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DTN Architecture With Resource-Aware Rate Adaptation for Multiple Bundle Transmission in InterPlanetary Networks

FLORIANO DE RANGO, (Member, IEEE), AND MAURO TROPEA, (Member, IEEE)
Department of Informatics, Modeling, Electronics and System Engineering (DIMES), University of Calabria, 87036 Rende, Italy
Corresponding author: Floriano De Rango (derango@dimes.unical.it)

ABSTRACT The world of telecommunications, from some years, is revitalizing an high interest to Deep Space Communication (DSC) and Delay Tolerant Network (DTN) architecture as enabling technologies to offer internet services for aerospace vehicles or orbital stations. The communications between the planets in the solar system is well known to present a series of problems that need to be faced. The fundamental challenge with InterPlanetary Communication (IPC) is the intermittent Line of Sight (LoS) caused by planets movement and the significant propagation time. A possible way to face with it is the use of a DTN approach where routers use a store-and-forward transmission in a hop-by-hop message exchange mechanism. Thanks to this approach, it is possible to face many issues related to the transport layer. The main contribution of this work concerns the proposal of a bundle management layer able to assign at the receiver the appropriate bundle rate on the basis of concurrent bundle transmissions, the output link capacity and buffer resources. The proposed strategy can be integrated with a routing algorithm for InterPlanetary Networks (IPNs) and DTN networks. In our case we consider the Earliest Arrival Optimal Delivery Ratio (EAODR) routing that applies a modified temporal graph to select the IPN nodes. Performance evaluation have been led out to show the benefits of our proposal on the single links and also on the routing scheme in terms of bundle delivery ratio and average bundle delivery time.

INDEX TERMS InterPlanetary networks, deep space communications, delay tolerant networks, route adaptation, buffer overflow.

I. INTRODUCTION

Finding new kind of communications located in a disparate parts of the world have led the scientific researchers towards communications that involve not only the Earth planet but also other planets of the sun system. Moreover, the spatial missions development, such as Mars exploration, in the last years and in the near future [1], will make necessary the study of transmission systems alternative to the classical used in the current internet. The peculiar characteristics of the links that are involved in these systems pose serious challenges for the transport layer [2]. The TCP protocol is based on some key assumptions like the existence of an end-to-end path between source and destination characterized by a little percentage of packet loss and a small RTT (Round Trip Time). There are many situations in which one or more of these assumptions cannot be verified for InterPlanetary Network (IPN). The researchers call these networks ‘‘challenged networks’’. The Deep Space Communication (DSC) needs of more advanced architectures, protocols and technologies. An alternative approach is to adopt the Delay Tolerant Network (DTN) [3], [4] architecture that is based on the introduction of the new ‘‘bundle’’ layer in the protocol stack [5]. The ‘‘bundles’’ layer, added between the application and transport layers, is responsible for storing and delivering data packets using a technique based on a *store-and-forward* paradigm guaranteeing so the communication between devices otherwise unable to communicate. The DSC tries to realize an huge Internet able to connect devices in everywhere, the so called IPN [6], [7]. In this new type of network, the well known mechanisms of transport protocols cannot be used, so the DTN approach [3], [4] is proposed as mechanism able to permit communication between different planets such as Earth and Mars, where long propagation time and intermittent

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connectivity are the main characteristics. The primary goal of the deep space environment is to create a massive Internet capable of enabling connectivity to nodes in various networks. The main issues in IPN are: long propagation delay, intermittent connectivity, asymmetric channel, high signal to noise ratio. The IPN architecture hypothesizes a set of conventional, planetary internet connected by a deep space backbone. Unlike real-time TCP/IP protocols, nodes on the IPN backbone will "bundle" communications together in a *store-and-forward* fashion. An IPN node will take responsibility (until some more distant timeout) for forwarding its data, deleting it from persistent storage only after receiving the next node's acknowledgement of receipt. In this research work, a receiver oriented rate adaptation mechanism integrated with a DTN routing next hop selection is proposed in IPN network for enhancing IPN performance through the exploitation of DTN architecture and bundle layer management. Through an explicit input termed Availability Timeline Information (ATI), this system provides traffic information and local resource availability such as connection capacity or buffer space to store bundles. An hop-by-hop rate adaptation scheme accounting for bundle occupancy, neighbour output link data rate and concurrent bundle transmission has been proposed with the purpose to reduce the buffer overflow issue, to increase the bundle delivery ratio and reduce the average bundle delay. Moreover, the rate adaptation strategy has been also tested over a DTN routing using the Contact Plan (CP) of orbital stations [8]–[12]. The system has been developed in ONE simulator [13] and different simulation campaigns are carried out in order to show the goodness of the proposed approach.

The paper organization is as follows: Section II presents the related works; in Section III an overview of IPN is introduced. Section IV presents the description of DTN architecture used in the IPN context. In section V our proposed hop-by-hop rate adaptation with bandwidth fair sharing approach is explained. Section VI presents the Modified Temporal Graph (MTG) routing over IPN. The performance analysis of our proposal is provided in Section VII and, at the end, the conclusions are outlined in Section VIII.

II. RELATED WORK

The increasing interest in DSCs has led to develop new approaches in the design of novel reliable transmission protocols and of new routing strategies in a DTN environment. Many contributions related to the reliable bundle transmission considering DTN architecture and hop-by-hop flow controls have been also presented. In all these works DTN offers an intrinsic greater robustness against intermittent or disruptive channels. Moreover, many works presented for DTN and IPN networks regard also the routing problems and, in particular, the dynamic routing under dynamic link activation and deterministic mobility patterns. In the next subsection some papers related to reliable data transfer and routing applied to DTN and IPN are presented.

A. TCP AND FLOW CONTROL OVER IPN

Other studies have been interested of the transport layer for IPN like the TP-Planet [14]. It is intended to address the challenges and to achieve high throughput performance and reliable data transmission on deep space links of the IPN Backbone Network. In fact, the inadequacy of the current TCP protocols in the IPN backbone network has already been known and the need for new transport protocol has been pointed out in [8]. TP-Planet [14] deploys a rate-based Additive-Increase Multiplicative-Decrease (AIMD) congestion control, whose AIMD parameters are tuned to help avoid throughput degradation exalting the collaboration hop-by-hop. It runs on top of the IP layer and does not require any specific modification to the lower layers in the current TCP/IP suite. Performance evaluation via simulation experiments revealed that TP-Planet significantly improves the throughput performance and addresses the challenges posed by DSC networks. In [15] a Delay Tolerant Transport Protocol (DTTP) to serve efficient data transports in challenged space networks has been proposed. DTTP complements delay tolerant architectures by inspecting network performance and providing reliable and relatively fast transports. An end-to-end retransmission framework for dynamically calculating efficient retransmission timeout intervals in DTNs with scheduled connectivity has been proposed in [16]. Bundle Protocol (BP) and an underlying Convergence Layer Protocol (CLP) [5], [17] stack have been introduced in DTN architecture in order to better face specific issues of IPN. The CLPs in DTN are roughly classified as the TCP-based CLP (i.e., TCPCL) [17], User Datagram Protocol (UDP)-based [18], [19] CLP (i.e., UDPCL), Saratoga CLP [20], and Licklider Transmission Protocol (LTP)-based [21], [22] CLP (i.e., LTPCL). In our case we considered LTPCL because it is designed to operate over point-to-point, long-haul, deep space radio frequency links or similar links characterized by an extremely long transmission delay and/or frequent interruptions in connectivity. Moreover, according with our previous contribution in [23] where an hop-by-hop flow control has been applied considering the rate adaptation, we applied a resource-aware rate adaptation considering the bundle buffer occupancy level and the output link capacity such as will be shown in the next sections.

B. ROUTING APPROACHES OVER IPN

A detailed description of the routing problem in IPN Internet is presented in [24] where the authors analyze the characteristics of DSCs and how many routing proposed algorithms attempt to address the deep space issues. There are studies like the Movement-Aware Routing oVer Interplanetary Networks (MARVIN) [25] and Location-Predicted Directional Broadcast (LPDB) [26] algorithm routing. Both the algorithm employ the Dijkstra to calculate the shortest path and attain the topology of the network from the predictable location information. The MARVIN is a table-driven routing while the LPDB employs flooding to forward the data and

TABLE 1. Abbreviations.

