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ScienceDirect

Computer Networks 51 (2007) 4032–4049

Computer Networks

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Performance analysis of CCSDS File Delivery Protocol and erasure coding techniques in deep space environments ☆

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Received 27 March 2006; received in revised form 16 April 2007; accepted 16 April 2007
Available online 22 May 2007

Responsible Editor: I.F. Akyildiz

Abstract

The rising demand for multimedia services even in hazardous environments, such as space missions and military theatres, and the consequent need of proper internetworking technologies have revealed the performance limits experienced by TCP protocol over long-delay and lossy links and highlighted the importance of the communication features provided by the protocol architectures proposed by the Consultative Committee for Space Data Systems (CCSDS). This paper proposes a CCSDS File Delivery Protocol (CFDP) extension, based on the implementation of erasure coding schemes, within the CFDP itself, in order to assure high reliability to the data communication even in presence of very critical conditions, such as hard shadowing, deep-fading periods and intermittent links. Different encoding techniques are considered and various channel conditions, in terms of Bit Error Ratio and bandwidth values, are tested.

Keywords: CFDP, Erasure coding; Transport layer; Satellite communication

1. Introduction

Over the last years, increasing advancement in communication technologies has fostered a number of space missions, aimed at carrying on scientific studies on characteristics of planet surfaces and exploring the frontiers of deep space. Besides, the need to remotely control spacecrafts and to retrieve sensor measurements as well as planet images, has raised the necessity of designing communication

☆ This work has been carried out within the European-funded network of excellence SatNEx II (Contract No. IST-027393).
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doi:10.1016/j.comnet.2007.04.015

architectures, based on packet-switched networks, able to transport data directly to Earth gathering and processing centres, by means of long-haul links. From this point of view, the design and the deployment of appropriate protocol architectures suited to transport data over deep space environments have been evaluated within the Scientific Community. The major challenge has been represented by the realization of communication infrastructures, able to tolerate typical impairments introduced by deep space links, such as frequent link disconnections, large propagation delays and scarce availability of network resources (e.g., downlink/uplink bandwidth and spacecraft/satellite onboard-processing capability). From this standpoint, the migration from TCP protocol-based architectures to protocol stacks more suitable to space environments seems to be unavoidable. In practice, given the high TCP sensitivity to link errors (misinterpreted as congestion collapses) and large propagation delays, a promising protocol architecture candidate is proposed by the Consultative Committee for Space Data Systems (CCSDS) [1,2], which has produced, since the end of eighties, a large series of protocol recommendations for accomplishing data communications over space networks. In more detail, a dedicated protocol stack, based on CCSDS protocols, has been studied together with protocol implementations to be adopted from the physical up to the application layers.

In this work, a particular attention has been dedicated to the performance of higher layer protocols, and namely to the CCSDS File Delivery Protocol – CFDP [3], which ensures the reliability of the communication by means of either recovery schemes implemented therein or complementary schemes implemented at the lower layers (i.e., Forward Error Correction at the datalink layer). However, recent studies have shown how CFDPs performance is not completely satisfactory when one-way connections are established over long-delay links. In this case, the use of supplementary mechanisms, able to positively counteract the environment challenges, is expected and recommended. A possible solution is represented by the transport/application layer coding approach. It means implementing correcting (erasure) codes at the higher layers, in order to mitigate the negative effect of high Bit Error Ratio (BER) on the overall performance. The rationale behind this idea stems from the observation that in presence of link disconnections and deep-fading periods, the sole application of FEC (at datalink layer) is not sufficient to guarantee good performance. The adoption of correcting codes, complementary to FEC mechanisms, is expected to bring significant improvement to the overall communication performance.

Actually, this work takes the CCSDS protocol stack and the Transport Layer Coding approach [4] as reference and proposes a combined use of erasure codes [5] and of the CFDP protocol to overcome impairments posed by deep space links. CFDP covers functionalities commonly located at transport and application layer. Such a solution is taken as viable approach alternative to TCP-based protocols and the related performance has been thoroughly investigated by means of proper simulation tools, specifically designed to reproduce data communications over space networks.

