This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE Globecom 2010 proceedings.

Joint Use of Custody Transfer and Erasure Codes in DTN Space Networks: Benefits and Shortcomings

Tomaso de Cola
DLR- German Aerospace Center
Institute for Communications and Navigation
82234 Wessling, Germany
tomaso.decola@dlr.de

Mario Marchese
DIST – Department of Communication Computer and System Sciences,
University of Genoa, Italy
mario.marchese@unige.it

Abstract — **The features that DTN protocol architecture offers are particularly appealing to handle intermittent links and disruption events, by means of the Custody Transfer option. On the other hand, the implementation of long erasure codes proved to be promising to contrast short fading events in long delay networks, where the high latency makes the use of ARQ schemes less profitable.**

This paper proposes a protocol design to incorporate long erasure codes into the Bundle Protocol specification. The conducted performance analysis shows the benefits coming from this integrated approach but also points out the possible shortcomings deriving from the saturation of the buffer implemented at the Bundle Protocol layer.

Index Terms – **Interplanetary Networks, Delay Tolerant Network architecture, Custody Transfer, Erasure Codes, Congestion.**

I. INTRODUCTION

THE Delay/Disruption Tolerant Network (DTN) architecture is expected to play a crucial role in future deep space missions, where network infrastructures offering high data rates will be deployed. In this perspective, the availability of protocol architecture, such as DTN, enabling autonomic node re-configuration and effective data forwarding will be of utmost importance to guarantee high performance of the overall telecommunication system. In particular, the store/forward capabilities of the Bundle Protocol implemented within DTN will be crucial to recover from possible disruption events, link interruptions or even temporary malfunctioning of software or hardware components.

On the other hand, some of the recent literature showed that short fading events can give origin to frame erasures, which would be efficiently recovered by appropriate coding schemes implemented at the higher layers. The so-called packet-level coding or also erasure coding actually complements the forward error correcting schemes implemented at the physical layer to provide greater robustness against link errors, which extend over several codewords.

Starting from this standpoint, this paper proposes a protocol design, actually extending the functionalities of the Bundle Protocol, so to incorporate erasure codes. The attention is then focused on the performance benefits that the double protection offered by packet-level coding and DTN custody transfer option can bring to the deep-space telecommunication system, in terms of communication reliability. Furthermore, it is also worth noticing that this increased robustness is achieved at cost of larger buffer usage, thus possibly resulting critical in deep-space networks, where usually spacecrafts can implement storage units of reduced capacity (few Megabytes). Hence, the problem finally considered is the performance degradation that can arise from congestion events determined by the reduced available bandwidth (because of redundancy packet transmission) and by the limited on-board buffer space.

The remainder of this paper is structured as follows. Section II overviews the state of the art of DTN architecture and erasure codes, whereas Section III draws the principles behind these two approaches and sketches the integrated architecture design. Section IV presents the performance analysis results, by highlighting the benefits and the shortcoming deriving from the proposed approach. Finally main conclusions and considerations about possible extensions of this work are reported in Section V.

II. BACKGROUND AND STATE OF THE ART

DTN protocol architecture has been conceived within the homonymous working group, being part of the Internet Research Task Force (IRTF) [1]. Great efforts have also being done in the Consultative Committee for Space Data Systems (CCSDS) to promote and standardise the use of this architecture for future deep-space missions [2].

Besides, a part of the scientific community too dedicated some attention to the advanced functionalities of DTN and their application to space communications. The advantages and the advanced features of the DTN architectures have been extensively investigated in the literature [3] since the first introductory work was published [4]. In particular the store/forward capabilities of DTN have been explored in [5] and then in [6] from an implementation point of view. On the other hand, the application of the DTN concept and the implementation of the protocol stack for deep space missions have been thoroughly analysed during the EPOXI and DINET [7] experimentations, carried out by NASA over the last two years. As remarked in Section I, an important role is played by the on-board storage capabilities that can be constrained to a few Megabytes, as reported in [8]. Hence, the possibility of congestion events cannot be completely disregarded, although it will be more likely in more complex space missions as analysed in [9].

Reliability issues in deep space networks have been already explored in terms of erasure codes in [10], where a packet-level coding was proposed at the application layer of the CCSDS protocol stack for cislunar space missions. The use of this approach within the DTN architecture was also considered in [11] to implement an adaptive coding mechanism.

Even though both erasure codes and DTN store/forward mechanisms have been explored, an appropriate design of the protocol stack hasn't yet been provided. Besides, the implications that erasure codes may have on the spacecraft storage capabilities resulting in possible buffer overrun events have not been considered either.