Acronym	Description
ADU	Application Data Unit
AIMD	Additive-Increase Multiplicative-Decrease
ATI	Availability Timeline Information
BC	Bandwidth Capacity
BER	Bit Error Rate
BP	Bundle Protocol
CCSDS	Consultative Committee for Space Data Systems
CGR	Contact Graph Routing
CLP	Convergence Layer Protocol
CP	Contact Plan
DSC	Deep Space Communication
DTN	Delay Tolerant Network
DTNRG	DTN Research Group
DTTP	Delay Tolerant Transport Protocol
EAODR	Earliest Arrival Optimal Delivery Ratio
FIFO	First Input First Output
ION	Interplanetary Overlay Network
IPN	InterPlanetary Network
IRTF	Internet Research Task Force
LPDB	Location-Predicted Directional Broadcast
LTP	Licklider Transmission Protocol
LTPCL	LTP-based CLP
MARVIN	Movement-Aware Routing oVer Interplanetary Networks
MTG	Modified Temporal Graph
OS	Orbital Station
OWLT	One Way Light Time
RABF	Rate Adaptation with Bandwidth Fair-sharing
RIOR	Receiver-Initiated On-demand Routing
RTT	Round Trip Time
SCPS-TP	Space Communications Protocol Specification-Transport Protocol
SDN	Software Defined Networking
TCPCL	TCP-based CLP
UDPCL	UDP-based CLP

directional antenna to limit the broadcast area in space and time. Besides, the MARVIN takes the metric of distance, power and delay, while the LPDB only takes the delay as metric. After all, the two algorithms solve the main problem in deep space but they do not take into account the characteristics of intermittent connectivity and limitation of buffer and congestion that it can be necessary on the IPN network. In [27] the authors present two different routing mechanisms that propose to addresses the delivery of remote control messages and scientific data in deep space networks. The LPDB is proposed for the fast delivery of remote control messages and automatic data delivery. For controlled data delivery, the Receiver-Initiated On-demand Routing (RIOR) is proposed. In RIOR, the route discovery is initiated on-demand by the receiver, and routing tables are maintained in soft state at intermediate nodes. A nice overview about routing strategies that take advantage of the deterministic Contact Plan (CP) among space objects is presented in [28] where many variants of Contact Graph Routing (CGR) are recalled. CGR was first implemented in the Interplanetary Overlay Networks (ION) [13], and then was introduced to the ONE simulator by Berlati *et al.* in [29] using ION version 3.6.0. In [30] a temporal graph is introduced to consider the link evolution through the contact plan. Through a Modified Temporal Graph (MTG) it is possible to improve the routing performance such as shown in [31], [32] where a modified Djkistra that assures the earliest arrival time of bundled in comparison with CGR. In our proposal we considered this last routing strategy to evaluate the performance of our rate adaption scheme integrated with an efficient routing strategy.

C. MAIN NETWORK ARCHITECTURES FOR IPN

An efficient and scalable architecture is a key issue to be addressed for IPN considering the multiple challenges that are present such as very long distances among planetary entities, link failure and obstructions on the basis of the orbital motion, limited available standards and multiple technologies to be integrated (GEO, MEO, LEO and cubesat [33]) in an unified architecture [34]. Some architectures proposed in these years focused more on mission-centric architecture whereas some other proposals focused on network-centric architecture. A software defined Space-Terrestrial architecture has been proposed in [35]. Authors consider a Software Defined Networking (SDN) paradigm to manage resources of Satellite-Terrestrial and space elements. However, a few contributions addressed an unified architecture to be deployed in the future IPN. Bhaisin and Hayden proposed an evolutive network architecture able to provide high communication bandwidth, high data volume and data delivery [36], [37]. Other authors such as in [38] proposed a mission-oriented architecture where the purpose is the cost reduction for near term, medium term and long term space explorations. Our idea is to use a DTN based architecture for the bundle layer management with the hop-by-hop control of data flow and an IP-based architecture at network layer for the routing considering the deterministic planetary movements of spatial nodes (entities), orbital stations and planets such as considered in [28], [39]. When more space objects will populate the IPN, the network management will become more complex such as shown in [40] and a tighter cooperation and interaction among LTP, BP and network (routing) layer need to considered to optimize the network performance.

In all related work presented above, there is no integrated approach that show the bundle management and the routing strategies to see the impact on the bundle performance metrics such as bundle delivery ratio and average bundle delay. Moreover, a few work addressed the problem of bundle fragmentation and bundle concurrent transmission with a receiver-oriented and resource-aware rates selection. This is the first work to integrate a routing strategy such as EAODR where a deterministic Contact Plan (CP) is applied with a Rate Adaptation with Bandwidth Fair-sharing (RABF) at bundle layer and where a resource-oriented and time-scheduled bundle rate management with bandwidth fair-sharing policy is applied. Differently by [23], we applied the rate-adaptation over LTP and the policy is applied considering multiple connections with parallel bundle transmissions. In future scenario, such as presented also in [41], files or multiple connections could be activated between source and destination stations and the concurrent bundle management need to be faced.

The novelty points of our proposal in comparison with the listed state of the art are the following:

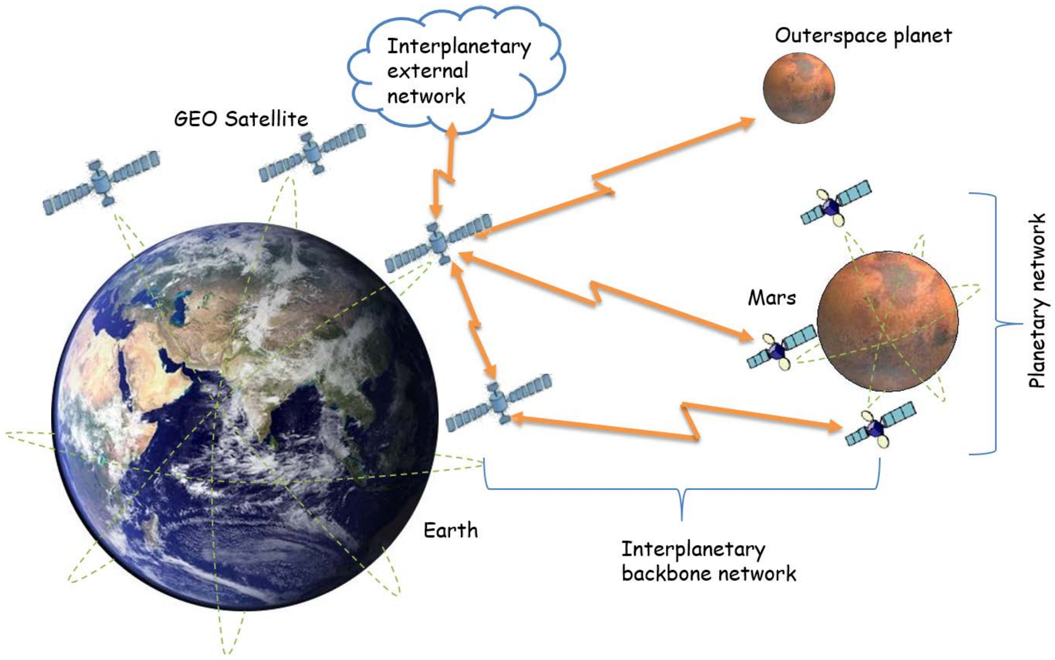

FIGURE 1. The IPN internet architecture.

1. The application of a rate adaptation mechanism over LTP for supporting multiple bundle transmission belonging to different connections.
2. The formalization of a resource and receiver oriented bandwidth fair sharing policy applied to a time-ordered bundles to reduce the buffer overflow situation.
3. The integration of the rate adaptation policy within a DTN routing such as EAODR to evaluate the joint effect of an efficient routing with a rate adaptation algorithm.

III. INTERPLANETARY NETWORKS

The advancement in the deep space research is due to the missions operated by the international space organizations such as NASA, Jet Propulsion Laboratory (JPL) and European Space Agency (ESA) [7]. Due to the large delays associated with this type of communication (the speed of which is limited to that of light) it is necessary to draft new communication protocols, which are able to tolerate the large delays inherent in this type of communication, as well as the creation of new technologies compatible with these conditions. A new overlay protocol called Bundle Layer was created for facing with unstable communications networks. It groups data blocks into bundles and transmits them using a *store-and-forward* technique. An IPN node is responsible of the delivery of the data then it custodies the data until it receives the acknowledgement of the next hop and then it is able to delete data from persistent storage. In Fig. 1 it is depicted a typical representation of a IPN network which includes IPN Backbone network, that provides a common infrastructure for communications among earth and other planets. Planetary Networks which is composed of planetary satellite network and planetary surface network. This architecture can be implemented at any outer-space planet, providing interconnection and cooperation among the satellites and surface elements on a planet like rovers and landers. The literature presents some work about IPN Networks and DSCs that treat about different issues. Some authors describe the missions exploring the space in order to allow an ubiquitous communication in a not too distance future such as in [42]. The Consultative Committee for Space Data Systems (CCSDS) has produced a relevant number of recommendations, concerning architectures and protocols to enable efficient navigation and communication services in space environments [43]. CCSDS activity has been primarily focused on the definition and implementation of a protocol architecture, alternative to the existing ones (e.g., the TCP/IP suite), to support data transfer effectively over long delay and lossy networks, as in the case of IPN networks. Moreover, CCSDS has developed the Space Communications Protocol Specification-Transport Protocol (SCPS-TP) [44] to provide end-to-end reliable communication.

