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DTN performance analysis of multi-asset Mars-Earth communications

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Summary
The delay-/disruption-tolerant networking (DTN) architecture is considered the key enabling technology for future space communications, as confirmed by the current standardization within CCSDS and the experiments carried out onboard the International Space Station. Despite the scientific community efforts to analyze DTN architecture performance, most of the studies have focused on individual protocols, or have considered simple test cases, thus missing a whole system view. To bridge these research gaps, this paper presents a comprehensive analysis of DTN performance in Mars-Earth communications, considering a realistic and complex end-to-end scenario, where multiple assets and multiple data flows are involved, as envisioned for future space missions. To this end, a virtualized testbed based on ION software was used for an extensive emulation campaign, focusing particularly on Bundle and Licklider Protocol interaction with the CGR routing algorithm.

KEYWORDS
Bundle Protocol, CGR, delay-/disruption-tolerant networking, interplanetary networking, Licklider Transmission Protocol

1 | INTRODUCTION

The unsuitability of the TCP/IP architecture for space environments made a few researchers at NASA Jet Propulsion Laboratory conceive a novel architecture, able to cope with long delays, deterministic intermittent contacts, and possible significant packet losses. These preliminary studies on interplanetary networking (IPN)[1] led to the definition of the delay-/disruption-tolerant networking (DTN) architecture[2] of its related bundle protocol (BP)[3] and Licklider Transmission Protocol (LTP)[4] all promoted by the homonymous Internet Research Task Force (IRTF) working group, in 2007-2008. Since then, DTN standardization for space environments has been conducted by the Consultative Committee for Space Data Systems (CCSDS) in parallel with IRTF to tailor the DTN model to specific space mission requirements.[5-7] Recently, CCSDS standardization has also included contact graph routing (CGR), a routing algorithm specifically designed to cope with the scheduled intermittent connectivity typical of space environments.[8] In the meantime, thanks to the maturity of the DTN architecture and related protocols, DTN standardization moved from IRTF to the IETF (Internet Engineering Task Force).[9]

This paper is an extended version of Alessi et al,[27] where preliminary results were presented. In the current paper, many additional results are shown, and performance analysis has been greatly extended.

The main components of the DTN architecture, namely, BP, LTP, and CGR, have continuously evolved over more than a decade, and this development has constantly been supported by studies and experiments, following or anticipating the release of draft standards or the availability of new implementations in ION, the DTN suite designed and maintained by NASA-JPL.[10,11]

Most of the DTN literature, however, has focused on the study of single DTN components, rather than the DTN architecture as a whole. In more detail, the assessment of BP and LTP protocols has mostly been aimed at performance modeling and analysis[12-14] when intermittent links and packet losses were present and/or at introducing and assessing new features[15] without exploring interactions with CGR. Conversely, routing has generally been studied alone to study its mechanisms[16] or to propose enhancements.[17,18]

Another limitation of the current literature is that only simple network configurations that were more suited to the study of specific features than to a comprehensive assessment of DTN architecture have been considered. By contrast, the most recent space exploration plans[19] envision the presence of multiple assets (several ground and space nodes interconnected) and the support of multiple services (telemetry, telecommand, sensors data, and images), in a unique system.[20]

In the DTN literature, a first attempt to consider realistic network configurations can be found in Wyatt et al[21] where the DINET experiments conducted by NASA on the EPOXI spacecraft is described. However, since this study was conducted, BP and LTP implementations have been enhanced, and CGR has evolved significantly. Other experiments, carried out by some of the present authors, consider the case of Mars-Earth communications[22] but are mainly focused on the impact of long delays and intermittent connectivity and do not require complex routing strategies. Finally, it is worth recalling the experiments carried out by the International Space Station (ISS), to prove the effectiveness of the DTN architecture in real space operations[23] by means of flight-qualified DTN software. In this case too, however, the network configuration includes only a limited number of nodes, so that routing has no impact on performance.

This paper aims to close these gaps and to provide the reader with a comprehensive analysis of DTN performance in a multi-asset interplanetary scenario, under realistic operating conditions. To this end, we consider the case of Mars exploration missions, where data communication between Mars and Earth can be accomplished through a variety of intermediate nodes connected by intermittent links of very different natures, in terms of nominal Tx speed, length, and frequency of contacts. Moreover, aiming to consider different services, the scenario in question includes many concurrent data flows specifically designed to represent real traffic from Mars to Earth, but also vice versa with different characteristics for emulation fidelity (bundle dimension, generation rate, and priorities). The variety of possible paths, links characteristics, and data flows pose real challenges to CGR and is one of the most significant aspects of the scenario considered here.

To analyze DTN performance in this Martian environment, an experiment campaign was carried out using a virtual testbed where GNU/Linux virtual machines host the full DTN protocol stack and the CGR implementation provided by ION. A selection of the most important numerical results is presented and analyzed in the paper to provide the reader with a comprehensive understanding of all networking issues that may occur in such complex networks. This analysis also allows the authors to make a few general considerations about DTN performance in space networks, from both operational and research perspectives.

The rest of this paper is organized as follows. The DTN architecture and its related protocols, BP and LTP, are briefly introduced in Section 2, while CGR is summarized in Section 3. An illustration of the Mars-Earth scenario is then presented in Section 4, where details of the network topology, traffic data flows, and link intermittency are provided. The testbed and experiment description (Section 5) introduces the performance analysis that follows in Section 6. Finally, conclusions are drawn in Section 7.

2 | DTN ARCHITECTURE

2.1 | DTN architecture essentials

The DTN architecture originated from interplanetary networking (IPN) research, when the scope of IPN was broadened to include all “challenged networks” whether terrestrial, maritime, or in space. After more than a decade, however, IPN is still the most important application environment and the main research driver. The DTN architecture is based on the insertion of the new “bundle layer,” between application and lower layers. The interfaces with lower layers (usually transport) are called “convergence layer adapters” (CLAs) (Figure 1). Although the usual Internet architecture and its related protocols are not replaced but augmented by the insertion of the bundle layer, there are many differences.[1,2,24] The following two are essential and need to be briefly recalled here.