This paper aims at addressing the aforementioned issues, by proposing some extensions to the Bundle Protocol specification, in order to implement the packet-level coding concept. The interaction between erasure codes and store/forward capabilities is finally investigated, by analysing the case of deep-space data communications.

III. The Proposed Framework

A. Delay Tolerant Network Architecture

The Delay Tolerant Network protocol architecture builds on the Bundle Protocol, which offers advanced store/forward capabilities. In particular, the DTN architecture develops the concept of "internet of internets", according to which a reference network is logically subdivided in topological regions implementing dedicated protocols. The interaction between the different regions is then managed by edge DTN nodes, which are responsible for routing, fragmentation/ re-assembling operations, congestion control and QoS handling operations. The aforementioned services are implemented within the Bundle Protocol, which also offers reliability capabilities, by means of the Custody Transfer option. Once enabled, DTN nodes with appropriate storing capabilities can be elected as custodial, taking responsibility for the reliable delivery of data towards next-hop. In case of unsuccessful data delivery, either notified by the next-hop DTN nodes (through "failed" custodial signals) or detected through timeout expiration, the custodial will handle the retransmission of the missed bundles. In this respect, each custodial is expected to implement a storage unit, able to keep a copy of all bundles.

On the other hand, successful bundle transfer will be notified through "succeeded" custodial signals.

B. Erasure Coding

The principle behind packet-layer coding (here referred to as erasure coding) is to provide additional robustness at the higher protocol stack layers to contrast packet erasure events, resulting from channel fading. To this end, a set of k information packets are encoded into n ones, with $n-k$ redundancy packets, then corresponding to code-rate k/n [12]. Recent findings in coding theory showed that LDPC (Low Density Parity Check) schemes are particularly efficient, thanks to the low encoding/decoding complexity and the high recovery capacity [13]. In particular, it is possible to implement erasure codes relying on Maximum Likelihood decoding schemes, which are able to attain the singleton bound, thus performing as perfect codes.

This paper is actually more focused on the networking implications rising from the use of packet-level coding than on the design of the code. The interested reader can refer to [13] for the design of efficient LDPC erasure codes.

C. Extensions to the Bundle Protocol

From a protocol point of view, the integration of erasure codes into the DTN architecture can be achieved by either providing a new convergence layer towards the underlying protocol layers or introducing some extensions to the current Bundle Protocol specification. In this paper, we will pursue the second approach since bundle PDUs are inherently capable to support protocol extensions.

In more words, a bundle is a concatenation of a non-fixed number of blocks [14]. The first block, *primary block*, acts as header; following blocks are inserted to accomplish specific functionalities such as data block transport, administrative records management, just to cite a few. In this light, it is immediate to see in these additional blocks the candidate where information about coding strategy could be handled. In particular, size of the encoding block and positions of information and redundancy packets, respectively, should be transported in bundles so to ensure effective decoding procedures at the destination. To this end, bundles will be structured as concatenation of primary block, data body block (i.e., bundle payload) and an additional block, containing the fields necessary to the decoding process.

The overall encoding scheme is depicted in Fig. 1.

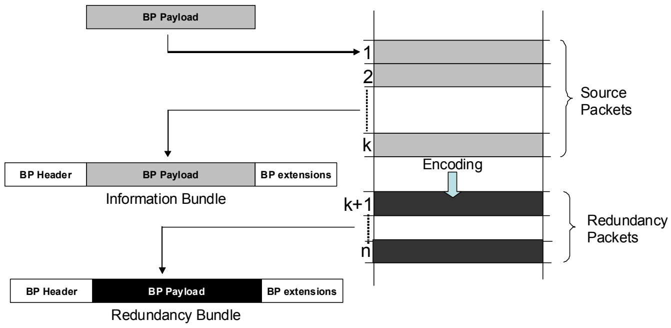

Fig. 1. The encoding scheme within the Bundle Protocol (BP) entity.

The implementation of the coding engine within the Bundle Protocol requires a buffer, subdivided in several encoding blocks, containing the encoded packets. To this end, the payload extracted from each incoming bundle is used as source packet (k) and then used to generate the redundancy packets ($n-k$). Once the encoding process is completed, each packet (source or redundancy) will be appended to the primary block and the extension block will be eventually inserted as trailer, in order to have a regular bundle PDU. Therefore, the soconstructed information and redundancy bundles will be forwarded to the underlying layer through the appropriate convergence layer (e.g., UDP or CCSDS Space Packet Protocol). Finally, the decoding process at destination will be straightforward and will basically consist of the same steps in the reverse order. It is omitted here for the lack of space.