A. MAIN FLOW CONTROL PROBLEMS OVER IPN

The main problem in the IPN communication is the very long propagation delay that has a significant effect on the traditional reliable transport protocol like TCP and on real-time multimedia application. An important aspect is due to the RTT value that affects the performance of the protocol; it affects the time to reach a certain window size. If the RTT value is too high the performance of the system are degraded. In the classical transport protocol the initial phase covers an important role. For a higher RTT value an appropriate initial value of transmitted data is much more complicated to decide. Hence, the need of developing new transport protocol approach. In particular, networks that do not satisfy the following equation, called Mathis equation [45], do not belong to the set that it is possible to manage with the TCP protocol suite:

$$B_W < \left(\frac{MSS}{RTT}\right) \cdot \frac{1}{\sqrt{p}}$$

where:

- B_W is the bandwidth;
- MSS is the maximum size of the TCP segment;
- RTT is the round trip time;
- p is the lossy packet probability.

In Table 2 the RTT min and max of sun system planets are shown, It is possible to view that, in the case of Mars, the RTT min is about 8 minutes and the RTT max is about 40 minutes.

TABLE 2. **Minimum and maximum RTT (in minutes) for different planets.**

Planet	RTT min	RTT max
Mercury	1.1	30.2
Venus	5.6	35.8
Mars	8.0	40.0
Jupiter	81.6	133.3
Saturn	165.3	228.4
Uranus	356.9	435.6
Neptune	594.9	646.7
Pluto	593.3	1044.4

The flow control technique over IPN networks poses a number of challenges, prompting the researcher to seek novel solutions. In the following the main issues for a deep space network: *Long Propagation delays*: the distance from the Earth to the Mars is more than 60 million kilometers with the RTT from 8 to 40 minutes approximately. In the IPN communications, the long delays mean that protocols that use many round-trips to accomplish some task pay a significant time penalty. *Transmission Errors*: the current satellite Bit Error Rate (BER) is high on the order of 10^{-6} on average and 10^{-4} at worst case. The BER on the backbone links is usually much higher than 10^{-2}. *Asymmetry Channels*: Many satellite systems offer users with a download capability at tens of Mbps but the upload capability is only hundreds of kbps *Blackouts*: Because of the movement of planetary bodies and spacecraft, the periodic link outage may occur. In our work we have considered an approach based on [24] in which a link switches between active and inactive states over time. Since the movement of planet nodes is periodic, the links also show periodicity. *High link error rates*: The raw BERs on the IPN backbone links are on the order of 10^{-1}.

The well known transport layer protocols can be implemented to IPN Networks with ad-hoc changes and upgrades. Anyway, the IPN Backbone Network's issues necessitate custom-tailored new transport layer solutions [14]. In our case, we considered the LTP over UDP (LTP/UDP) with the integration of a rate adaptation mechanism over LTP to manage concurrent bundle transmissions.

B. MAIN ROUTING ISSUES OVER IPN

The implementation proposed in [13] presents two variations of CGR: 1) the CGR in its original implementation designed for scheduled networks only and 2) the Opportunistic CGR, which was enhanced to be used in networks that are not completely scheduled. The "cgr-jni-Merge" package introduced in [29] with the ONE simulator (version 1.6.0) can be a good simulation tool to do some experiments on routing and BP in DTN architecture through the class ContactGraphRouter.java. Moreover, the new connections class provided by the cgr-jni-Merge package allows to set the speed of individual connections according to the contact plan. Starting from version 3.6.1, the bundle fragmentation has been also introduced to evaluate the effect of bundle fragments in the routing and adaptive rate selection. Even if a lot of work has been done also on routing strategies, there are many routing issues to be yet fully addressed such as listed below:

1. The impact of the fragmentation on the routing strategy considering only end-device fragmentation or in-network fragmentation.
2. A cross-layer between routing and physical layer in order to get advantage in the route selection also about the link degradation in the time.
3. The security over routing layers to provide more secure topology building and route selection.
4. The interaction of upper layers (BP and LTP) with different routing strategies to understand the most performing CGR under different traffic load conditions or different network scaling.

In our case, the work presented in [31] has been considered to see the effects of our rate adaptation strategy applied in concurrent connections and bundle transmissions. This choice does not reduce the validity of the proposal because it could be extended in future works also to other routing strategies such as listed in [28] and [32].

IV. DTN ARCHITECTURE

DTN represents a possible approach to be used for IPN networks [3], [4], [46]. DTN is officially developed by DTNRG (DTN Research Group) that is chartered as part of the Internet Research Task Force (IRTF). DTNRG are concerned with how to address the architectural and protocol design principles arising from the need to provide interoperable communications with and among extreme and performance-challenged environments where continuous end-to-end connectivity cannot be assumed. The DTN architecture uses a *store-and-forward* strategy to tackle the challenge of reliable message delivery in intermittent networks by storing messages in persistent memory at DTN routers for relatively long periods of time. These new networks, defined "challenged networks" provide communications by implementing the new layer called "bundle layer" [5] (see Fig. 2). This new component gives a uniform view of the network, even though different protocols may exist in the system. The communication between different DTN bundle layers happen utilizing simple sessions with a minimum or no RTT,

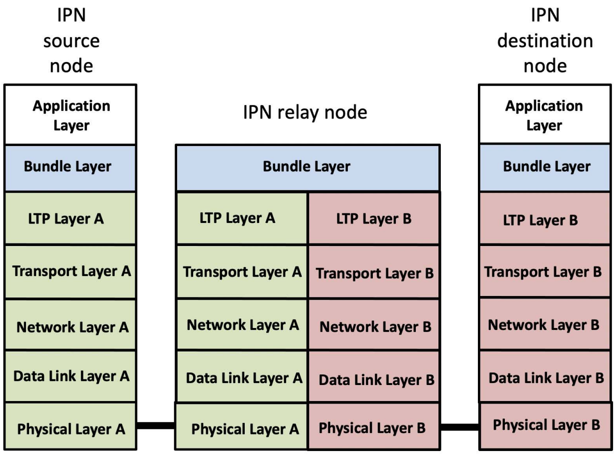

FIGURE 2. **DTN basic architecture.**

removing the source-destination communication control interaction (acknowledgement is optional and depending of the selected class of service). This layer is responsible for storing and transmitting full bundles across nodes in a DTN area. A DTN area presents homogeneous communication properties, independently from network topologies and addressing schemes. Nodes from distinct networks with different addressing schemes are usually unable to communicate.

The overlay protocol serves to bridge between different stacks of the different networks.

A DTN-enabled application sends messages of arbitrary length, also called Application Data Units or ADUs. ADUs are transformed by the bundle layer into one or more protocol data units called "bundles", which are forwarded by DTN nodes. Bundles have a defined format containing two or more "blocks" of data. Each block may contain either application data or other information used to deliver the containing bundle to its destination(s). Bundles may be split up into multiple constituent bundles (also called "fragments" or "bundle fragments") during transmission. Fragments are themselves bundles, and may be further fragmented. Two or more fragments may be reassembled anywhere in the network, forming a new bundle. These bundles are sent by a node called "custody node". DTN as an "overlay" architecture is intended to operate above the existing protocol stacks in various network architectures and provide a gateway function between them when a node physically touches two or more dissimilar networks. The DTN architecture includes two distinct types of message routing nodes: persistent (P) and non-persistent (NP). P nodes generally participate in custody transfer using the appropriate transport protocol(s) of the containing region. The custody transfer concept is fundamental to the architecture in order to combat potentially high loss rates and to relieve potentially resource-poor end nodes from the responsibilities related to maintaining end-to-end connection state. In particular, end nodes do not ordinarily need to keep a copy of data that has been custodially transferred to a DTN next hop. Custody transfer can be viewed as a performance optimization for end-to-end reliability. Another aspect fundamental for this type of network (a kind of hop-by-hop network) is the flow control and congestion mechanism. Flow control in this context refers to limit the sending rate of a DTN forwarder to its next hop. Congestion control refers to the handling of contention for the persistent storage at a DTN forwarder. The services offered by bundle layer are optional for the sender application and they can be requested trough an appropriate flag setting on the sent bundle. The preview classes of services are: Custody transfer, Return receipt, Custody transfer notification, Bundle forwarding notification, Priority of delivery, Authentication.

V. AN HOP-BY-HOP RATE ADAPTATION WITH BANDWIDTH FAIR-SHARING (RABF) APPROACH

In this work, due to the impossibility of using classical end-to-end control of transport layer, the LTP protocol over a DTN architecture is applied according to [41]. However, in order to support concurrent bundle transmission through a resource receiver oriented approach, a RABF based on a hop-by-hop logic is proposed and applied. [47], [48]. Our bundle rate selection is applied over the LTP layer in the DTN architecture such as shown in Fig. 3 with the aim to further reduce the buffer overflow and guarantee, at the same time, reliability mechanisms over links with intermittent connectivity. The proposed RABF approach is able to provide traffic information and local resource availability on the receiver side in order to increase or decrease the sending rate of a sender thanks to a feedback to a request of transporting a bundle. These information can be used also from the upper layers. The proposed study tries to improve the link utilization in order to prevent congestion situations. The congestion situation can occur in the case of simultaneous transmissions of multiple bundles towards the same device. In fact, these bundles compete into the acquisition of bandwidth and storage buffer. In Table 3, a list of parameters used in the mathematical formulation is given. These parameters are used in the RABF algorithm described in the following section.