The remainder of the paper is structured as follows. Section 2 introduces the relevant works recently made in this area of research also linked to real space missions. Section 3 describes the CCSDS protocol stack, as well as the protocol solutions recommended for layers ranging from application down to physical. Section 4 presents protocol the new solutions that rely upon the integration of erasure codes into the CFDP core, by pointing out also implementation issues. The performance analysis follows in Section 5, while Section 6 draws the conclusions and gives an outlook for possible extensions of this work.

2. Overview

Since the advent of space exploration with satellites and spacecrafts, the challenge of performing data communications over space and deploying suitable telecommunication infrastructures has been increasingly capturing interest within standardization committees as well as space technology-oriented companies. In this perspective, a particular note has to be reserved to the role played by the Consultative Committee for Space Data Systems (CCSDS) over the years in the study and design of protocols to transport data over interplanetary environments [1] efficiently. From this point of view, a number of CCSDS working groups has carried on tasks to propose architectures and protocols suitable to transfer data in the deep space. In particular, it is worth mentioning the Cislunar and the CCSDS File Delivery Protocol (CFDP) working groups, whose activity is aimed at providing protocol architectures for Earth–Moon communications and beyond, and file transfer protocols, respectively [6].

Recently also the Internet Engineering Task Force (IETF) and especially the Internet Research Task Force (IRTF) have made big efforts to provide proposals of architectures suited for this environment. The Delay Tolerant Network architecture [7,8] has been conceived from these activities, and, recently, its scope has been extended also to other challenging environments. The need to extend the frontiers of terrestrial networks towards an Interplanetary Networks has been also highlighted in a special issue of Computer Networks on "Interplanetary Networks" [9], where recent space missions and interoperability issues between TCP/IP suite and space protocol stacks are analyzed. Moreover, again in [9], the limitations of using the TCP protocol over deep space networks are shown by proposing the implementation of ARQ schemes below AIMD-oriented (Additive Increase, Multiplicative Decrease) transport protocols [10]. In this view, the study of TCP modifications and, consequently, the design of new transport protocol proposals have proliferated in the literature [11,12]. TP-Planet [13], among the others, deserves special attention, because it is able to recognize link disruptions (i.e., blackout events) and, hence, to tune the transmission parameters efficiently.

Designing novel protocols able to provide satisfactory performance results has captured the interest of channel coding engineers too. Actually, in alternative to highly efficient Automatic Retransmission reQuest (ARQ) schemes, the implementation of erasure coding schemes either at the transport or at the application layer can bring further improvement to the overall performance. From this point of view, a solid framework is then represented by the Transport Layer Coding scheme [4] and, in general, by the ALC (Asynchronous Layered Coding) [14]/LCT (Layered Coding Transport) [15] architecture, defined to interwork with FLUTE (File Delivery over Unidirectional Transport) protocol [16] and conceived within the Reliable Multicast Transport (IETF) Working Group. The basic idea behind all these approaches is to employ erasure coding schemes (able to recover from packet losses in correspondence of strong link degradations) directly at higher layers. Other proposals have been advanced and include Low Density Parity Check (LDPC) [17], Reed Solomon [18], and the more recent Digital Fountain scheme [19], implemented through LT (Luby Transform) [20], Tornado [21] and Raptor codes [22].

In addition to the communication reliability, the interest of deep space scientists is also moving towards Quality of Service (QoS) issues. At present, the limited sizes of interplanetary networks (in terms of number of nodes and hops) and their limited channel capacity make the definition of service classes not immediately applicable. However, as future space missions will test also broadband multimedia communications, defining proper scheduling policies and resource reservation mechanisms will be necessary to meet specific QoS constraints. Already in the literature: [23] proposes the use of an extended version of Resource Reservation Protocol (RSVP); and [6] considers Diffserv-based solutions. Also in this case the characteristics of the deep space link may have a heavy effect on the performance: in presence of lossy and long propagation delay links, it is most likely that IP signalling flow, carrying QoS information, will suffer from link disruption.