D. Interaction of Erasure Codes and Custody Transfer

The effective interworking of Erasure Codes and Custody Transfer option within the Bundle Protocol has to be achieved by an attentive design of the extended-protocol functions.

The erasure codes are intended to make communication more robust against short fading events. On the other hand, the custody transfer option is a more general protection against bundle loss. In this respect, the following methodology is adopted:

- At the sender side, *n-k* redundancy bundles are generated out of *k* bundles formerly stored. The custody transfer option is then enabled for the full set of *n* bundles, which are in turn transmitted.
- At the receiving side, in case of successful decoding, a "succeeded" custodial signal is sent to the sender in order to reset the retransmission timers and free the buffer space formerly allocated to the unacknowledged bundles.
- In order to prevent unnecessary timeout expiration, the retransmission timeout is set equal to twice the propagation delay plus the transmission time necessary to send n bundles and the custodial signal and an additional margin time.
- In case of decoding fail, the receiver issues a "failed" custodial signal informing the sender which bundles are still needed at destination to complete the decoding process. A maximum number of retransmission loops is set as well.
- In case of timeout expiration, the full set of *n* bundles will be subject to retransmission.

For the sake of simplicity, both "succeeded" and "failed" custodial signals are hereafter referred to as bundle acknowledgment.

The overall protocol dynamics is depicted in Fig. 2.

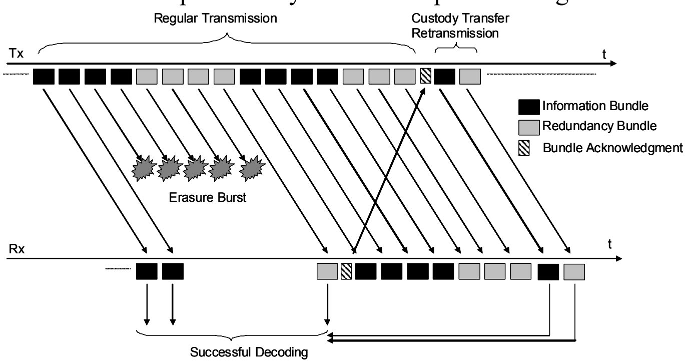

Fig. 2. Overall protocol behaviour.

IV. PERFORMANCE ANALYSIS

A. Reference Scenario

The proposed extensions to the Bundle Protocols have been assessed by taking as reference a common deep-space scenario, composed of different elements:

- Transmitter nodes (e.g., sensors, landers and rovers): they are located on remote planet surface (e.g, Mars). They can communicate with an orbiter, working as relay node towards Earth, through an RF proximity link.
- Relay node: it is an orbiter that forwards information received from the transmitter nodes towards Earth through a deep space link.
- Earth station: it is a gateway in charge of receiving and processing the incoming data packets.

In particular, it is worth remarking that all nodes implement a full DTN protocol stack and are elected as DTN custodial, owing to storage capabilities. Finally, the packet-layer coding approach is pursued only on the relay node (encoding part) and on Earth station (decoding part), since the attention is here mainly addressed to channel impairments introduced by the deep space links. In this respect, a 2-state Discrete Time Markov Chain (DTMC) embedded at the beginning of each packet transmission is introduced to characterise the channel time-varying fluctuations. States "0" and "1" correspond to the case of successful and unsuccessful transmission, respectively. The correlated nature of DTMCs allows taking into account the burst frame erasures that may arise in this context in consequence of fading events ranging between 1 and 100 ms.

As to the link quality degradations that can be observed on the proximity link, it is assumed that they can be completely compensated by the powerful Forward Error Correction schemes implemented at the physical layer.

The conducted performance analysis is aimed at showing the interaction between erasure codes and the possible saturation of the buffer (on-board storage unit) implemented at the bundle layer, when custodial-transfer option is enabled. In particular, the study is addressed to the case of large propagation and lossy links, where the combined use of erasure codes and ARQ schemes (as implemented in terms of Custody Transfer) can produce harmful congestion events.

B. Testbed Configuration

The performance analysis was carried out by means of simulations campaigns performed through ns-2. A number of runs sufficient to obtain a width of the confidence interval less than 1% of the measured values for 95% of the cases were imposed, while a simulation time of 5000 s was set for each test.