A. RABF ALGORITHM DESCRIPTION

The first operation of the proposed mechanism in the case of communication between nodes is to verify by IPN source node IPN_T that a link towards the next node IPN_D is active with a sufficient bandwidth capacity. The flow diagram of IPN sender and receiver nodes is respectively depicted in Fig. 4. In the following, the steps necessary to estimate the bundle rates and their application times will be explained. We have considered with BC_{TD} the total Bandwidth Capacity (BC) in output between the transmitter IPN_T and the destination IPN_D. The condition for guaranteeing availability of bandwidth capacity is defined as follows:

$$\sum_{j=1}^{N_0} R_j < BC_{TD} \tag{1}$$

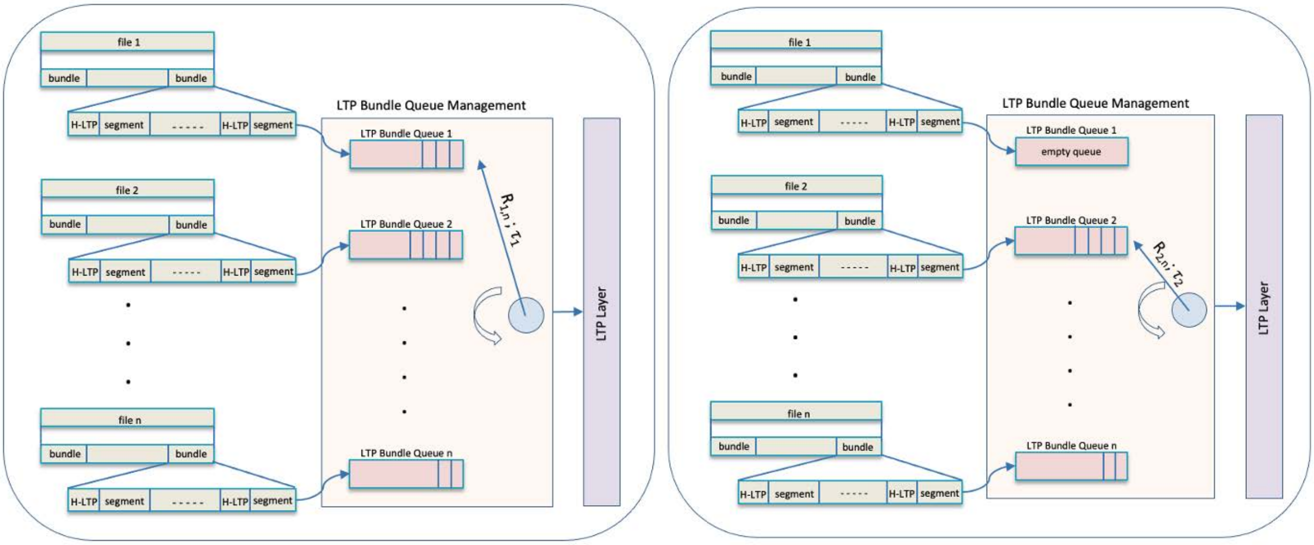

FIGURE 3. Transmission concurrency of n bundles with fair sharing scheduler and rate adaptation.

TABLE 3. Parameters considered in the RABF algorithm.

Parameters	Description
N^r	number of correctly received bundles at receiver (IPN_D)
N_0	number of transmitted bundles from sender (IPN_T)
S_k	length of the generic bundle k
$W_k(t)$	portion of the bundle k that has been received and stored in the buffer at time t
$R_k(t)$	data rate of the bundle k at time t
C_r	input link capacity at IPN_D
C_i	total received traffic at IPN_D that can be managed in order to avoid buffer overflow
BC_{TD}	output bandwidth capacity of sender IPN_T towards destination IPN_D
$R_{k,j}$	rate applied to k-th bundle when it is in transmission concurrency with bundle j-th
τ_k	duration of transmission concurrency of k-th
τ_k	arrival time of first fragment of k-th bundle at the destination (IPN_D)
t_{arr_k}	maximum residual duration among all currently active bundles N_i
RTT	$Round\ Trip\ Time$ from sender IPN_T to receiver IPN_D
B_r	total buffer capacity
$B_u(t)$	occupied buffer size at time t
$t_{MAC} + RTT/2$	time of ATI necessary to reach the sender (IRS_s)
Δ_{ATI_k}	residual time between the arrival of first ATI of bundle k-th and its sender side effective application
t_{f_j}	time when j-th bundle is transmitted
δ_k	expiration time of k-th bundle

where R_j is the current data rate of a generic j-th bundle sent by IPN_T. Otherwise, if the condition in (1) is not true the mechanism previews to memorize the k-th bundle in a queue waiting for a new capacity availability. In order to send the k-th bundle, the IPN_T begins the connection transmitting a *Send Connection* message as shown in flow diagram of Fig. 4. The bundle will contain into its header a time constraint condition, added by the application layer, that can be equal to zero ($\delta_k = 0$) if no time condition is set. The connection can be restored when the node receives the acknowledgement (ACK) in response to the *Send Connection* message. In the case of $\delta_k > 0$ the transmitter IPN_T will send the bundle considering the following rate:

$$R_k(0) = min\left\{\left[BC_{TD} - \hat{R_k}\right], \hat{R_k}\right\} \tag{2}$$

where BC_{TD} is the output bandwidth capacity of the transmitter IPN_T, $\hat{R_k}$ is the considered initial rate for the k-th bundle computed as $\hat{R_k} = S_k/\delta_k$, with S_k indicates the size of the k-th bundle.

The receiver IPN_D, upon receiving *Send Connection* message, increases a counter N^r indicating the active connections number. Moreover, at the reception of a bundle the destination will memorize some information contained in the header like *bundle ID*, length S_k, expiration time δ_k, used for computing important bundle transmitting parameters. An example of bundle header is shown in Fig. 5.

Another fundamental condition to be respected and related to buffer overflow condition is the following:

$$C_i \leq C_r \tag{3}$$

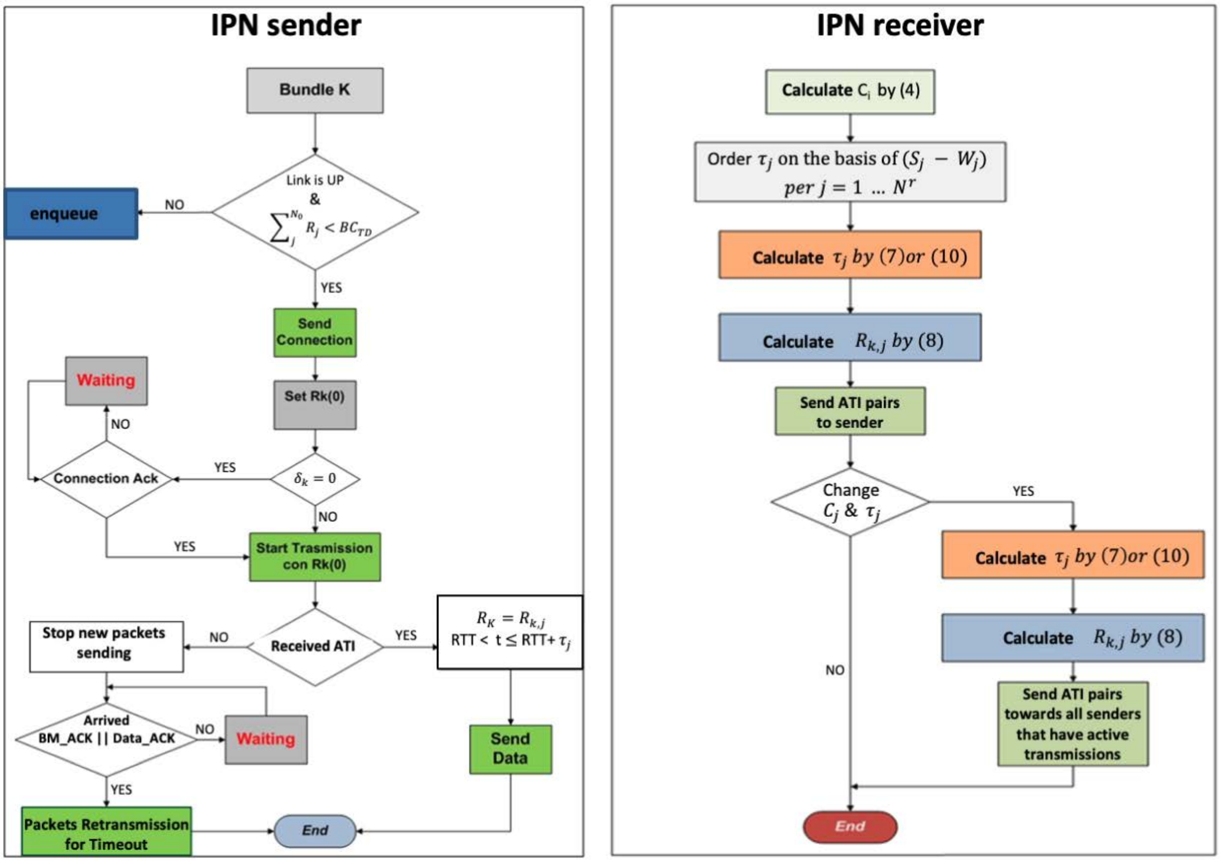

FIGURE 4. Flow diagram of the algorithm steps on sender and receiver side.