Attention has to be paid to past and ongoing research projects in this field. Operating Missions as Nodes on the Internet (OMNI) and Tracking and Data Relay Satellites (TDRS) are research activities developed within NASA. They are aimed at providing communication systems for satellite tracking and data acquisition. Ref. [24] shows experiments conducted between 2002 and 2003 to investigate the effectiveness of geographic information networks for planetary exploration.

A special note has to be dedicated to the CCSDS File Delivery Protocol (CFDP) standardized by CCSDS and aimed at transferring data in space communications systems, even in very critical operative conditions. The extension of its features to improve reliability is the key point of the paper.

3. CCSDS protocol stack

Consultative Committee for Data Space Systems (CCSDS) activity has been primarily focused on the definition and implementation of a protocol architecture, alternative to the existing ones (e.g., TCP/IP suite), to support effectively data transfer over long delay and lossy networks, as in the case of interplanetary networks. The full protocol stack, including all the protocols from the application to the physical layer, has been recommended, designed and deployed in spacecrafts and satellites. The protocol stack composition may be summarized as follows:

- *Physical layer*. The CCSDS Recommendations on Radio Frequency and Modulation Systems provide viable and effective indications on the most suitable transmission schemes to be adopted in space missions, achieved over either long-haul-links (long range, bidirectional, established to allow communication between spacecrafts and satellite very far to each other) or proximity links (short range, bidirectional, generally used to communicate among landers, rovers, orbiting constellations, and orbiting relays).
- *Datalink layer*. CCSDS has developed four protocols: namely Telemetry (TM) Space Data Link Protocol [25]; Telecommand Space Data Link Protocol (TC) [26]; Advanced Orbiting Systems (AOS) Space Data Link Protocol [27]; and Proximity-1 Space Link Protocol-Data Link layer [28]. Their basic function is to encapsulate Protocol Data Units (PDUs) coming from the Network Layer and to transmit them to the Physical Layer in forms of Transfer Frames, whose length may be either fixed or variable. In more detail, TM and TC Space Data Link Protocols are responsible for sending telemetry information (from a spacecraft to a ground station, in the reverse link) and commands (from a ground station to a spacecraft), respectively. AOS Space Data Link Protocol has been designed to allow two-way data transmission (on both forward and reverse directions) as in the case of real-time communications (e.g., audio and video). Proximity-1 Link Protocol defines the procedures implemented at the datalink layer and suited for proximity links. Along with encapsulation and framing operations, also synchronization and channel coding functions are performed. In practice, TC, TM and Proximity-1 Space Link Protocols recommend to use Reed Solomon, BCH and Turbo Codes. Sync Marker bits are defined to match synchronization needs [29–31].
- *Network layer*. Two protocols have been proposed: the Space Packet Protocol and the Space Communication Protocol Standards-Network Protocol – SCPS-NP. Both are responsible for addressing and routing operations, by means of Path, End System Addresses and other specific identifiers [32,33].
- *Transport layer*. CCSDS has developed the SCPS Transport Protocol (SCPS-TP) [34] to provide end-to-end reliable communication. It uses control mechanisms (congestion avoidance and flow control) inherited from TCP and improved for the deep space environment. It is relevant to note that, even though recommendations for the transport layer have been produced within CCSDS, actually the use of transport protocols is not mandatory in CCSDS protocol stacks. In practice, most applications, such as CCSDS File Delivery Protocol, do not require running over a transport protocol, but can work directly over the network layer. It is the choice followed in this paper. Actually, SCPS-TP assumes that it will be operating over a lower layer protocol such as the SCPS Security Protocol (SCPS-SP), the SCPS Network Protocol (SCPS-NP), or the Internet Protocol (IP) [34]. Even if interoperability with IP protocol is ensured, SCPS-NP is a network protocol, which implements enhanced capabilities to manage data routing and addressing tasks in deep space networks. For this motivation only SCPS-NP is considered in this paper as the network protocol working below the SCPS-TP protocol.
- *Application layer*. CCSDS File Delivery Protocol (CFDP) is designed to get reliable transfers of files by following a FTP-like paradigm. Its implementation spans over the Application and Transport layers. Being CFDP essential part of this paper, its description is postponed to the next session.