2.1.1 | DTN as an overlay

The insertion of the bundle protocol (BP) on endpoints and some intermediate nodes splits the end-to-end path into multiple DTN hops as shown in Figure 1. The first consequence is that the scope of transport is no longer end-to-end, but instead confined into one DTN hop. This naturally recalls the architecture of TCP splitting PEPs, widely used in GEO satellite systems. In fact, the DTN architecture can be interpreted as a powerful extension of the PEP architecture.[24] On each hop, a different transport layer protocol (e.g., LTP or TCP) or a different version of the same protocol

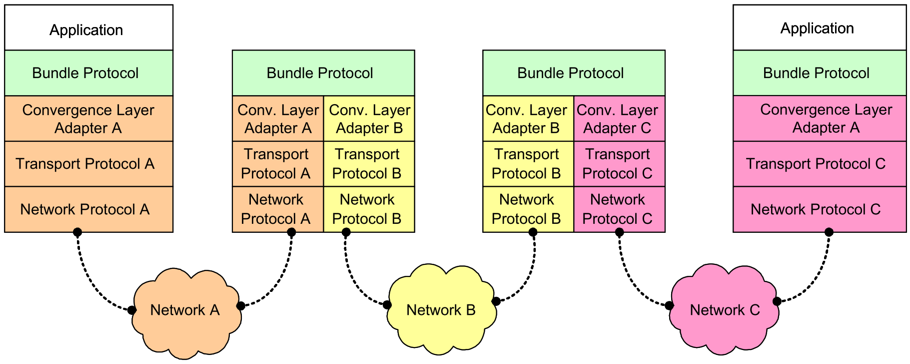

FIGURE 1 The DTN architecture. The end-to-end path is divided into multiple DTN hops by the insertion of the Bundle layer on endpoints and few selected intermediate nodes. On each hop, a different transport protocol can be used, to better match the impairments of the leg (e.g., LTP on space links) [Colour figure can be viewed at wileyonlinelibrary.com]

(e.g., TCP variants) may be used. This way, it is possible to counteract the heterogeneous channel impairments present in different hops, with specialized transport protocols, such as LTP in space legs.

Data packets at bundle layer are called "bundles"; uniquely, they do not have any dimension constraints, thus, they can be potentially much larger than ordinary IP packets, especially when they contain bulk data (e.g., an image). End-to-end bundle transfer is provided by the bundle layer through a store-and-forward relay.

2.1.2 | Link intermittency and storage at intermediate nodes

The most important novelty brought by the store-and-forward mechanisms, and likely also the most evident feature of DTN, is the fact that packet storage is not limited to the very short intervals required for packet processing, as in IP router, but can encompass long periods, such as hours. This is dictated by the need to cope with link intermittency, a distinctive characteristic of challenged networks. In case of next-link unavailability, bundles must potentially be stored for long periods in a database at intermediate DTN nodes while waiting for a new opportunity of transmission (the next "contact"). When the custody option[2,3] is enabled, bundles can be retransmitted by intermediate nodes, each acting as a custodian. If, however, all hops use reliable convergence layers, there should be no need for bundle retransmission, unless the bundle is lost within a node and not during a transfer. The key point is that lower layer losses are tackled inside one DTN hop, without requiring retransmission from the source endpoint, which could take several minutes or even hours in IPN, instead of few milliseconds as in the Internet.

2.1.3 | Licklider transmission protocol (LTP)

The LTPs are the convergence layer of choice for space legs of interplanetary networks, where the long propagation delay prevents the use of TCP. The most important feedback-based TCP mechanisms, such as congestion control and error recovery, require a prompt response from the peer node, ie, a short RTT. Typical RTT values on the Internet are in the range [1, 200] ms and can reach 600 ms if a GEO satellite leg is included, which is probably the extreme case (in facts, this RTT is already very challenging for standard versions of TCP). On a Mars-Earth link, where the two-way propagation delay may vary in the range between 6 and 46 minutes, it becomes essential to minimize interaction ("chattiness") between sender and receiver, which is exactly the LTP aim. In the DTN architecture, LTP is located beneath the bundle protocol and on top of UDP, or equivalent CCSDS space protocols in real deployments, eg, the space packet protocol or the CCSDS encapsulation service.

LTP has been designed to offer both reliable and unreliable services via the use of "red" and "green" parts, respectively. Let us focus on red parts, which are the most interesting, and list the key features that differentiate LTP from TCP.[4,7]

- Rate-based transmission speed, to reduce interaction.
- No connection establishment, to reduce interaction.
- Unidirectional data flow to cope with possible channel asymmetry; the reverse channel is used only for signaling.
- One or more bundles are aggregated in one LTP "block"; each block is independently transmitted and acknowledged during one LTP "session"; multiple sessions in parallel are allowed.
- A block is split into a number of LTP "segments," each passed to UDP, or other equivalent protocol.
- Acknowledgments (LTP "report segments," RS) are sent back only in response to confirmation requests, or "checkpoints" (CPs); these are usually set only on the last segment of a block, to minimize chattiness (a sole RS per block in the best case).

A typical session including segment losses for completeness is shown in Figure 2. A block containing one or more bundles is sent, the last segment flagged with a CP. Segments 2, 5, and 6 are lost and thus not confirmed by the first RS; this report is confirmed by a Report-Ack (RA) followed by retransmissions of lost segments (the last flagged with a CP); the final RS (all segments arrived), confirmed by a RA, concludes the session.

The interested reader is referred to Alessi et al[15] for a comprehensive analysis. Here, let us highlight two points of special interest in deep space links. First, if the propagation delay is much longer than the time required to transmit a block, as is typical in deep space, the delivery time of one LTP block becomes equal to the propagation delay from the LTP source to LTP destination (1/2 RTT), which is the theoretical minimum. Second, as the time to recover from all losses (assuming no further loss on retransmitted segments) is of about 1 RTT, the delivery time becomes equal to 1.5 RTT, which is the theoretical minimum for ARQ (Automatic Repeat reQuest)–based protocols. Both remarks prove the extreme effectiveness of LTP in coping with space challenges.

3 | CONTACT GRAPH ROUTING (CGR)

Routing in "challenged networks" is much more complex than on the Internet, because link intermittency and long delays prevent a rapid exchange of information between nodes, as is essential in ordinary routing protocols. In most challenged networks, the opportunities of transmission between adjacent nodes, i.e., "contacts," derive from the motion of nodes. This motion is assumed to be random in terrestrial networks, while is deterministic in space, as it derives from the motion of planets and spacecraft. This dichotomy between random and deterministic necessarily leads to completely different routing algorithms for the two environments. As in space, the intermittency is scheduled; ie, known a priori, it must be opportunely used by nodes to carry out routing decisions. To this end, within an IPN contact information (length and nominal Tx speed) is passed to all nodes through the dissemination of "contact plans" issued by a mission control center (MCC). Starting from the contact plan, the task of CGR is to find the most suitable route (series of contacts) from source to destination, based on some routing metrics such as the earliest delivery time.

CGR has been designed by NASA-JPL, and it is an integral part of ION.[10,11] The algorithm is complex, as routing in intermittent networks is per se an arduous problem. Here, we will limit the overview to a few key points, referring the reader to Araniti et al[17] for a more comprehensive treatment. In order to facilitate the comprehension, let us note that the CGR routing problem is similar to planning the best sequence of flights to a distant destination. In this analogy, contacts are flights, and bundles are passengers.