FIGURE 5. Header format of the bundle message.

where C_i has the following definition:

$$C_i = min\left\{C_r, \frac{1}{t_{max}-t}\cdot\left[B_r - B_u(t) + \int_t^{t_{max}} C_0(\delta)d\delta\right]\right\} \tag{4}$$

where the main terms in (4) are so defined:

- $t_{max} = \frac{S_i - W_i}{R_i}$, with $i = argmax(S_j - W_j)$ and $j = 1, \ldots, N^r$;
- $C_0 = min(C_l > 0 | l \in L_{node_r})$, with $L_{node_r} = l_1, \ldots, l_n -> node_r = 1, \ldots, (MaxNode - 1)$

C_0 is defined as the utilization of the instantaneous output link at the destination node, that is, the minimum capacity value over all output links $l \in L_{node_r}$ from the receiver node $node_r$ where at least an active connection exists. We highlight that the C_i computation is done by receiver/forwarder nodes that have links in output towards other nodes and not by terminator/receiver nodes that have the task to send bundles towards application layer.

The proposed RABF method takes into account the total received traffic C_i on the receiver side for promoting a policy based on a *fair sharing of the bandwidth* among bundles of multiple connections and it assigns to the k-th bundle suitable for transmitting a data rate defined as follows:

$$R_k = \frac{C_i}{N^r + 1} \qquad with \quad i = 1, \ldots, N^r \tag{5}$$

Upon receiving the k-th bundle at the destination node some active connections may expire. This means that the bandwidth R_k allocated for a bundle is set only for an amount of time. To optimize link usage, R_k must be adjusted when the available resource (bandwidth) at the receiver node (IPN_D) increases/decreases at most N^r times due to the maximum number of active/terminated connections. The destination node IPN_D will now calculate the following three parameters for k-th bundle:

- $R_{k,j}$, transmission data rate to be assigned to a generic bundle k, when $j - th$ bundle is still active on the same link and where $j = 1, \ldots, N^r$
- τ_j, time window where the data rate is valid, and
- $\tau_j' = \tau_j(t)$, time evolution of τ_j.

The above information are sent back to the transmitter IPN_T node in a message called Availability Timeline Information (ATI). In the proposed approach we have considered

τ_j sorted in ascending order on the basis of $S_j - W_j$ data, so to have $\tau_1 < \tau_2 < \ldots < \tau_{N^r}$ where τ_1 is defined as follows:

$$\tau_1 = \frac{(S_1 - W_1) - \left(\left\lceil \frac{R_1 \cdot RTT}{W_1} \right\rceil \cdot W_1\right)}{R_{1,1}} \tag{6}$$

where:

- S_1 is the first bundle size;
- W_1 is the first bundle fragment size received from IPN_D
- $R_{1,1}$ is the first bundle rate that will be applied by sender on the basis of the ATI message;
- τ_1 is the time computed by the receiver at the second bundle arrival.

In particular, an explanation of the terms in numerator and denominator of (6) is provided in the following.

For the numerator:

- $(S_1 - W_1)$ is the residual bundle size at IPN_D node;
- $\left\lceil \frac{R_1 \cdot RTT}{W_1} \right\rceil \cdot W_1$ is the amount of fragments sent in RTT time by the transmitter before receiving the ATI message.

For the denominator:

- $R_{1,1} = \frac{C_i}{N^r+1}$

Each time that a bundle is entirely received at the IPN_D node, the new bundle sending data rate is changed. This means that the data rate of the j-th bundle with $j \geq 2$ is different and this affects the bundle residual transmission time. On the basis of these considerations the τ_j can be defined as follows:

$$\tau_j = \frac{(S_j - W_j) - \left(\left\lceil \frac{R_j \cdot RTT}{W_j} \right\rceil \cdot W_j\right)}{R_{j,j-1}} - \frac{\left(\left\lceil \frac{R_{j,1} \cdot \tau'_1}{W_j} \right\rceil \cdot W_j + \ldots + \left\lceil \frac{R_{j,j-1} \cdot \tau'_{j-1}}{W_j} \right\rceil \cdot W_j\right)}{R_{j,j-1}} \tag{7}$$

where: the terms $\tau'_1, \ldots, \tau'_{j-1}$ represent the time evolution of the terms $\tau_1, \ldots, \tau_{j-1}$ calculated by previous bundles, whereas $R_{j,j-1}$ represents the rate applied to the j-th bundle when$(j-1)$-th ATI arrives at the transmitter. The importance of the ATIs are explained in the next section

Considering the proposed mechanism of bandwidth assignment based on a policy of *fair-sharing* the following expression represents the k-th bundle data rate $R_{k,j}$ in concurrency with j-th one for a time of τ'_j with $j < k$ and all bundles l are expired with $l = 1, .., j-1$:

$$R_{k,j} = \frac{C_i}{k-j+2} \tag{8}$$

The arrival of a new *Connection Request* message at the destination node in a case of variation in the capacity availability involves the rate notification to the transmitter node. In Fig. 6 it is shown the time diagram of the data and control packet exchange (SendConnection, ATI info, Custody Accept, Report-to Source, Ack Custody Transfer) for a new connection between two IPN nodes in a DTN architecture.

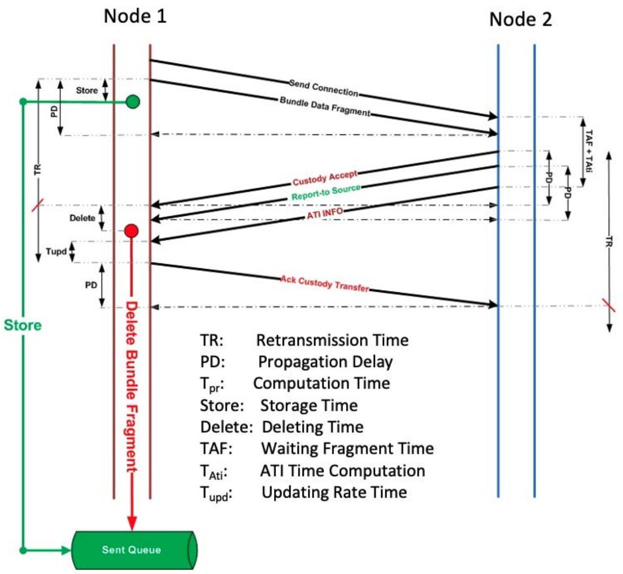

FIGURE 6. Data and control packets exchange between two IPNs under DTN architecture.

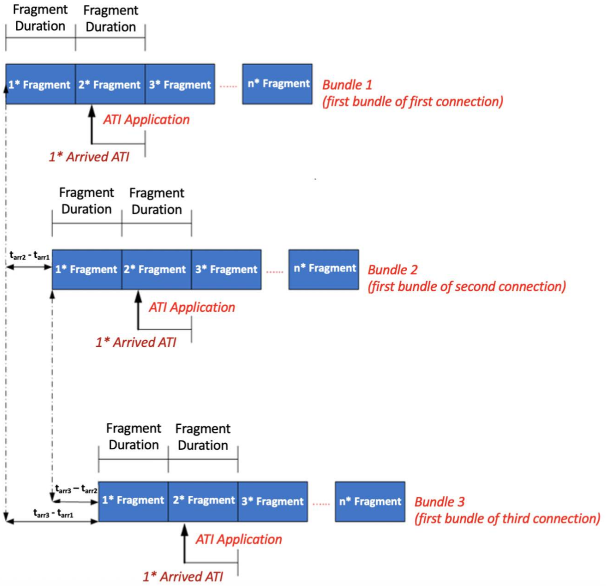

FIGURE 7. Transmission concurrency of three bundles and ATI packets arrival.