Recently, also issues about the interoperability with TCP/IP suite have been considered. Further encapsulation procedures have been designed to include CFDP over TCP/IP suite and IP over CCSDS Space Link Protocols [33,35]. The advantages offered by IP-based stacks are not limited to interoperability but concern also header compression issues, which have a very important role in case of largely asymmetrical link bandwidths. In this view, the ROHC (RObust Header Compression) recommendation [36], applied to UDP-IP datagrams, might be exploited to reduce the overhead introduced by Space Packet Protocol (equal to 6 bytes) to about 2–4 bytes. Actually, these solutions, still experimental, are not yet part of the CCSDS recommendation core. Being this work completely based on a homogenous CCSDS Protocol Stack, the possibility of addressing spacecrafts through IPv4/IPv6 mechanisms, even though it is attractive and may represent an interesting solution for future space communications, is not considered in this work.

4. Protocol solutions

4.1. CCSDS file delivery protocol (CFDP)

A file, which is going to be transmitted, is split into different units, to which CFDP add a header whose length can range up to 24 bytes; the payload can contain up to 65536 bytes. A CFDP PDU is often referred in the following as "CFDP block".

A particular note has to be dedicated to CFDP recovery functions. CFDP can work in either unreliable or reliable mode. The former implements no mechanisms to ensure complete data delivery; the communication reliability, where required, may be ensured, if possible, by proper mechanism implemented within the underlying layers. The latter implements NAK-based recovery mechanisms. Actually, the detection of missing CFDP blocks is performed by the receiver, which notifies the loss of data to the sender, by issuing NAK blocks, in accordance with four different algorithms: Immediate, Deferred, Asynchronous and Prompted. In the first case, as missing CFDP blocks are detected, a NAK issuance is released in order to trigger the recovery phase at the sender side as fast as possible. On the contrary, when CFDP is configured to run in Deferred mode, the detection of missing blocks is performed only at the end of the file transmission. As far as prompted and asynchronous modes are concerned, the detection of missing blocks is dependent on external events, such as explicit (asynchronous mode) or periodical (prompted mode) requests by the sender. The recovery phase is managed also by means of NAK-timers, necessary to re-issue NAK notifications in the case of CFDP blocks are still missing after initial retransmission rounds.

4.2. Transport layer coding and erasure codes

The transport Layer Coding approach, as defined in [4], implements a coding sublayer, placed between application and transport layer, responsible for implementing effective encoding techniques, able to contrast link degradations. The operation may be implemented also directly at the application layer so justifying the notation "application layer coding". In practice, this approach consists in the implementation of appropriate erasure codes acting on packet basis, complementing FEC schemes already working at the datalink layer and able to recover from packet losses occurred in presence of very strong link degradations. Encoding procedures take a number of data packets as input and, accordingly to the coding algorithm, generate redundancy packets in a number depending on the code rate settings. The choice impacts on the overall performance. In the reminder of the paper: "k" is the number of the encoding input packets and "n" of the encoded packets; "Fec_ratio" is the ratio n/k (i.e., the inverse of the code rate). It is immediate to see that higher the amount of redundancy is, more robust the data communication is to counteract errors. On the other hand, a large number of redundancy packets increases the communication overhead and sensitively reduces the channel bandwidth available to transmit information.