- Each node uses the contact plan information (flight schedules) to build a "contact graph" and then a routing table with the plausible routes (sequence of flights to arrive at destination).
- For each bundle (passenger), CGR checks the available routes and chooses the best. In contrast to booking flights, once the route is selected, CGR uses only the information related to the first contact. Namely, it selects the next DTN node to which to send the bundle, and it sets a time

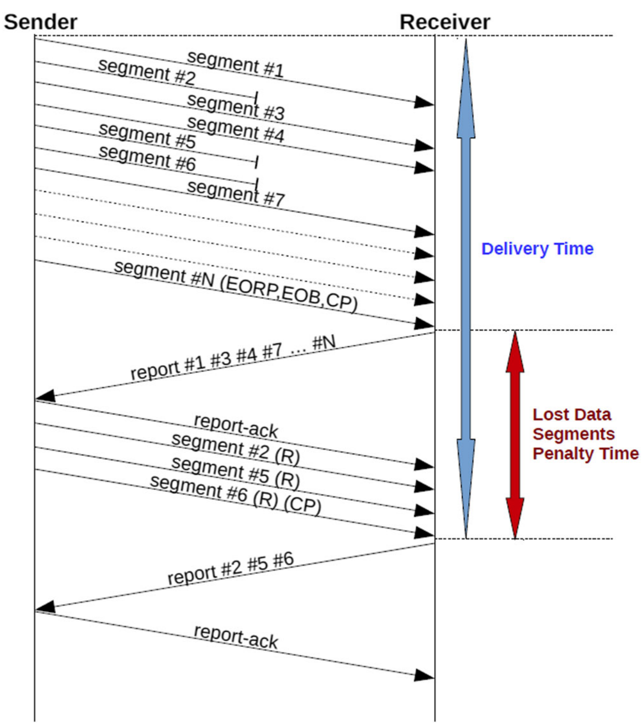

FIGURE 2 Example of LTP session (red-data only) in the presence of losses on data segments; delivery time and penalty time due to loss recovery are indicated by arrows on the right. The latter corresponds to one RTT. Time intervals between consecutive segments are enlarged in the figure to make segment labels readable [Colour figure can be viewed at wileyonlinelibrary.com]

limit ("forfeit" time) for successful transmission to the next node by means of the selected contact. In the analogy, this is equivalent to booking the first flight only. The reason for this behavior is given below.

- For safety, the best route is recomputed at each node along the path to destination. This is justified by the fact that, by contrast to flight booking programs, DTN nodes cannot inform other nodes of their decisions in time; thus, they are all unaware of other node bookings on connecting flights.
- CGR enforces bundle priority. This means that a higher priority bundle has the right to use a contact already fully allocated to lower priority bundles. This, on the other hand, may lead to the need to re-forward lower priority bundles. This is realized as soon as possible by the recently introduced "overbooking management" policy.[18]
- If a bundle is not transmitted before its "forfeit" time elapses, it is immediately re-forwarded as a safety measure.
- In the route selection process, recent versions of CGR take account of data already scheduled for transmission to nearby nodes in order to determine the corresponding queueing delay ("earliest transmission opportunity" enhancement[18] limited to the first hop). The same mechanism allows CGR to skip a route if the bundle's estimated volume consumption is larger than the residual volume of the first contact for its level of priority. In the analogy, if the flight is fully booked by passengers of the same or higher priority.

Last, it is important to point out that CGR is constantly evolving, and new features or variations of the basic protocol are introduced at almost any new release of ION. The latest version is going to be standardized by CCSDS as SABR (scheduled aware bundle routing).[8]

4 | MARS-EARTH SCENARIO

4.1 | Overview

The Mars-Earth scenario considered here takes as reference the case of a Martian exploration mission.[25] It is quite complex as the current study aims at highlighting the interactions of the three key elements of DTN (BP, LTP, and CGR) more than the performance of a single component.

It is composed by a Mars and an Earth segment. The former consists of one lander, sending telemetry data and science data (images, etc.) to Earth, and of two Martian orbiters, acting both as space relays and as autonomous sources of telemetry and science data (Figure 3). The terrestrial segment used as scenario experiment includes two destination nodes (the ESA [European Space Agency] MCC and the ESA PDGS [payload data ground segment]) and four relays, namely, three ground stations (GSs) and the EDRS (European Data Relay Satellite) GEO satellite gateway. Note that EDRS is used here more as a symbolic name for a (future) relay satellite to communicate with the Mars assets than to actually denote the current EDRS system[26] and analogously for PDGS. The Martian orbiters are connected to these four terrestrial relay nodes, while the lander is connected to orbiters and to ground stations, but not directly to the EDRS gateway.

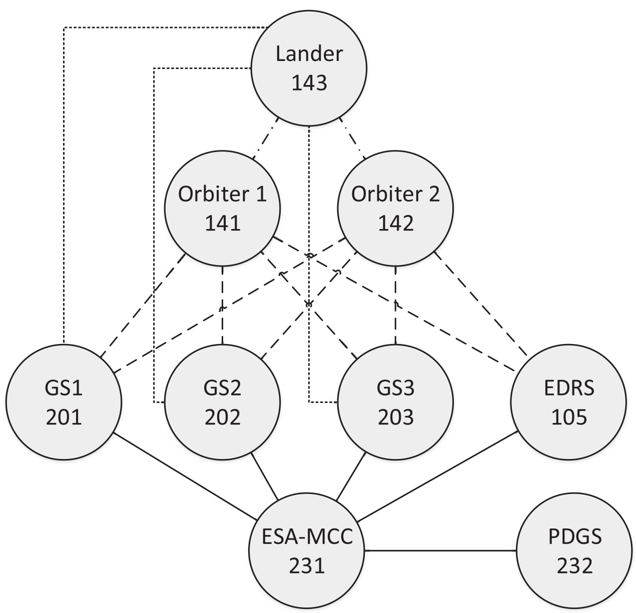

FIGURE 3 Layout of the Mars-Earth network considered in the paper. Dotted/dashed lines, space intermittent links (with LTP); continuous lines, terrestrial continuous links with TCP

The current scenario largely extends that already considered in Caini et al[22] where data download from Mars to Earth was possible via only one orbiter, and thus, there was only one route, by contrast to the present one, which is very challenging for CGR. Moreover, this paper takes different applications as reference, with different generation rates, bundle dimensions, and priorities, all of which must be multiplexed together and then properly handled by BP and LTP, hence making the overall scenario more realistic and simultaneously more challenging. The current scenario is the same as that considered in Alessi et al[27] where preliminary results were presented.