Deep space links were configured with 3 Mbit/s bandwidth and propagation delay of 5 s and 100 s. The 2-state DTMC was configured with average duration for state "0" and "1" set to 10 ms and 6 ms, respectively, resulting in a packet erasure rate of 37.5%.

The proximity link is configured with 10 Mbit/s bandwidth and 1 ms propagation delay.

As far as DTN node configuration is concerned, the relay node implements binary LDPC codes (1024, 2048), with a resulting code-rate 1/2. Each encoded bundle can handle up to 1024 bytes. The buffer implemented at the bundle protocol layer was configured with varying capacity: 1 Mbytes or unlimited. The second case was also tested to show the maximum queue length than can be achieved during intense retransmission phases. Finally, according to the implementation guidelines drawn in Section III-D, the custodial timeout is set to 16 s and 206 s for propagation delays of 5 s and 100 s, respectively.

Two transmitting nodes (denoted as "Transmitter 1" and "Transmitter 2") located on the remote planet surface (e.g., Mars) send a fixed amount of data, set to 10 Mbytes, encapsulated in bundles, at constant bit-rate 256 Kbit/s.

C. *Performance Results*

The assessment of the proposed framework was carried out by measuring:

- Average Data Delivery Latency: measured between the transmission of the first bundle and the reception of the last one.
- Instantaneous Buffer Queue Length: measured for each new incoming or outgoing bundle.
- Average Bundle Loss Rate: measured as the ratio between the number of information bundles correctly received at destination and the transmitted ones.

When the deep space link is configured with propagation delay 5s, the data delivery latency measured in absence of losses is 310 s. On the other hand, when the 2-state Markov chain is considered, the performance in strictly dependent on the capacity of the buffer implemented at the bundle layer. In case of unlimited buffer space, the delay rises to 431 s because of the additional latency introduced by retransmission loops triggered by the custody transfer option. It is particularly interesting to note that despite the implementation of erasure codes, in some cases the number of erased bundles make the decoding process to fail. Accordingly, the custodial transfer feature is then exploited, resulting in bundle loss rate equal to zero, at cost of increased delay. As far as the instantaneous buffer queue length is concerned, it can be observed from Fig. 3 that it increases up to a maximum of 5.5 Mybtes, and then slowly drops to 0, as the transmitter nodes stop sending data.

Interestingly, in case all DTN nodes implement limited buffers (capacity 1 Mbytes), the obtained results showed that the combination of erasure codes and custody transfer option is detrimental to the overall performance. This is due to the fact that the available buffer space, for accommodating information and redundancy bundles until a bundle acknowledgment is received, allows only a reduced number of retransmissions. Consequently, in case of long erasure bursts, the bundle protocol is not able to recover all the missing bundles. Alternatively, it is also possible to allow an indefinite number of retransmissions, resulting however in buffer overflow, with a consequent discard of all incoming bundles during the recovery procedure. As a confirmation of this observation, a bundle loss rate of 37.3% was registered during the performed tests.

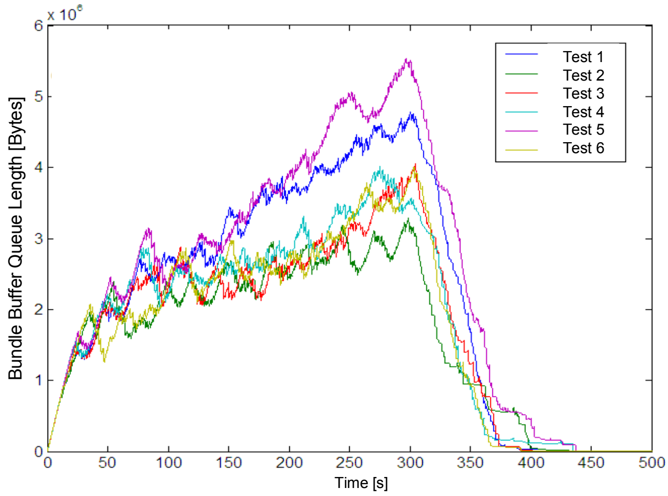

Fig. 3. Bundle Buffer Queue Length in case of unlimited buffer capacity and propagation delay 5 s, for several realisations (Tests 1 through 6).

From Fig. 4 is then possible to note that the nodes' buffer queue length keeps saturated (1 Mybtes) for a long time portion (extending over 400 s) because of the combination of retransmissions and storing new bundles. In this case, the delivery delay (larger than 700 s) is not meaningful, being the data delivery not accomplished.