Erasure codes based on Reed Solomon (RS) and Low Density Parity Check (LDPC) have been considered in this paper, taking [18] as reference. Also a very simple scheme (RT – Repeated Transmission), based on the repetition (replication) of the same data packet, has been reported and analyzed for its simplicity and satisfactory performance.

As far as Reed Solomon and LDPC codes are concerned, a short characterization is given in the following:

- *Reed Solomon*. Invented in 1960 [37], Reed Solomon codes belong to the category of Minimum Distance Separable (MDS) codes, since the decoding procedure can be performed as soon as k out of n packets are received. This is optimal, since k is the number of packets the information itself needs. Despite this attractive property, several drawbacks limit the efficiency of Reed Solomon codes if implemented at packet level. Firstly, as they work within Galois Fields (GFs), k and n values are limited by the value of GF itself. For instance, if the GF(256) is assumed, a maximum number of $n = 256$ packets (k information plus $(n - k)$ redundancy packets) can be generated and, as a consequence, for high Fec_ratio values, only a small number of information packets (k) can be encoded together. Secondly, Reed Solomon erasure codes experience very long encoding/decoding times for larger values of k and n. Ref. [5] shows that encoding times complexity for a RS standard implementation is $O(k(n - k))$

while decoding times complexity is O(kl), where l stands for the missing packets. Usual Reed Solomon configurations are defined in GF(256), thus implying limited performance, due to the lower number of packets, which can be concatenated together.

- *Low Density Parity Check (LDPC)*. Invented in 1966 by Gallager [38] and then investigated further by MacKay and Neal in 1996 [39], LDPC codes allow the usage of large k and n values, since LDPC codes use sparse parity check matrices. In contrast to the Reed Solomon codes, they need slightly more packets than k before all data can be reconstructed. This overhead ε can be reduced with increasing value of k and can approach zero for unlimited sizes of k [22,40]. Moreover, the use of sparse generator matrices brings several advantages in terms of reduced resource consumption, fast encoding/decoding operations, and decoding times, which grow only by O(k) and a constant factor depending on the allowed overhead [41]. Because of the particular structure of the parity check matrix, the decoding phase is performed by iteration, for each new packet received, so reconstructing original data packets as soon as possible. In this work, the LDPC codes generated by a Staircase sparse matrix with a constant weight are considered [18]. They belong to the family of Low Density Generator Matrix (LDGM) codes, since not only the check matrix, but also the generator matrix is sparse. LDPC codes based on a staircase approach with constant weight are less efficient than the before mentioned LT [20] and Raptor [22] codes, but are not so much covered by patents. In the following the used staircase LDPC code from [18] are referenced simply as LDPC.

4.3. Combined approach

The advantages provided by erasure codes in terms of increased communication robustness against strong link degradations are very evident when applied in space environments because of physical characteristics of the considered scenario. In practice, usual space missions use communication links exhibiting large delays (ranging from some seconds up to minutes) and highly bandwidth asymmetry (a ratio of 1000:1 between forward and reverse directions is common). Under these operating conditions, the use of TCP protocol as it is, hardly gives satisfactory performance results. Flow control and congestion avoidance algorithms strongly degrade the overall data communication, in terms of large times incurring in the data delivery and, as a consequence, very low throughput results. Conversely, the implementation of erasure codes within the CCSDS protocol stack is expected to be promising. It has been deeply investigated throughout the rest of the paper. In particular the integration of Reed Solomon, LDPC and repeated transmissions schemes into CFDP protocol running in unreliable mode has been considered by extending the capabilities of standard CFDP. This new version has been named CFDP-UE (Unreliable Extended) followed by the specific erasure coding technique therein applied.

In few words, three brand new protocol proposals have been devised, CFDP-UE-RT (Repeated Transmissions), -RSE (Reed Solomon Encoding), -LDPC (Low Density Parity Check), whose implementation details reported in the following.