4.2 | DTN topology and links

The DTN layout is shown in Figure 3. We have a total of nine DTN nodes: one lander on Mars, two Mars orbiters, three terrestrial ground stations, one node for the EDRS gateway, one for the ESA MCC, and one for PDGS. Note that the EDRS node does not denote the GEO satellite, which is not included in the layout as it is not a DTN node, but its terrestrial gateway. Dotted/dashed lines denote intermittent space links where LTP is used; continuous lines represent continuous terrestrial links, with TCP.

Link characteristics are summarized in Table 1. Note that terrestrial and Martian links have negligible delays (third column), while on Earth-Mars links, the propagation delay is lengthy, namely, 23 minutes (scaled down to 23 s in the experiments for convenience). Given the complexity of the experiments, losses have been assumed to be negligible on all links. Concerning transmission rates (fourth and fifth columns), it is worth noting the very limited bandwidth (only 32 kbit/s) of the three lander-GS links (dotted lines in Figure 3), the much faster rate (1 Mbit/s) on lander-orbiters links (dashed-dotted) as well as the rate asymmetry (2 Mbit/s in downlink, 32 kbit/s in up) on the four orbiter-GS&EDRS links (dashed lines).

4.3 | Mission application data flows

Data flows are summarized in Figure 4. All spacecraft receive telecommands (TC) from the ESA-MCC, which consists of small bundles with low generation rates (see Table 2). A prompt delivery is paramount; thus, this flow has the highest priority: “expedited.” Urgent telemetry (TM-EXP) has the same characteristics but is sent in the opposite direction. Telemetry (TM) is also sent to ESA-MCC; in this case, bundles are small too, but much more frequent and with “normal” priority. Last, we have four science flows with “bulk” priority, all addressed to PDGS: Science 1 and 2 from Orbiters 1 and 2; Science 3 and 4 from the lander. In contrast to the previous flows, science flows consist of large bundles (especially for Science 1, 2, and 3) and have a relatively fast generation rate; Science 4, sent by the lander, is the largest. We have a total of 13 flows, which makes result analysis particularly demanding.

4.4 | Contact plan

The contact plan used in the experiments was derived by an orbital simulator based upon EOTOOL by GMV[28]; Mars and Earth have been considered at their maximum distance (about 23 light min.). An excerpt from the contact plan, exclusively including intermittent contacts, the only ones of real interest, is plotted in Figure 5. Contacts have been timescaled by a factor of 60 (as delays), which makes the experiment manageable and allows for easy conversion, as seconds in the chart correspond to minutes in reality. The experiment length (1440 s) corresponds to a 24-hour interval.

Starting from the top of Figure 5, we can see that links between lander (143) and orbiters (141 and 142) have two pairs of short contacts each (first pair after 400 s and second pair at about 1200 s), while links to the three GSs (201, 202, and 203) have just one long contact starting towards the end of the experiment (from 1000 s). If we consider that links to GSs have a very small Tx rate, it is evident that the volume available from lander to Earth will be very limited, and contact opportunities few. Then, when we consider Orbiter 1 (141), we can observe more frequent contacts for all the outgoing links. Contacts to GSs are concentrated in the second half of the experiment, while contacts on the link to EDRS (105) are much more uniformly distributed over time. Orbiter 2 (142) presents only minor differences.

From a thorough cross-analysis of contact plan and data flows, the confirmation that the traffic offered is compatible with network capacity emerges. The margin is limited for lander to Earth flows, for the aforementioned reasons. Moreover, as we have no contacts from lander prior to 400 s, all traffic generated in this interval must be stored on board, waiting for the first contact to open. The amount of traffic generated by the orbiters is less critical, as those assets are better connected to Earth, especially due to EDRS. This traffic, however, competes with traffic generated by lander on contacts from orbiters to Earth.

TABLE 1 Link characteristics

Link	CLA	Delay, min/s	Tx Down, Mbit/s	Tx Up, Mbit/s
Lander-GSs	LTP	23	0.032	0.032
Lander-orbiters	LTP	0	1	1
Orbiters-GSs&EDRS	LTP	23	2	0.032
Earth	TCP	0	10	10

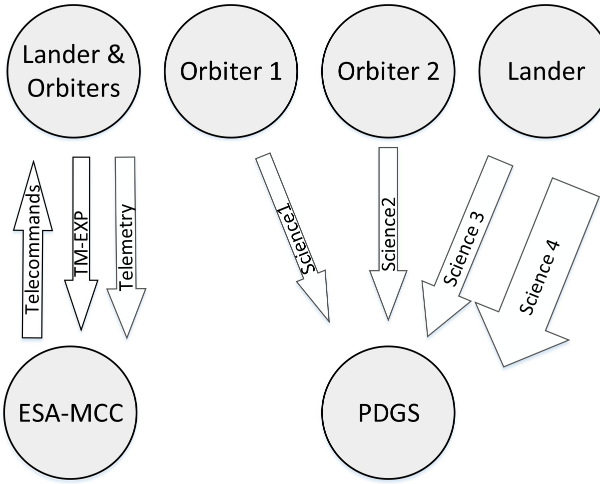

FIGURE 4 Bundle flows considered in the experiments. Each spacecraft receives telecommands (expedited priority) from ESA-MCC and sends back TM-EXP (telemetry with expedited priority) and telemetry (normal priority). Different science flows ("bulk") are sent to PDGS [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Mission application data flow characteristics

Flow Name	Source	Dest.	Bundle Size, B	Prior.	Gen. Rate, B/s
TC (3 flows)	ESA-MCC	Lander, orbiters	1024	Exp.	11
TM-EXP (3 flows)	Lander, orbiters	ESA-MCC	1024	Exp.	11
TM (3 flows)	Lander, orbiters	ESA-MCC	4096	Norm.	2000
Sc. 1	Orbiter 1	PDGS	256 000	Bulk	555
Sc. 2	Orbiter 2	PDGS	512 000	Bulk	666
Sc. 3	Lander	PDGS	512 000	Bulk	1778
Sc. 4	Lander	PDGS	64 000	bulk	2778

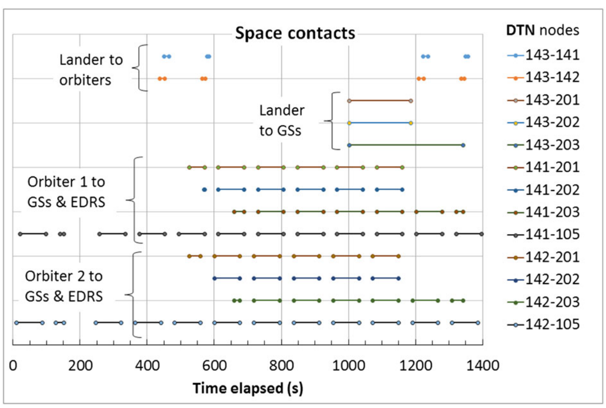

FIGURE 5 Excerpt of the contact plan used in the experiments: intermittent contacts from lander (143), Orbiter 1 (141) and Orbiter 2 (142) in top-down order. Note the few and short contacts between lander and orbiters (contacts 143-141 and 143-142). All contacts have been scaled down by a factor of 60 (seconds instead of minutes) with respect to the original contact plan [Colour figure can be viewed at wileyonlinelibrary.com]

