Preliminary Performance Evaluation

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Abstract. In the framework of the so called InterPlaNetary (IPN) Internet, the paper surveys possible advanced communications and networking solutions applied by a specific IPN node architecture. The proposed solutions have been preliminarily evaluated by using the ns2 simulator by considering possible network status changes due to the nodes' movements, typical in the deep space scenario. In particular, the performance study on one hand highlights the role of the Multicast and, on the other hand, it shows the effects of new possible control approaches such as the dynamic Link Selection in the IPN network. The performance study represents the main paper contribution.

Keywords: Interplanetary Networks Architecture, Advanced IPN Node, Multicast, Link Selection.

1 Introduction

The IPN Internet, described in [1] and here synthesised, is supposed to be split into different sub-networks that encounter different problems and, as a consequence, different technical challenges. The IPN includes the IPN Backbone Network, IPN External Networks, and PlaNetary (PN) Networks. The IPN Backbone Network provides a common infrastructure for communications among Earth, planets, moons, space probes and spacecrafts through satellites, 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 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

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network and between two or more parts of the surface network. The latter provides the communication links between 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.

In this paper, the study of a specific IPN network architecture has been proposed. That network, depicted in Fig. 1, is exactly composed as described previously. In more detail, three PN networks have been included in the architecture. 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).

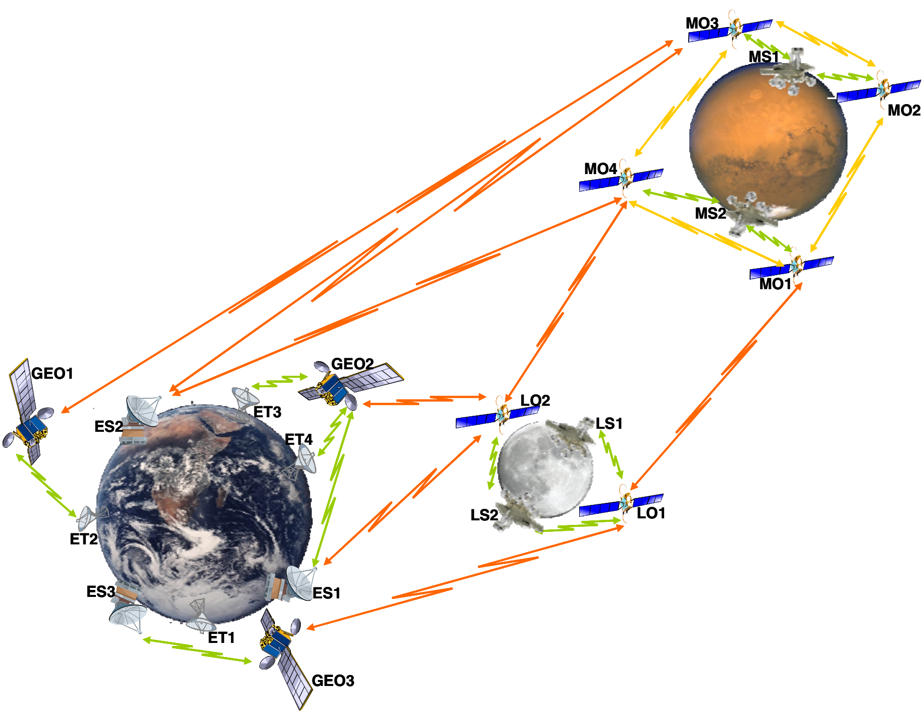

Fig. 1. Interplanetary Network Architecture

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. Each orbiting satellite of the IPN network has been also considered as a node of the Backbone Network. Satellites can exchange information each other, if a link is available among them. 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 reported in the following.

It is worth noting that this architecture, as well as the analysis reported in the following, is a synthesis of the main contributions of the paper [2] by the same authors, here reported for the sake of completeness.

The remainder of this paper is structured as follows. Section 2 reports the simulative IPN network study concerning bandwidth availabilities, delays and link blackouts. Section 3 revises a functional architecture suited to be employed in the IPN scenario and, in particular, analyses the Multicast Transmission [3] and Link Selection [4] necessities with an introductive performance investigation carried out again by *ns-2* simulation. Conclusions are drawn in Section 4.

2 IPN Network Architecture Study

The analysis of the proposed architecture (described in Section 1) has been carried out for a sample period of 24 hours and in this analysis only the former cause has occurred. The architecture considered in this paper is an example of a possible realization of IPN Internet with planetary networks on Earth, Moon and Mars and the performance evaluation of link parameters (i.e., availability, delay and path loss) have been used for the simulation of networking solutions (Section 3).

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 1.