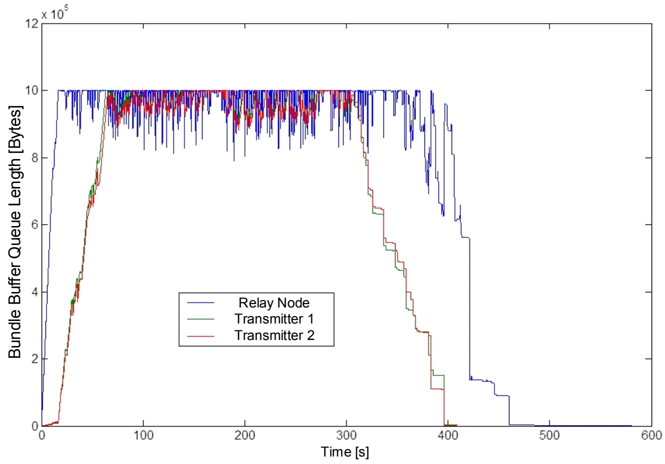

Fig. 4. Bundle Buffer Queue Length in case of 1 Mbytes buffer capacity (all DTN nodes) and propagation delay 5 s.

Finally, when the capacity of buffer is constrained only at the relay node, the combination of erasure codes and custody transfer is then able to guarantee reliable data transfer, with zero bundle loss rate. On the other hand, the buffer capacity keeps saturated for nearly 600 s (see Fig. 5), resulting in a total delivery delay of 699 s, much higher than that registered in case of no buffer capacity limitations (431 s). Apparently, the unlimited capacity of buffer implemented at the transmitting nodes should be a critical factor, since it could allow a larger amount of data to be transmitted over time. However, it is important to remark that also transmitting nodes enable the custodial transfer option: in case of congestion events on the gateways, the discarded bundles are then retransmitted by the senders. It is also straightforward to see that such procedure could not be carried out in the previous configuration, where the senders implemented a reduced buffer capacity, thus limiting the efficiency of recovery procedures.

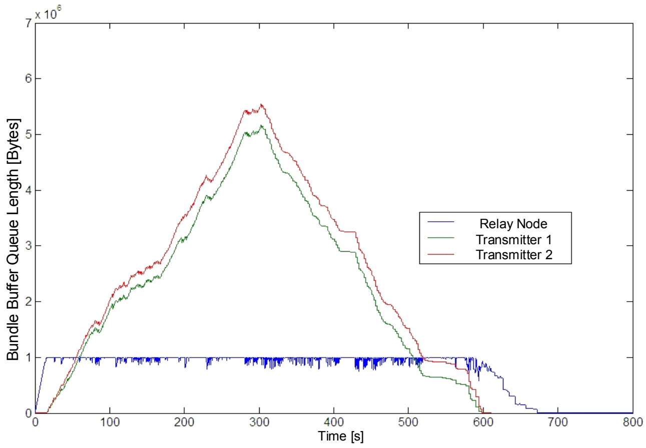

Fig. 5. Bundle Buffer Queue Length in case of 1 Mbytes buffer capacity (only relay node) and propagation delay 5 s.

A very interesting case was observed when the deep space link exhibits a propagation delay of 100 s. In this configuration, with unlimited buffer capacity, overall data delay of 2987 s with zero bundle loss rate was measured. Besides, it is possible to see from Fig. 6 that the buffer queue length increases dramatically up to a maximum of nearly 20 Mbytes in the initial 400 s. The decrease of the queue length is instead slower and takes nearly 3500 s. This behaviour stems from the large propagation delay that causes the buffer queue to increase until the first bundle acknowledgment is received, in order to store a copy of the bundles "in flight" and to accommodate the incoming ones.

From Fig. 6 it is also possible to argue that in case of limited buffer capacity (1 Mbytes, not illustrated here for lack of space) the congestion effects would be even more disgraceful to the overall performance.

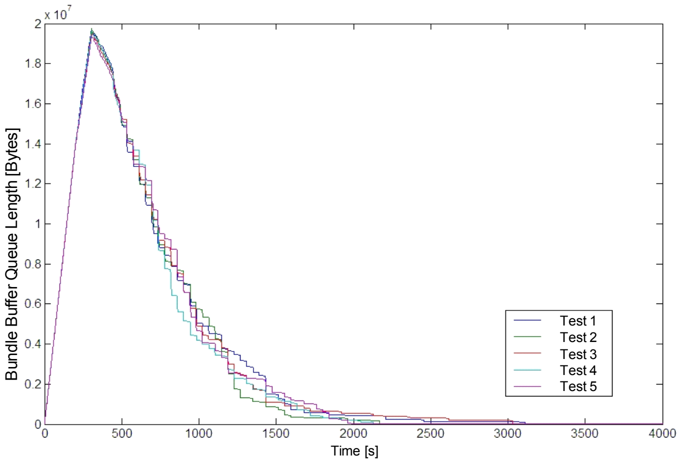

Fig. 6. Bundle Buffer Queue Length in case of unlimited buffer capacity and propagation delay 100 s, for several realisations (Tests 1 through 5).