5 | TESTBED AND EXPERIMENT DESCRIPTION

5.1 | Virtual testbed

Our experiment was performed on a GNU/Linux virtual testbed created and managed by means of Virtualbricks.[29] The testbed consists of nine virtual machines (VMs), one for each DTN node, connected by virtual switches and channel emulators. The VMs are based on QEMU-KVM, which enables them to interact directly with the host processor, which is essential for performance, and use the Linux OS as well. The channel emulators "CHXband" and "CHEDRS" are essential to add the desired delay on Mars to Earth links (see Figure 6), while the channel emulator between lander and orbiters is not used in the present experiment (it has been inserted only to cope with future needs).

In our experiment, each traffic flow is generated by a unique instance of the DTNperf_3 client[30] (13 in total), with specific parameters (destination, priority, bundle dimension, and Tx rate). Bundles are received by one of the five instances of the DTNperf_3 server. Status reports are collected by a DTNperf_3 monitor on ESA-MCC. The whole experiment is managed by a "do-test" script running on the host, which is connected to all VMs thanks to a dedicated control network, with ideal links (no delay, no losses, and no disruption). Clocks are perfectly synchronized, as VMs set their clock from the host.

On LTP links (dashed lines in Figure 3), the LTP aggregation time limit is set to 1 second, and we set both import and export sessions to the length (in seconds) of the longest contact to the neighbor, in order to fill the bandwidth delay product.

5.2 | CGR and ION versions

The ION suite is installed on all DTN nodes and contains all elements essential to determine performance in space environments, BP, LTP, and CGR. Different ION releases implement slightly different versions of CGR. We used ION 3.6.0b,[11] but we patched the official version to tackle a few problems encountered during tests. All results reported here are updated to the latest patch and created after preliminary results were presented in Alessi et al[27]; the most significant improvement is on Science 4 data, as discussed later.

ION maintainers have already been informed of the problems found and of the fixes made.

5.3 | Status reports, data collection, and processing

As bundles are generally larger, but also fewer, than IP packets, they can conveniently be tracked in tests by means of bundle status reports, which are extremely valuable for performance analysis. A status report is an administrative bundle (ie, a bundle autonomously generated by the bundle protocol) containing information about the time when a specific data bundle (the subject bundle, or bundle X) is either received, forwarded, taken into custody, deleted, or delivered.[3] Status reports can be selectively requested by the bundle source by setting corresponding flags in the bundle primary block.

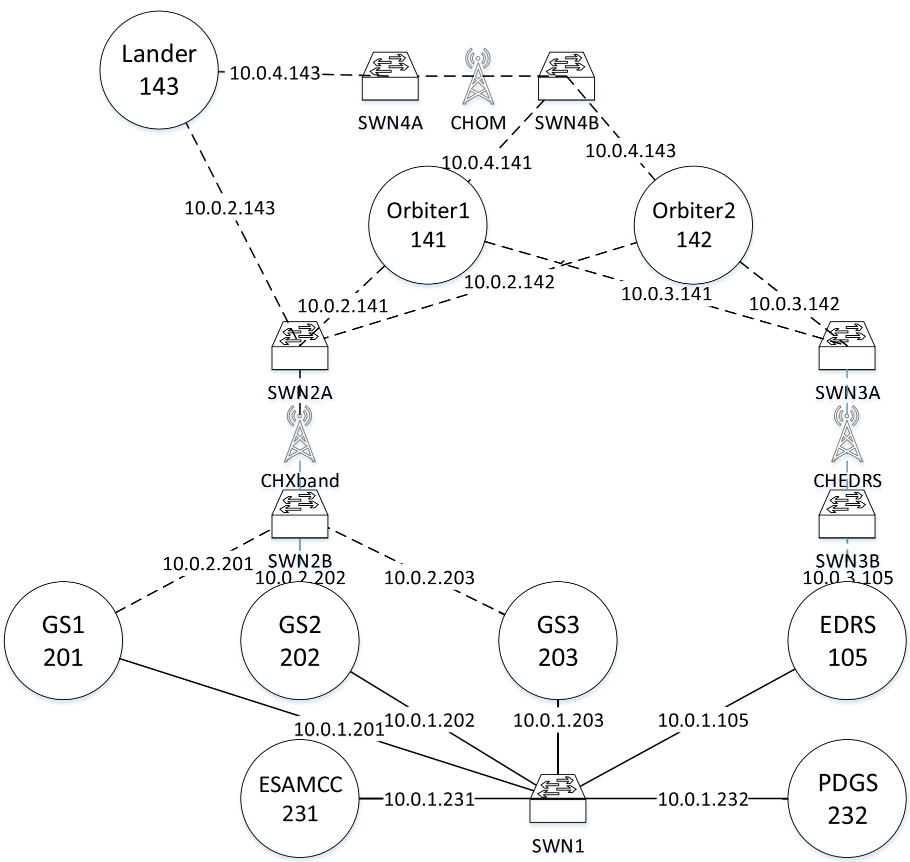

FIGURE 6 The layout of the Virtualbricks testbed used in experiments [Colour figure can be viewed at wileyonlinelibrary.com]

Each status report contains the source EID and the generation timestamp of the data bundle to which it refers, as well as one or more additional timestamps. In the experiments examined here, only delivered and received reports are enabled (the latter to investigate routes in special cases).

As previously stated, bundles were collected by the DTNperf monitor into a.csv file. This file, containing all data necessary to evaluate the experiment, was then processed by a data-sheet application, to extract the desired information and plot the graphs. The file analyzed in next section contains 4645 status reports, of which 1313 “delivered” plus 3332 “received” referring to the 13 data flows previously described. Flows generated by the same source can be differentiated by means of the source EID demux token, as this contains the PID (Process IDentifier) of the DTNperf client that has generated the flow (eg, ipn:141.16540, where 141 is the node number and 16540 the PID of the client). Table 3 shows an excerpt of the.csv file, containing four status reports referring to the flow 141.16540.

6 | PERFORMANCE ANALYSIS

We will start the analysis with the data flows directed to Earth.

6.1 | Data download (from Mars to Earth)

As illustrated in the previous section (Figure 4 and Table 2), different application flows are exchanged between the three Mars spacecraft and the Earth infrastructure. In the analysis, we will follow a gradual approach, starting from the least challenging, i.e., those generated on orbiters.