B. CONCURRENCY TRANSMISSION TIME UNDER MULTIPLE BUNDLES TRANSMISSIONS

The concurrency transmission of three bundles is shown in Fig. 7. In order to determine a correct rate selection policy it is important to consider the ATI packet arrivals. The concurrency transmission time τ'_j for the transmission of an asynchronous bundle is defined in the following equation. Before giving the general formula, a list of terms applied in the math formulation is provided below:

- $R_{k,j}$: rate applied to bundle k-th when it is in concurrency with bundle j-th;

- τ'_j: how long time the bundle k-th is in concurrency with bundle j-th;
- $t_{R^j_k}$: time in which the sender side rate R^j_k is applied;
- t_{arr_k}: arrival time of first fragment of bundle k-th at destination;
- $t_{Mac} + RTT/2$: ATI necessary time to reach the sender;
- Δ_{ATI_k}: residual arrival time of first ATI_k for its effective sender side application;
- Δ_{ATI_j}: residual arrival time of first ATI_j for its effective sender side application;
- t_{f_j}: ending time of bundle j-th;

$$t_{R^j_k} = t_{arr_k} + t_{Mac} + \frac{RTT}{2} + \Delta_{ATI_k} \tag{9}$$

$$\begin{aligned}\tau'_j &= t_{f_j} - t_{ATI_k} = \left(t_{arr_j} + t_{Mac} + \frac{RTT}{2} + \Delta_{ATI_j} + \tau_j\right)\\ &\quad - \left(t_{arr_k} + t_{Mac} + \frac{RTT}{2} + \Delta_{ATI_k} + \tau_k\right)\\ &= \tau_j - \tau_k - (t_{arr_k} - t_{arr_j}) - \left[\Delta_{ATI_k} - \Delta_{ATI_j}\right] \end{aligned} \tag{10}$$

Eq. (10) defines the concurrency transmission time τ'_j between two different bundles, k-th and j-th bundle, on the basis of the following information:

- the effective duration τ_j of j-th bundle;
- the time shift between the bundles arrival time $(t_{arr_k} - t_{arr_j})$;
- the time shift in the application of first ATI $\left[\Delta_{ATI_k} - \Delta_{ATI_j}\right]$.

VI. MODIFIED TEMPORAL GRAPH FOR BUNDLE ROUTING OVER IPN

According with proposal in [31], we applied a Modified Temporal Graph (MTG) to find a path from a terrestrial source to a Mars destination considering some orbital stations that compose our spatial backbone. It is preferred the application of EAODR because authors showed some improvements in comparison with Contact Graph Routing (CGR) [28]. In particular, we extended the EAODR to consider not only the earliest arrival optimal delivery ratio but it can apply the modified version of Dijkstra for each ATI arrival time. This can assure that the overall time necessary to traverse the selected path p from a source to a destination can be updated and it can consider the real resource availability on the link to avoid the buffer overflow. The EAODR in the predetermined and recurrent Contact Plan (CP) considers the following values to compute the routing cost: (1) the time to reach the source; (2) the time it takes the bundle with size S_i to travel at a data rate R_j; (3) a variable ϵ to consider the queuing time in addition with the One Way Light Time (OWLT). However, the basic version of EAODR does not consider a data rate R_j that is able to account for the concurrent bundle transmission such as explained in the previous section. The knowledge of the resource availability can allow the transmitter to properly trigger the bundle data rate change on the basis of the output link capacity of the selected neighbour DTN node and on the basis of current number of concurrent bundle transmissions. At this purpose, the idea is to consider as R_j data rate for each new bundle a variable data rate $R_j(t)$ that can potentially change for each ATI message generated by the receiver towards the source. Because the IPN receiver IPN_D, such as explained before, can know the buffer overflow condition on the basis of the output link capacity C_0 and considering the number of bundle requests on the input link, it can generate ATI message where information such as explained in Section V-B can be sent allowing the computation of $R_{j,1}, R_{j,2}, \ldots, R_{j,N^r-1}$ for each bundle j-th during the termination of previous concurrent bundles k-th with $k = 1, .., N^r - 1$. We did not show the algorithm details because they are explained in [31] where the convergence of the algorithm is also proved. In our case, differently by the classic EAODR, it is applied a cross-layer approach that allows the computation of $R_{k,j}$ on the basis of the concurrent bundle management applied at upper layer.

$$R_j^{l_i} = \frac{R_{j,1}\tau'_1 + R_{j,2}\tau'_2 + \ldots + R_{j,j-1}\tau'_{j-1}}{\sum_{i=1}^{j-1}\tau'_i} \tag{11}$$

where R_j is the rate associated to link l_i during the time window of l_i between two IPN nodes. This means that bundle rate is not assigned on the basis of a nominal capacity of the link but on the basis of its concurrency with other bundles. In this case, if the bundle to be transmitted on the selected link is the first without time overlapping with other bundles it will start with an higher rate R_1. When multiple bundles will arrive the data rate is distributed with a fair-sharing policy among the other bundles and when this bundle will terminates, the bundle rate will change in the time such as explained in the previous section. The advantage of selecting dynamically a rate on a bundle/fragment basis of neighbour IPN resource availability and on the basis of the bundle concurrency will provide benefits in the bundle buffer management such as will be shown in the next section.

VII. PERFORMANCE EVALUATION

In this section we present the simulation results of a system with the proposed RABF mechanism. The considered scenario depicted in Fig. 8 shows the communication between the Earth and Mars through the use of a intermediate satellite called *Orbital Station (OS)*. Two terrestrial terminal stations connected to the respective satellites are placed on the terrestrial side and a mars terminal station connected to a mars satellite is placed on mars surface. The communication among these terminals is considered in our experiments taking into account different bundles size in the range [20000, 80000] bytes. The simulation parameters used in the simulations are given in Table 4.

A. IPN NETWORK UNDER DTN WITH UNLIMITED BUFFER SIZE

IPN Network with a classical DTN where the buffer is considered unlimited has been considered in the first scenario.

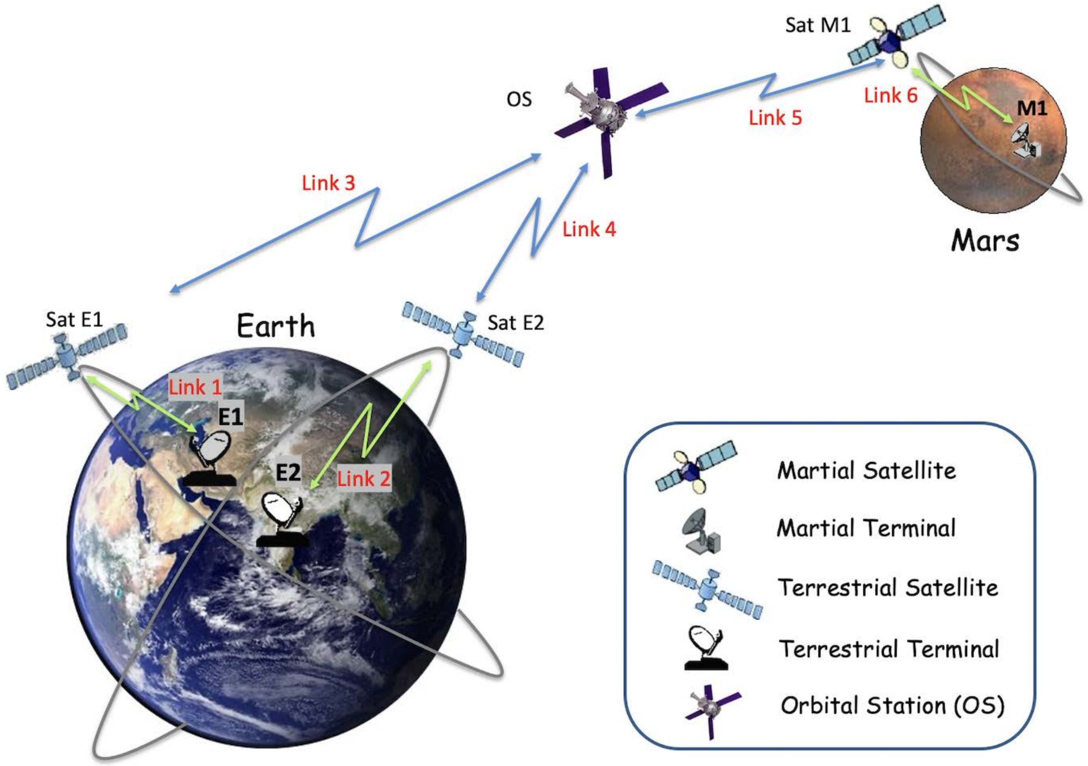

FIGURE 8. Simulated scenario.

TABLE 4. Simulation parameters.

Network Entities		
Terrestrial Terminal	E1	
Terrestrial Terminal	E2	
Terrestrial Satellite	Sat E1	
Terrestrial Satellite	Sat E2	
Orbital Station	OS	
Martial Satellite	Sat M1	
Martial Terminal	M1	
Network Parameters		
Link 1	E1 – Sat E1	4 Mbit/s
Link 2	E2 – Sat E2	4 Mbit/s
Link 3	Sat E1 – OS	512 kbit/s
Link 4	Sat E2 – OS	256 kbit/s
Link 5	OS – Sat M1	256 kbit/s
Link 6	Sat M1- M1	64 kbit/s
Bundles size	[20000,80000]	

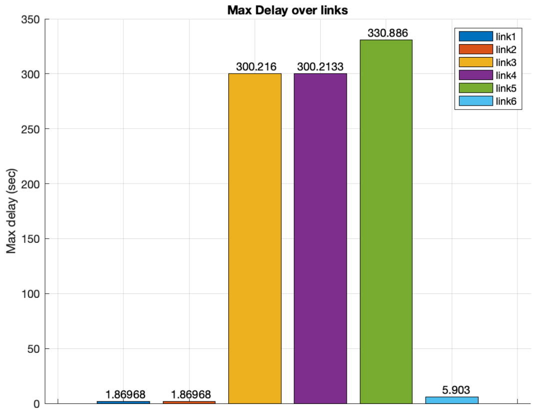

FIGURE 9. Maximum delay over all IPN links.