Table 1. 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 2 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 2. 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 [9]. 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}) [10]. 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 64800 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 3. 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 1, 2 and 3 have been presented in [2] and they represent the input of the simulations performed with *ns2* and described in the following Section.

3 The IPN Node Functional Architecture

A possible functional architecture suited to be employed in IPN networks has been proposed starting from its definition originally proposed in [5]. 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 Fig. 2. 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

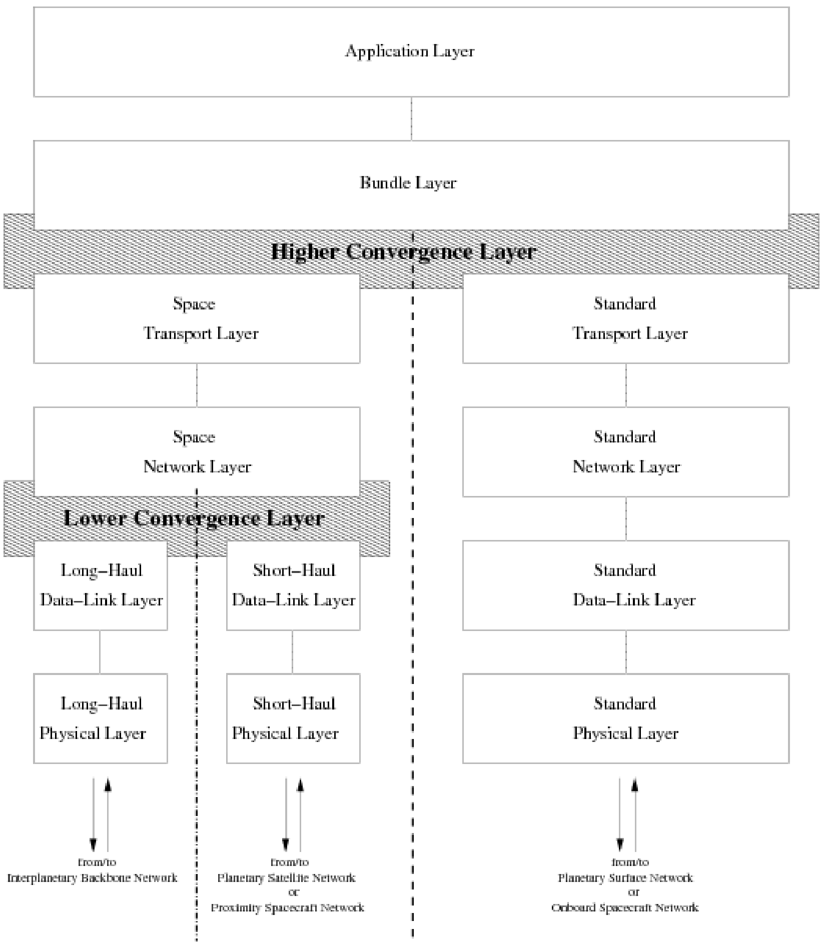

Fig. 2. IPN Node Protocol Stack

environment. The Higher Convergence Layer will allow managing traffic flows both sent by standard hosts 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.

3.1 Bundle Layer

To match the IPN environment requirements, the Bundle Layer [6] 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.

3.2 Transport and Network Layers

The performance issues of the space transport and network layers represent another important research topic of the IPN node design [1]. 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 *ns2* simulator, have been provided. 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 Fig. 1) 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.

In the following simulation campaign, the network architecture of Fig. 1 has been considered. It has been assumed, for each link, the propagation delay and data rate values reported in Section 4. 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 Fig. 3 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.

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. Fig. 4 depicts the obtained results for a MFC connection in term of Packet Delivery Ratio (PDR).

How mentioned above Unicast transmissions foresee that the same information is sent on the channel for all the receivers. From Fig. 3 such a 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.

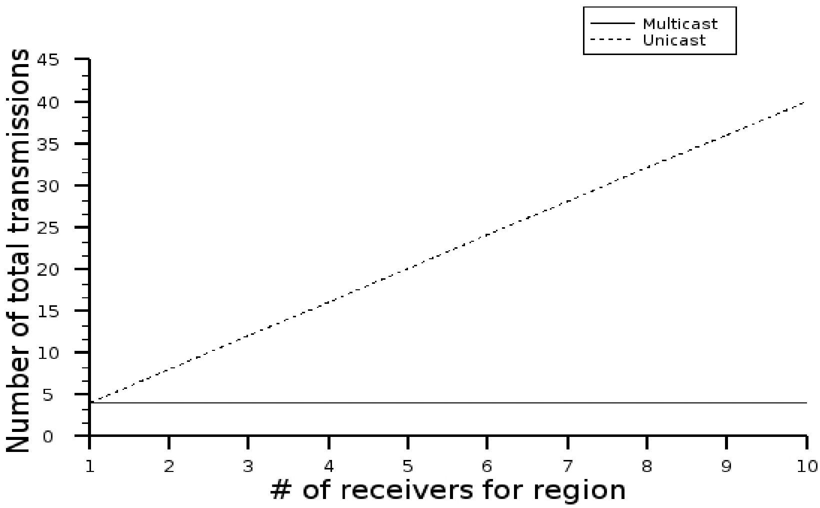

Fig. 3. Number of accesses to the links varying the number of receivers per region