6.1.1 | Data from orbiters (Mars relays)

As orbiters have better connectivity to Earth (see frequent contacts to both GSs and EDRS in Figure 5), traffic generated by orbiters presents fewer challenges. As the two orbiters have similar data and orbital characteristics, their performance is similar. Consequently, we will focus only on Orbiter 1. Let us start with the urgent telemetry (TM-EXP) data flow, which is the least challenging as characterized by a slow generation rate, small bundles, and the highest priority. Two series, for bundles generated and those delivered, are shown in Figure 7. The latter (delivery) monotonically increases, following the former (generation) closely, as should occur in the absence of challenging routing situations or congestion events. The delivery time, ie, the time between bundle generation and delivery, is the best performance indicator; it is given by the distance between “generated” and “delivered” markers with the same ordinate. By examining the figure, it is evident that the delivery time is very regular. As this flow has the highest priority, it is only marginally influenced by concurrent traffic and the few, limited variations in the delivery time can all be ascribed to corresponding gaps in connectivity between the orbiter and Earth. Note for example, how the gap between Orbiter 1-EDRS contacts at around 200 seconds (see 141-105 contacts in Figure 5) results in an increase of the delivery time of bundle 2, as there are no alternative contacts via the GSs. This kind of cross-analysis highlights the usefulness of the EDRS GEO satellite, which provides a regular and almost continuous connectivity to the orbiter.

Telemetry traffic is shown in Figure 8. The major difference is that TM bundles are much more frequent; thus, the impact of connectivity gaps is clearer. These gaps highlight the store and forward mechanism of BP: Bundles are immediately delivered if a contact to Earth is available; otherwise, they are kept on board waiting for the next available contact to open. In the figure, this results in small bursts of deliveries when the contact eventually opens due to the high rate of links to Earth. Looking at “received” status reports (not shown in the figure), we observed that most bundles are routed to destination via EDRS and not via GSs, because Tx rates are the same but contacts to EDRS are more frequent. As TM traffic has normal priority, deliveries could, in theory, be influenced by TM-EXP (generated by the Lander and routed via Orbiter 1), but in practice, this is not the case, because this traffic is too small to have a significant impact.

6.1.2 | Data from lander

Data flows generated on board the lander are much more challenging, for the following three reasons: First, the overall amount of traffic generated on board the lander is close to the sum of the volumes of contacts departing from it, thus leaving a limited margin to cope with possible CGR inaccuracies. Second, there is a great variety of possible paths to reach destination; bundles generated by the lander can either be directly forwarded to GSs or sent to orbiters; in this latter case, they can then be routed to their destination (ESA-MCC or PDGS) either via GSs or EDRS. Third, CGR

TABLE 3 Excerpt from the.csv file

Report_SRC	Report TST, s	Bundle SRC	Bundle TST, s	Dlv, s	Rcv, s
ipn:205.0	26	ipn:141.16540	0		26
ipn:231.0	27	ipn:141.16540	0	27	27
ipn:205.0	26	ipn:141.16540	2		26
ipn:231.0	27	ipn:141.16540	2	27	27

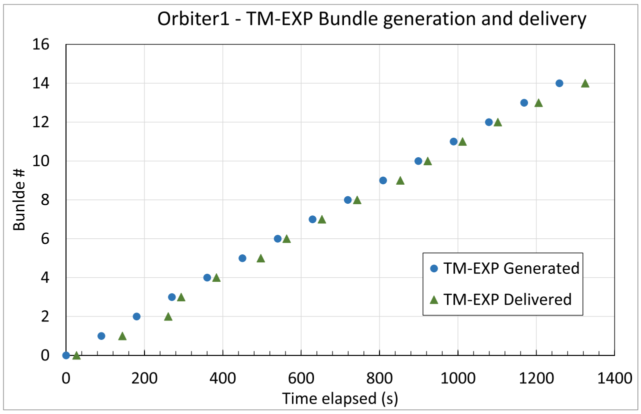

FIGURE 7 TM-EXP data flow (telemetry with expedited priority) from Orbiter 1 to ESA-MCC: time sequences of bundle generation and delivery [Colour figure can be viewed at wileyonlinelibrary.com]

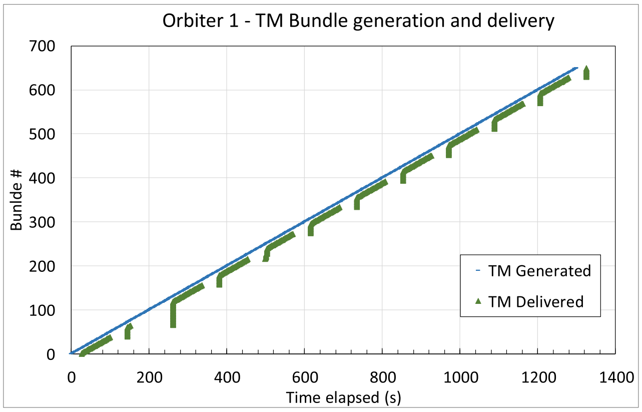

FIGURE 8 Telemetry data flow (normal priority) from Orbiter 1 to ESA-MCC: time sequences of bundle generation and delivery [Colour figure can be viewed at wileyonlinelibrary.com]

is unaware of the concurrent traffic generated by other nodes. Thus, CGR on the lander cannot consider the contact volume occupancy of traffic generated by the orbiters. As all these reasons impair optimal route selection, it is realistic to expect a more irregular bundle delivery. The lower the priority, the more evident performance degradation, as we are going to see.

As before, let us start with telecommand traffic (Figure 9), which has the highest priority and a very small generation rate. The few bundles are still delivered in order, but the delivery time has large variations and delivery bursts are evident, due to the much more frequent lack of connectivity. Note that no bundles are delivered before about 470 seconds, as there are no opportunities to leave the lander in the first third of the experiment duration (no contacts available to either orbiters or ground stations before 440 s; see Figure 5). Note that, in contrast to orbiters, it is impossible to reach the EDRS satellite directly from the lander. This negatively affects performance, as is evident by comparing the present results with those of Orbiter 1, shown in Figure 7.

Now, we can move on to telemetry data, presented in Figure 10. Gaps in connectivity are evident as before, but for the first time, we can also observe the first cases of disordered delivery. Although bundles are allowed to be delivered out of order,[3,6] this is inconvenient, and it is also a symptom of performance degradation. For telemetry data, disordered delivery is still limited to very few bundles, but in one case, the delivery delay is huge.