In this case DTN uses a sequential forwarding of bundles without defragmentation at intermediate hops and regeneration of bundles timestamp, and without applying a flow control mechanism. The maximum end-to-end delay for link is presented in the Fig. 9. For this case a bundle size of 20000 bytes has been fixed. It is observed higher delay for the link on the IPN connections that fall in the range [300-400s]. This is due to the considerable distances that separate the nodes. The queue utilization trend on the network nodes is shown in Fig. 10. In this case, this trend increases for higher bundle sizes and orbital station presents higher values because an heavy traffic overload is observed on its incoming link.

Fig. 11 and Fig. 12, show the queue size trend in the temporal interval. In particular, it is possible to note the dual trend of the queues between the orbital station and the martial satellite node. The different slope shown in the figure indicates the congestion grade that the terrestrial satellites make on the orbit station that represents a bottleneck link.

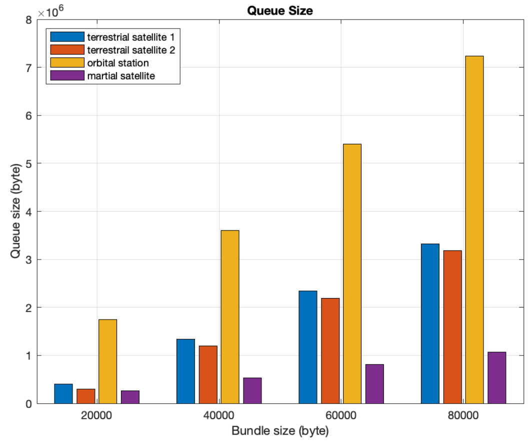

FIGURE 10. Queue size trend on the network nodes for increasing bundle sizes.

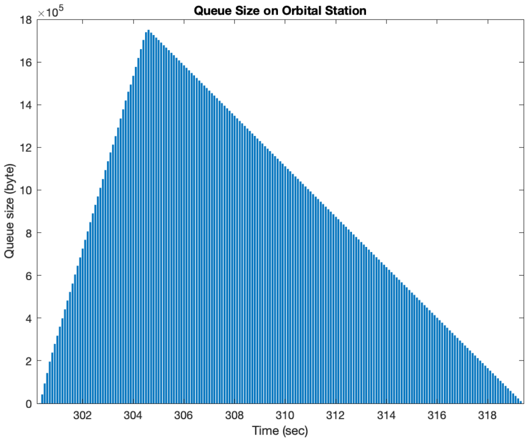

FIGURE 11. Queue utilization trend on orbital station.

TABLE 5. Buffer sizes associated with network topology.

E1	Limited Buffer 30000000 byte
E2	Limited Buffer 3000000 byte
Sat E1	Limited Buffer 3000000 byte
Sat E2	Limited Buffer 2000000 byte
OS	Limited Buffer 3000000 byte
Sat M1	Limited Buffer 3000000 byte
M1	Limited Buffer 30000000 byte

B. IPN NETWORK UNDER DTN WITH LIMITED BUFFER SIZE

In order to evaluate the behavior of the classical DTN with the introduction of limited buffer we have performed another simulation campaign. In Table 5 we show the buffer size on each link.

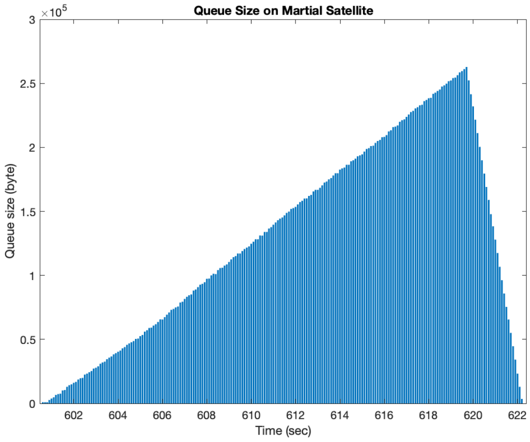

FIGURE 12. Queue utilization trend on martial satellite.

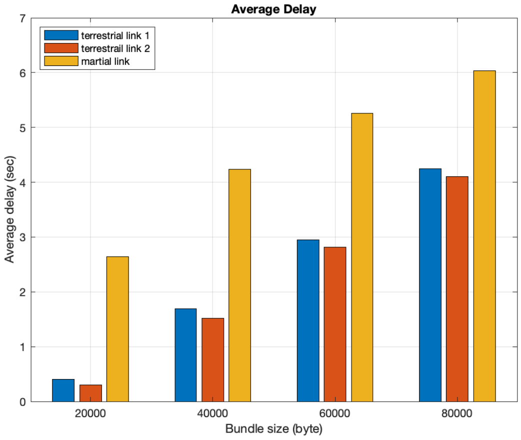

FIGURE 13. Average delay on terrestrial and martial links for increasing bundle sizes.

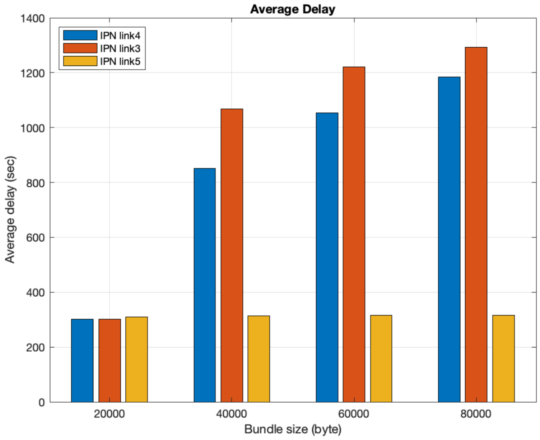

FIGURE 14. Average delay on IPN links for increasing bundle sizes.

Fig. 13 and Fig. 14 show the average delay graphics both on terrestrial and martial links and for IPN links. It is possible to note that the average delay increases at the increase of the bundle size both on terrestrial and martial link. Moreover, on the IPN links we make other considerations. On links between terrestrial satellites and orbital station we have

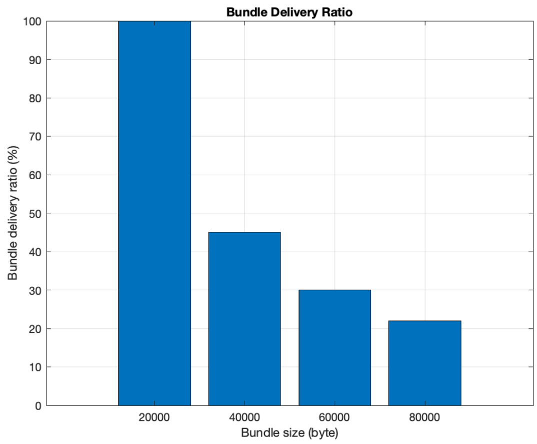

FIGURE 15. Bundle delivery ratio vs. bundles size.

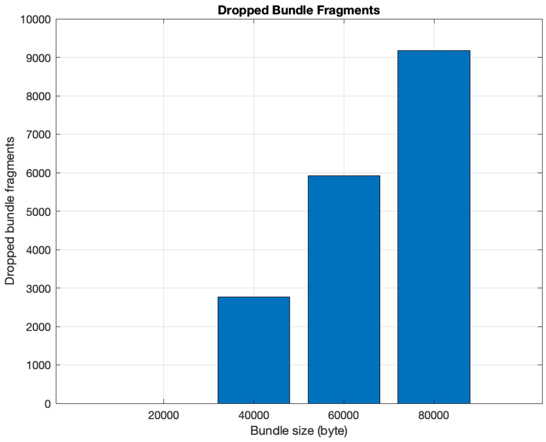

FIGURE 16. Dropped bundle fragments vs. bundles size.

higher average delay because congestion occurs on orbital station. On the other hand, on the link between orbital station and martial satellite we note that the average delay is almost constant because the transmission delay is negligible respect to the propagation delay and, furthermore, we do not have any congestion state on the satellite that orbit around the mars.

Fig. 15 shows a bundle delivery ratio in a IPN network with DTN architecture without bundle reassembly at intermediate node (just at the destination the fragments of each bundle are reassembled) and without rate adaptation. It is possible to note that the delivery ratio decreases increasing the bundle size with a delivery percentage comprised between 22% and 100%. We have noted the lowest bundle delivery ratio percentage with a bundle size of 80000 bytes due to limited buffer size that is saturated on the orbital station and to the bundle expiration time that determines bundles dropping. Fig. 16 shows the number of dropped bundle fragments for increasing bundle sizes. According with the previous explanation, it is possible to note as with a bundle size of 80000 bytes the system drops the greater number of fragments.