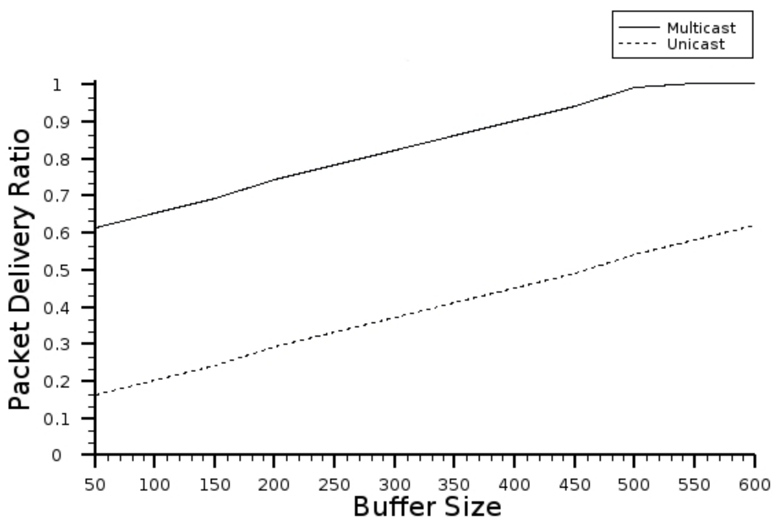

Fig. 4. MCF: PDR varying buffer size

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 Fig. 3 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 [2].

3.3 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.

Also space physical layer solutions that exploit Extremely High Frequency (EHF) bands can be taken into account. EHF employment, in particular the W-band, 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.

3.4 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).

3.5 Network Controls

In order to smooth the effect of the intrinsic heterogeneity of the IPN network, adaptive mechanisms [7], based on the cross-layer principle [1], 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 channel status. The same concept holds true for all protocol layers, also with respect to the position of the IPN Node within the IPN topology.

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.

The performance analysis has been conducted by taking network topology depicted in Fig. 1 as reference and by considering the bandwidth capacities and propagation delays reported in the analysis of Section 4. 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 4) for each test carried out by *ns2* 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 Fig. 5, 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.

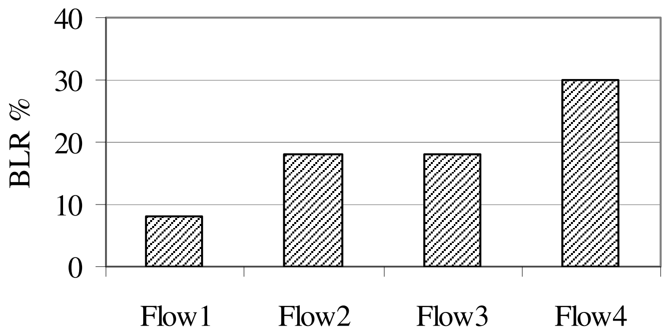

Fig. 5. Bundle Loss Rate [%]

On the other hand, as far as Data Delivery Time (DDT) is concerned, it can be observed from Fig. 6 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 Fig. 1): they require almost the overall time that has been simulates (about two hours). Transmission from the Moon requires about 260 [s] in average.

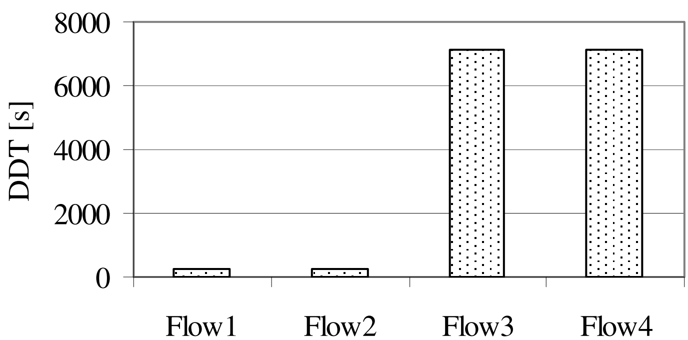

Fig. 6. Data Delivery Time [s]

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.

4 Conclusions

The presented work describes possible networking solutions jointly used with novel network control procedures that allow the optimization of the IPN network performance 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 extension of this work, which represents an introductive overview of them.

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