An accurate analysis of status reports highlighted that another less visible impairment was affecting lander TM data flows: Science 3 and Science 4 data use very large bundles, i.e., 512 and 64 kB, compared with the Tx speed of direct lander to GSs links, which makes for a very long bundle transmission time (defined as bundle dimension divided by the nominal Tx rate of the link). This impairs priority enforcement in two ways: First, when a large bulk bundle starts to be transmitted on the link to a GS, it makes the link unavailable for a long period, even for bundles of higher priority, such as TM. Second, if a large bulk bundle and a higher priority are both waiting to be transmitted when the contact opens, the higher priority one is passed to LTP first. However, because it is small, it may be aggregated with other bundles by LTP in order to reduce the LTP block overhead. In practice, we can have one LTP block containing both one TM bundle and one Science. At this point, the two bundles, independent of priority, share the same fate: The TM bundle cannot be delivered until the full block including the big bulk bundle of science data is successfully received. In the absence of losses, the delay penalization for the TM bundle is equal to bulk bundle transmission time (long on lander to GS links) and not taken into account by CGR. Penalization would be worse in the presence of losses.

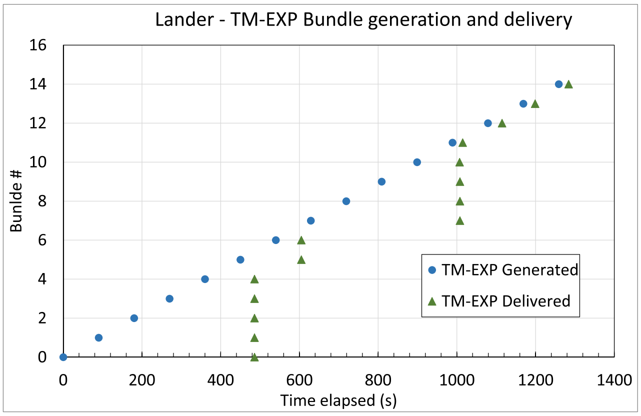

FIGURE 9 TM-EXP data flow (telemetry with expedited priority) from lander to ESA-MCC: time sequences of bundle generation and delivery [Colour figure can be viewed at wileyonlinelibrary.com]

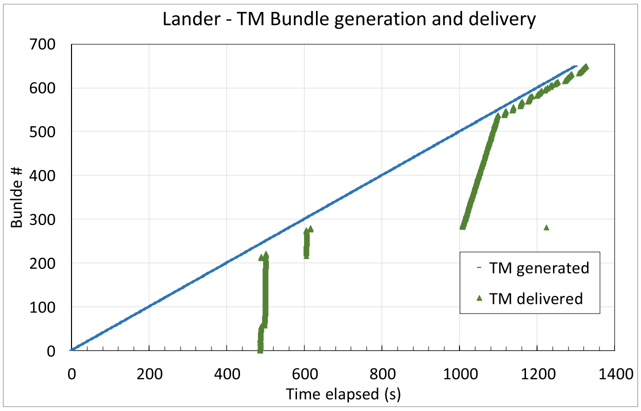

FIGURE 10 Telemetry data flow (normal priority) from lander to ESA-MCC: time sequences of bundle generation and delivery [Colour figure can be viewed at wileyonlinelibrary.com]

Last, we will examine the Science 4 data flow, which is the most challenging, given its fast generation rate, large bundles, and low priority (bulk, the lowest level). Examining the data (Figure 11), the disordered delivery is evident, largely caused by the scarcity of bandwidth between the lander and the other nodes. To allow all bundles the opportunity to be forwarded in time, we stopped the data generators (DTNperf_3 clients) at 1300 seconds, i.e., before the last lander-orbiter contacts start.

In more detail, as contacts between the lander and the two orbiters are few and short, and contacts to GSs have an extremely narrow bandwidth, the sum of all contact volumes available, i.e., the total amount of data that can be transferred during the experiment, is only marginally larger than the traffic injected. This is more challenging for bulk flows, as their bundles are sent last. If a contact is saturated, the last bulk bundles associated with it must be re-forwarded, i.e., transmitted during later contacts, therefore causing a disordered delivery.

It is worth noting that thanks to our latest fixes made to ION, all bundles are delivered before the end of the experiment (1440 s), without need for additional contacts, in contrast to the preliminary results presented in.[27]

6.2 | Data upload (from Earth to Mars)

It is time to consider the reverse traffic, consisting of telecommand flows sent by the ESA mission control center to the three space nodes. Again, we will proceed from the least to the most challenging case.

6.2.1 | Data to orbiters (Mars relays)

Results for Orbiter 1 are shown in Figure 12. The very regular delivery pace is mainly due to the excellent connectivity provided by the EDRS GEO satellite, as already outlined in the downlink case (Figure 7). Although the uplink bandwidth of both GSs and EDRS links is much slower here than the downlink (only 32 kbit/s instead of 2 Mbit/s; see Table 1), there are no contact saturation problems because telecommand traffic has a very low generation rate. Results for Orbiter 2, not reported here, are qualitatively the same.

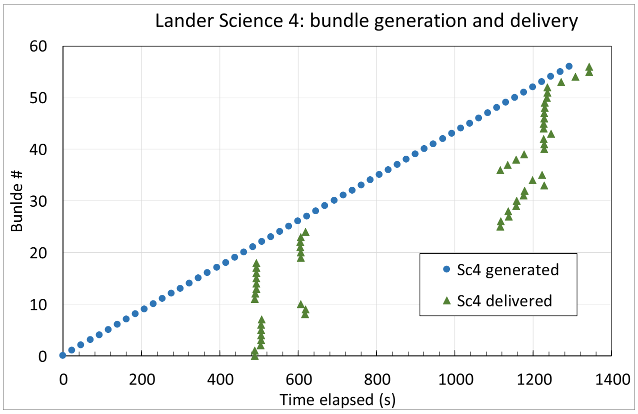

FIGURE 11 Science 4 (Sc4) data flow (bulk priority) from lander to PDGS: time sequences of bundle generation and delivery [Colour figure can be viewed at wileyonlinelibrary.com]

6.2.2 | Data to lander

The closer we get to the lander, the fewer contact opportunities are available. This is dangerous as, when coupled with a high level of symmetry of layout and contacts, it may cause instability in CGR decisions. This phenomenon will be explained later. To avoid this risk, we removed the visibility of GS to lander links from the orbiter configuration files. Results are shown in Figure 13. Apart from delivery in bursts, due to the usual large gaps in connectivity, here, we also have one bundle (number 6) delivered out of order and with a huge delay.

6.3 | General remarks

The analysis carried out in the previous section allows us to make some general remarks about DTN performance in space networks, from both the operational and the research standpoints.

Future interplanetary networks are expected to transport different data flows with different characteristics in terms of bundle dimension, generation rate, and priority. High priority data flows are generally characterized by small bundles and low generation rates (in byte/s). Here, they were represented by TC and TM-EXP. Normal flows, such as TM, have a higher generation rate, and low priority flows, such as Science, usually have large bundles and/or high generation rates.