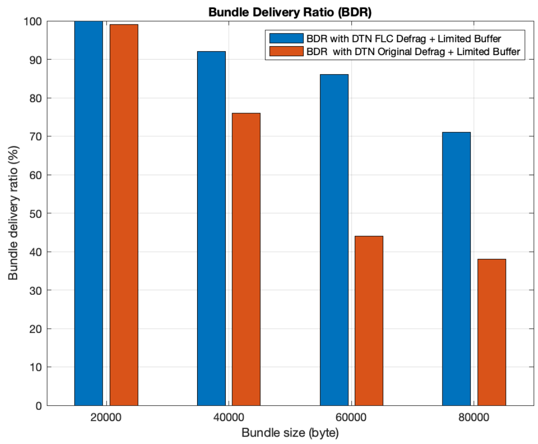

FIGURE 17. Bundle delivery ratio comparison between original DTN and modified DTN for increasing bundle sizes.

C. IPN NETWORK OVER ENHANCED DTN WITH RABF

In this sub-section, a comparison between a modified DTN with the hop-by-hop rate adaptation mechanism in each hop, regeneration of the bundles timestamp and limited buffer, and the classical DTN with only the bundles defragmentation and limited buffer has been led out. A simultaneous bundle forwarding, that is a possible cause of congestion has been considered in the simulations. Bundle delivery ratio under the condition of limited buffer is shown in Fig. 17. It is possible to see as RABF algorithm is able to mitigate the buffer overflow increasing the bundle delivery ratio in comparison with an IPN network with classical DTN without RABF. The improvement of RABF is more evident for higher bundle sizes that saturate more heavily the buffer of IPN nodes.

Our proposal improves the bundle delivery ratio in comparison with the original DTN where no rate adaptation is applied. This is due to the timestamp update that guarantees a bundle freshness at each hop. The RABF, on the other hand, mitigates the congestion by terrestrial satellite node but it has as trade-off a worst bundle delivery delay such as depicted in Fig. 18. In this case, the average delay on IPN link 5 is higher than delay experienced in Fig. 14.

D. EAODR VS EAODR WITH RABF

This last presented scenario considers an IPN backbone composed by 50 IPN nodes connected with deep space links that can forward bundles from terrestrial stations to Mars stations. The idea is to stress the bundle forwarding in a more populated scenario in order to see over future IPN networks where more objects or cubesats are located [49]. We used the same methodology proposed in [31] with the difference that a delay selected in the range [4-10] min. is considered

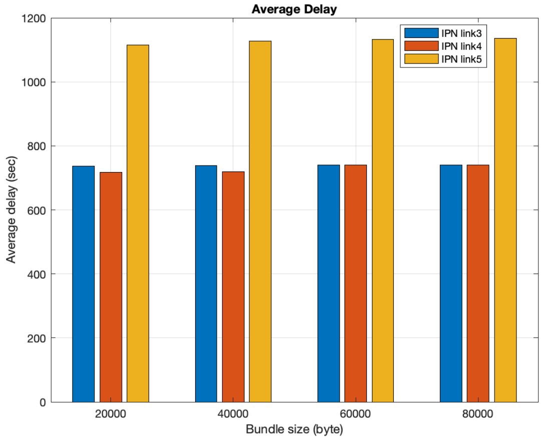

FIGURE 18. Average bundle delay on IPN links over modified DTN.

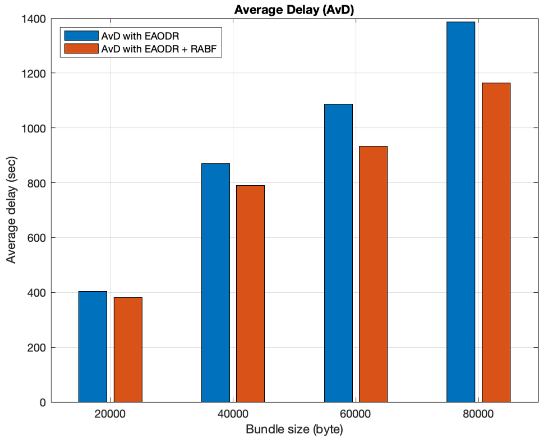

FIGURE 19. EAODR average bundle delay vs EAODR+RABF average bundle delay.

such as also referred in [50]. In particular, the edge start and end times are randomly chosen by setting but assuring that link duration of the contact is similar to that of the experiments performed in [31], [50]. This assumption does not affect the validity of the experiments because the idea is to show the performance of a contact-based routing applied to IPN under RABF and concurrent bundle transmission with or without a receiver oriented rate selection. The IPN links bandwidth considered for our simulations are selected in a range [32Kbit/s and 512Kbit/s] in order to create different bandwidth capacity on the IPN backbone links. Average bundle delays are presented in Fig. 19 for respectively the application of EAODR with first come first out (FIFO) bundle forwarding and EAODR with RABF bundle management. It is possible to see as EAODR+RABF can better manage the bandwidth supporting asynchronous concurrent bundle transmission and with a better buffer management over IPN relays. EADOR, instead, especially for longer bundle sizes increases the average bundle delay such as shown in Fig. 19.

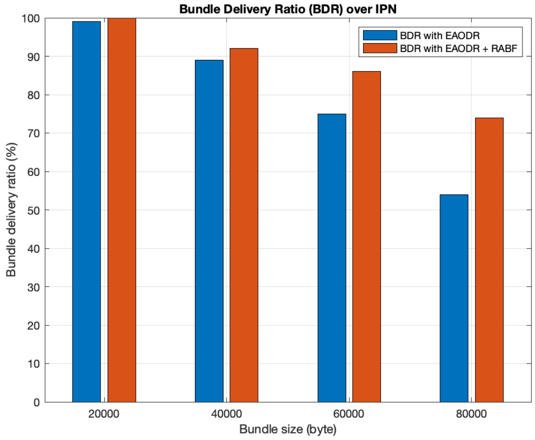

FIGURE 20. Bundle delivery ratio comparison between EAODR and EAODR + RABF.

On the contrary, EAODR+RABF can better manage the link capacity and bundle rate transmissions considering the bundle time limit and considering the output link bandwidth at each IPN relay. The bandwidth fair-sharing of RABF improves also the bundle delivery ratio such as shown in Fig. 20. This testifies as the management of concurrent bundles through a proper bandwidth sharing can assure that more bundles can be forwarded in the right time avoiding them to be deleted in the IPN node buffer. This improvement can be more evident for higher bundle size because buffers are more stressed and an efficient rate selection for each bundle can become mandatory.

VIII. CONCLUSION

The future will see an enormous space network capable of connecting overall planets in the space. Many spatial objects or orbital stations will populate the space with the hope to connect planets and offer good and scalable connectivity. IPN network, through the DTN technology, can be deployed trying to get advantage by deterministic contact pattern such as CGR and EAODR do. However, the bundle traffic, especially when concurrent transmission is supported, need to account for the resource availability of neighbour IPN nodes in order to avoid buffer overflow or to delay too much the bundle delivery time. A receiver-oriented RABF mechanism is proposed and it is integrated with a routing strategy with the aim to show as, in the near future, the interaction between bundle management layer and routing layer can improve the overall performance. Moreover, when multiple bundles can be properly managed, IPN link can benefit because an higher bundle delivery ratio can be guaranteed and also the bundle delay over IPN links can be better distributed without overloading buffers.

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FLORIANO DE RANGO (Member, IEEE) received the degree in computer science and the Ph.D. degree in electronics and telecommunications engineering from the University of Calabria, Cosenza, Italy, in October 2000 and January 2005, respectively. From January 2000 to October 2000, he was with the Telecom Research Laboratory CSELT, Turin, with a scholarship. From March 2004 to November 2004, he was a Visiting Researcher with the University of California at Los Angeles, Los Angeles, CA, USA. He is currently an Associate Professor with the DIMES Department, University of Calabria. He has authored or coauthored more than 270 papers among international journals and conferences. His research interests include the Internet of Things, IP QoS architectures, satellite networks, opportunistic networks, adaptive wireless networks, mobile *ad-hoc* networks, pervasive computing, and vehicular *ad-hoc* networks. In 2009, he founded Spintel s.r.l., a spin-off company, in the smart control tools design field for energy efficiency for smart building and cities and the Internet of Things (IoT) that won some awards in international competitions, such as the Intel Business Challenge Award. His company has been ranked in the first 20 innovative start-ups in the Intel Business Challenge Europe Competition (IBCE 2013). He was a recipient of the Young Researcher Award, in 2007.

MAURO TROPEA (Member, IEEE) received the master's and Ph.D. degrees in computer science engineering from the University of Calabria, Cosenza, Italy, in April 2003 and January 2009, respectively. From May 2008 to October 2008, he was a Visiting Researcher with the Telecommunication Department, ESA ESTEC, Noordwijk, The Netherlands. Since 2003, he has been with the Group of Telecommunications, DIMES Department. Since September 2018, he has been a Postdoctoral Researcher with the DIMES Department. His research interests include satellite communications, QoS architectures, bio-inspired algorithms, VANETs, FANETs, hierarchical networks, and multicasting.

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