On the one hand, the longer saturation of buffer would result in much larger transfer delay. On the other hand, the high packet erasure rate (37.5%) when not properly contrasted by erasure coding, would demand for a big number of retransmissions, which could not be allowed because of the buffer space limits. Ultimately, this should cause a very high bundle loss rate, thus completely cancelling the benefits of the joint use of erasure codes and custody transfer option.

V. CONCLUSIONS

This paper explored the possible benefits that can arise by extending the bundle protocol functionalities with erasure codes. In particular, the joint use of a packet-level coding approach with the Custody Transfer option offered by the Bundle Protocol resulted promising to improve the system robustness against link interruptions and disruption. The conducted performance analysis also showed that the interaction between this two-level protection can result underperforming because of the limited storage capacity of spacecrafts, which may introduce unexpected congestion events.

In this light, being the buffer space imposed by the hardware constrains of spacecrafts, it is immediate to see that an appropriate tuning of the code-rate and bundle size is fundamental to achieve high performance.

REFERENCES

[1] V. Cerf, S. Burleigh, A. Hook, L. Togerson, R. Durst, K. Scott, K. Fall, H. Weiss, "Delay Tolerant Networking Architecture," RFC 4838, Apr. 2007.
[2] "Rationale, Scenarios, and Requirements for DTN in Space" Draft Green Book, CCSDS 734.0-G-0, CCSDS, March 2010.
[3] "Delay and disruption tolerant wireless communication," IEEE JSAC Special Issue, vol. 26, no. 5, June 2008, pp. 745-747
[4] S. Burleigh, A. Hooke, L. Torgerson, K. Fall, V. Cerf, B. Durst, K. Scott, H. Weiss, "Delay-tolerant networking: An approach to interplanetary internet", IEEE Communications Magazine, vol. 41, no. 6, Jun 2003, pp. 128-136
[5] K. Fall, "A delay-tolerant network architecture for challenged internets," ACM SIGCOMM 2003, Karlsruhe, Germany, Aug. 2003.
[6] K. Fall, W. Hong, S. Madden, "Custody Transfer for Reliable Delivery in Delay Tolerant Networks," IRB-TR-03-030, July 2003
[7] J. Wyatt, S. Burleigh, R. Jones, L. Torgerson, S. Wissler, "Disruption Tolerant Networking Flight Validation Experiment on NASA's EPOXI Mission," First International Conference on Advances in Satellite and Space Communications SPACOMM 2009, Colmar, France, July 2009
[8] S. Shambayati, "On Selecting the Size of a Spacecraft's Buffer," IPN PR 42-174, pp. 1-25, August 15, 2008.
[9] I. Bisio, M. Cello, T. De Cola, M. Marchese, "Combined Congestion Control and Link Selection Strategies for Delay Tolerant Interplanetary Networks," IEEE GLOBECOM 2009, Honolulu, HI, USA; Nov.-Dec. 2009
[10] T. de Cola, H. Ernst, M. Marchese, "Performance analysis of CCSDS File Delivery Protocol and erasure coding techniques in deep space environments," Computer Networks, Elsevier, vol. 51, no. 14, Oct. 2007, pp. 4032-4049.
[11] I. Bisio, T. de Cola, M. Marchese, "Congestion Aware Routing Strategies for DTN-based Interplanetary Networks," IEEE GLOBECOM 2008, New Orleans, LA, USA, Nov.-Dec. 2008.
[12] L. Rizzo, "Effective erasure codes for reliable computer communication protocols," ACM Computer Communication Rev., vol. 27, no. 2, Apr. 1997, pp. 24–36.
[13] E. Paolini, G. Liva, B. Matuz, M. Chiani, "Generalized IRA Erasure Correcting Codes for Hybrid Iterative/Maximum Likelihood Decoding," IEEE Communications Letters, vol. 12, no. 6, Jun. 2008, pp. 450 – 452.
[14] K. Scott, S. Burleigh, "Bundle Protocol Specification," RFC 5050, Nov. 2007.