In our analysis, data flows generated by the orbiters show regular delivery, meaning that, with respect to the unavoidable time gaps between available contacts, no additional delays are introduced by inaccurate routing decisions. This is due to excellent connectivity, mainly provided by the EDRS GEO satellite, which turns out to be extremely useful.

Moving on to the lander, connectivity becomes much poorer (fewer contacts, poorly distributed in time, very low bandwidth for direct links to Earth) and routing much more complex, due to the variety of possible routes, some with very limited volume. For expedited-priority traffic, such as TM-EXP, there are no evident consequences, but the usual, unavoidable gaps in delivery. For normal-priority traffic, such as TM, we noticed minor

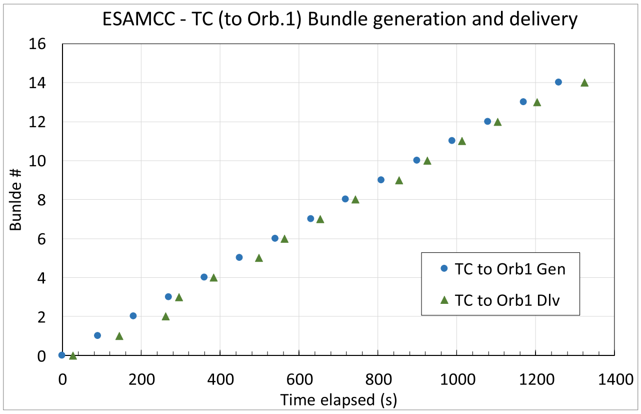

FIGURE 12 Telecommand data flow (expedited priority) from ESAMCC to Orbiter 1: time sequences of bundle generation and delivery [Colour figure can be viewed at wileyonlinelibrary.com]

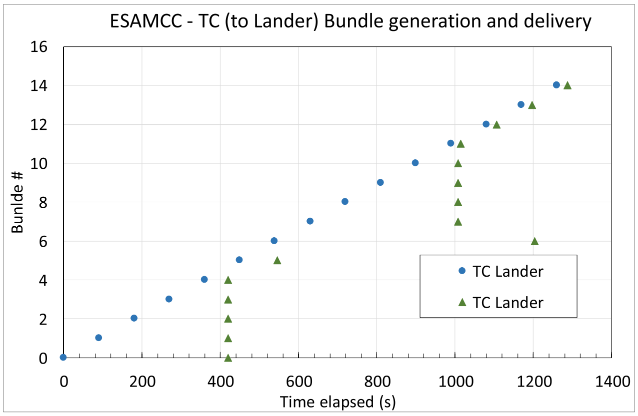

FIGURE 13 Telecommand data flow (expedited priority) from ESAMCC to lander: time sequences of bundle generation and delivery [Colour figure can be viewed at wileyonlinelibrary.com]

out-of-order delivery, except for one bundle that was severely delayed by its aggregation in one LTP block with a very large bulk-priority bundle of a Science flow. The first suggestion is thus that the current LTP aggregation mechanism needs some tuning to prevent this situation. Disordered delivery is more evident for bulk traffic and is largely due to a traffic load close to the overall volume of contacts from the lander. In these challenging conditions, successful delivery of all bundles can be considered a positive result. This, however, also confirms the fact that the dynamic routing mechanism provided by CGR has difficulty in coping with a fully loaded network (as is typical with routing). Therefore, the second remark is that in network management, a significant safety margin must be included to prevent the traffic load saturating the network. Moreover, in order to obtain the positive result of all bundles delivered during the experiment time, without extra contacts, we had to identify and fix several problems within ION. Therefore, the third remark concerns code reliability, which must be verified and possibly improved. This particularly applies to CGR, which is still evolving.

In the reverse direction, the decrease in connectivity from Earth to Mars (gradually fewer contacts, with less volume) poses a new and somewhat unexpected challenge to CGR. In our scenario, the network in the reverse direction is far from saturation due to the very limited traffic offered by the TC flows directed to Martian assets. The problem is that from ESA MCC to lander, there are three similar routes with almost the same contacts (the 3 GS-Lander contacts start exactly at the same time and have the same nominal Tx speed). Layout and contact symmetry, together with less connectivity, may lead to routing instability. In general terms, we can say that as CGR also takes local information into account, such as the amount of data in local queues, it is perfectly possible that CGR on two nodes has different "opinions" about the best route to follow. In extreme cases, this can lead to instability. Focusing on our experiment, let us consider the following situation. One TC bundle is sent by ESA-EDRS to GS1 to be then forwarded to the lander on the contact starting at 1000 seconds. On arrival at GS1, however, the bundle is reforwarded by CGR taking the local queue on this contact into account. Because of this queue, here, CGR could now think it is preferable to send it to GS2 to take the first GS2-Lander contact. It starts at exactly the same time as the GS1-Lander contact, but GS1 is not aware of bundles already queuing on this contact. As there is plenty of time before the opening of GS-Lander contacts, the bundle could therefore be sent by GS1 to GS2 (via Orbtier 1 or 2, as a bundle can never be sent back to ESA-EDRS, thanks to a "ping-pong" avoidance mechanism). On arrival at GS2, the bundle is reforwarded by CGR, which now could prefer to route it via GS1, as it knows the local queue but not that on GS1, and potentially so on, depending on contact availability between GS1 and GS2 via the two orbiters. This problem cannot occur in the opposite direction, because once a bundle destined to ESA-EDRS arrives at GS1, the link to ESA-EDRS link is always immediately available, being a terrestrial link; thus, the local direct link is always the best. Consequently, the fourth remark is that in the reverse direction, excessive symmetry should be controlled by manipulating configuration files or through another management mechanism. Last, as routing instability is possible, it is necessary to study adequate countermeasures to control it. Some of the authors have now started work on this urgent topic.

7 | CONCLUSIONS

This paper evaluates DTN performance in a complex Mars-Earth scenario, involving multiple space assets and multiple services. Based on status reports collection, the analysis does not focus on single elements of the DTN architecture (BP, LTP, and CGR), but rather provides a holistic analysis of the DTN network. The results clearly highlight the role of intermittent connectivity (frequency and volume of contacts) and of bundle priority in assuring a prompt and ordered bundle delivery. For Mars-to-Earth data flows, frequency and volume of contacts increase hop-by-hop; thus, the main challenge is on the links departing from lander where congestion can easily arise. Although in general our results are very positive, network management must introduce adequate safety margins to prevent network saturation. In the reverse direction, for Earth to Mars flows, opportunities of transmission decrease. If combined with an excess of symmetry, it may lead to routing instability (not observed in our experiments, but theoretically possible). Therefore, the amount of symmetry in the reverse direction should be kept under control. Furthermore, and from a research perspective, this behavior calls for the study of countermeasures.

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