CFDP-UE-RT. Each generated CFDP PDU is replicated $N-1$ times. N identical CFDP PDUs are transferred to the underlying layer, which will be responsible of all the necessary encapsulation procedures. A meaningful parameter influencing the overall performance is the number N of repeated transmission that helps increase the probability of data delivery at cost of bandwidth waste (proportional with N).

CFDP-UE-RSE. The adoption of erasure codes based on Reed Solomon codes (sketched in Fig. 1) deserves a particular attention because of its intrinsic limitations discussed previously. Reed Solomon codes defined over GF(256) have been considered, implying the generation of 256 (n) encoded packets. A full CFDP PDU (i.e., carrying 65536 bytes) is segmented into k packets, whose length is ruled by the datalink frame size; afterwards the Reed Solomon encoder generates $(n-k)$ redundancy packets according to the Fec_ratio value set at the beginning of the transaction. The n packets are encapsulated in corresponding PDUs at the network layer. The need to force CFDP to build a full PDU, before the encoding procedure, is due to the fact that, given the small value of n, it is preferable to encode as many information bytes as possible in order to reduce the transmitted overhead. On the contrary, using smaller CFDP blocks would imply transmitting a large number of very small encoded packets, carrying a very low information amount in percentage.

CFDP-UE-LDPC. The design of LDPC codes within CFDP core, given in Fig. 2 has been very

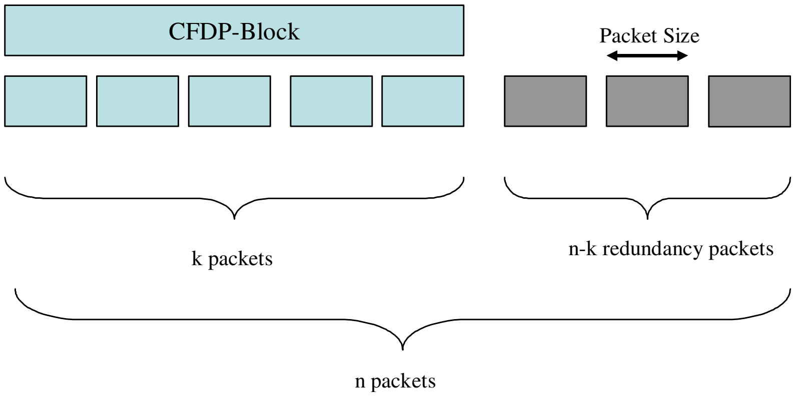

Fig. 1. CFDP-UE-RSE Creation of Redundancy Packets.

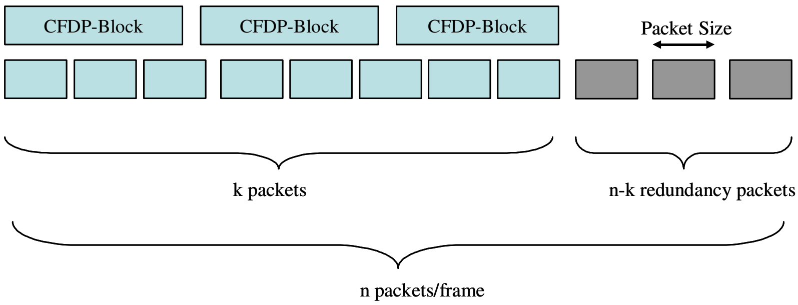

Fig. 2. CFDP-UE-LDPC Creation of Redundancy Packets.

tricky and delicate. Actually, LDPC codes perform effectively when a large number of encoding packets ($k >= 1000$) is available; on the other hand, as emerged from CFDP-UE-RSE design, it is preferable to transmit as less overhead as possible. In order to match these performance constraints, a number of CFDP blocks is firstly stored in a dedicated buffer, then merged into an unique bit vector and finally segmented into k packets, whose length was ruled by the size of datalink frame. Afterwards, the k packets are encoded into n packets, accordingly to the LDPC encoding procedure.

5. Performance analysis

5.1. Reference scenario

The scenario investigated throughout the rest of this work derives from the scientific activities currently in progress within CCSDS Cislunar Working Group, whose aim is to design and provide a telecommunication infrastructure suitable to allow efficient data communications (e.g., telemetry data exchange, audio/video transmission and measures/image retrieval) during robotic and human exploration missions on the Moon. Given the hazardous environment conditions, namely high propagation delay, deep-fading periods and disruption prone links, the need for a protocol architecture supporting robust, effective and multi-hop data communication is straightforward. In practice, the system design is not only influenced by performance factors, but also by considerations on power budget and cost of devices. In this view, the adoption of a two-hop architecture is beneficial since it allows splitting the whole data transfer over separated and cascaded network segments, thus exploiting the signal regenerative feature of intermediate nodes and reducing the overall resource consumption, at a minor cost of increased on-board processing.

Under this view, the reference environment considered in this paper (shown in Fig. 3) is composed of:

- Sensors, rovers and landers: placed on the Moon's surface, responsible of taking measures

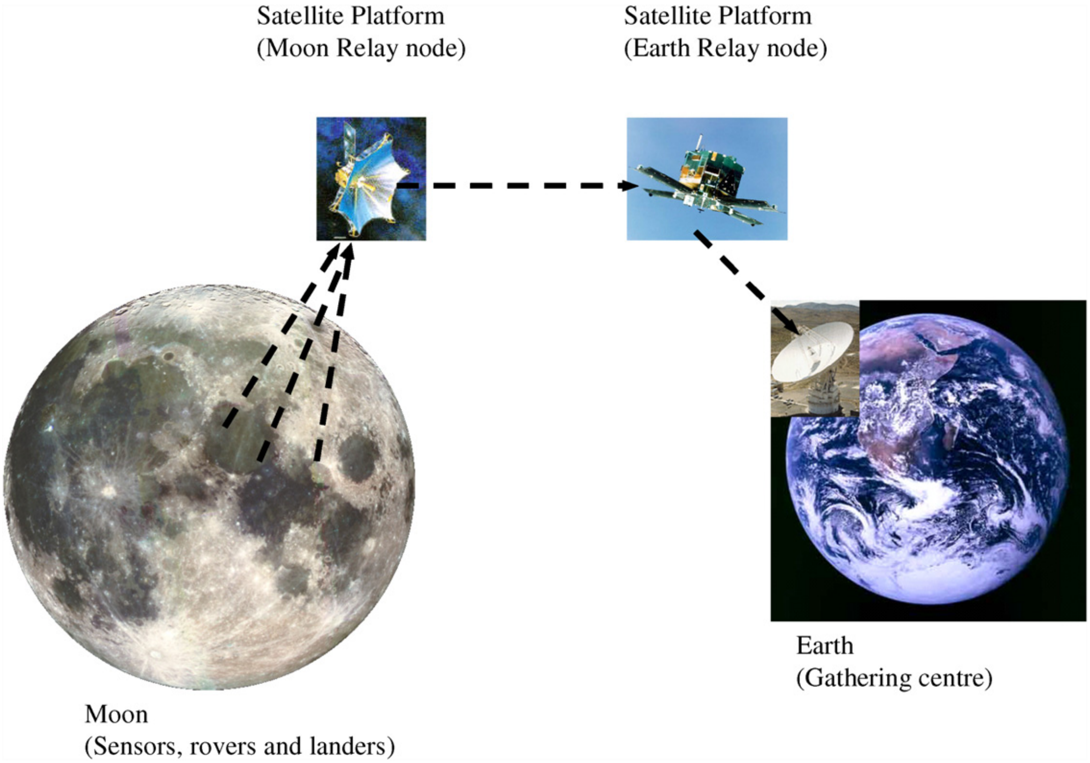

Fig. 3. The reference scenario.

and pictures, which will be sent towards a gathering centre on the Earth, by means of a two-hop satellite link.

- Gathering centre: located on the Earth's surface and responsible of collecting the data arriving from the Moon.
- Two satellites (relay nodes). One of them orbits around the Moon (Moon Relay node) and receives the data (e.g., images and measures) from sensors, landers and rovers located on the Moon's surface. The other one orbits around the Earth (Earth Relay node) and collects the data arriving from the Moon orbit satellite. It works as a relay node towards the gathering centre.

Taking advantage of link heterogeneity (proximity and deep space links) allows defining a communication architecture implementing, within each layer, protocols really suitable to perform data transfer on each network segment. Moreover, the separation among different network portions (heterogeneous for physical characteristics and applied transmission strategies) allows balancing power consumption more efficiently, so leading to lower costs. In this view, also the on-board processing required in each relay satellite node (orbiting around the Moon and the Earth) has to be attentively considered and discussed in the results.

As far as the protocol stack is concerned, a full CCSDS architecture has been assumed for each communicating node. All the nodes implement the full CCSDS stack running the CCSDS File Delivery Protocol on top of it and the Space Packet Protocol directly below in order to perform routing and addressing operations. No transport layer is used. The datalink and physical layer definition strictly depends on the link characteristics. The Proximity-1 Link Space Protocol is adopted for the interconnection between stations and relay nodes; the Telemetry Space Link Protocol is used for the deep space link established between the two relay satellites. It is important to note that assuming such network architecture does not limit the validity of the whole investigation and the protocol design, because it is in line with the protocol architectures defined within CCSDS and it is deployed in many space missions [6]. The extension to IP/CCSDS solution is forecast as IP over CCSDS protocols and CFDP over UDP encapsulation schemes are in phase of standardization [33,35]. It will be part of future research and experimental activity.

5.2. Testbed configuration

This work is mainly focused on the data performance achieved on the deep space link; as a consequence the considered testbed is composed of the satellite relay nodes, whose interconnectivity is guaranteed by means of a Radio-Frequency link. It exhibits a propagation delay of 1.28 s (round trip time of 2.56 s) as a result of maximum the Moon–Earth distance, equal to 384,000 km. Different channel bandwidth values have been explored, ranging from 256 kbit/s up to 2.048 Mbit/s, as provided by proper modulation and channel coding configurations available from the Telemetry Space Link Protocol. In more detail, these values correspond to the net bandwidth exploitable at the network layer and have been varied test by test, during the performance analysis. As far as the transmission channel model is concerned, the AWGN (Additive White Gaussian Noise) is assumed: corrupted bits are identically and independently distributed within each transmitted frame (i.i.d model).

As said, the protocol stack mounted on the two satellites is fully CCSDS-based (sketched in Fig. 4): it implements CFDP-UE layer on the top layer, as defined in Section 3; below, at the network layer, there is the CCSDS Space Packet Protocol responsible of routing and addressing tasks. As far as the datalink layer is concerned, two different protocols are implemented in order to transport data over the deep space and the proximity link, respectively: CCSDS Telemetry and CCSDS Proximity-1 Link Protocols. Both are responsible for performing framing, robust channel coding and modulation operations.

In general, the data flow is generated by Moon's nodes (e.g., rovers), encapsulated into CFDP blocks (indicated by white boxes in Fig. 4) and transmitted over a proximity link towards the Moon Relay node, which will perform specific encoding operations, as specified by the implemented CFDP-UE protocol. CFDP-UE blocks (indicated by grey boxes in Fig. 4) are sent towards the Earth Relay node over the deep space link. Finally, the Earth relay performs decoding operations on the received CFDP-UE blocks and forwards CFDP blocks to the Earth Station, where they will be gathered and processed.

As outlined before, the main focus of this work is on the communication performance offered on the deep space environment, enclosed in a dashed circle

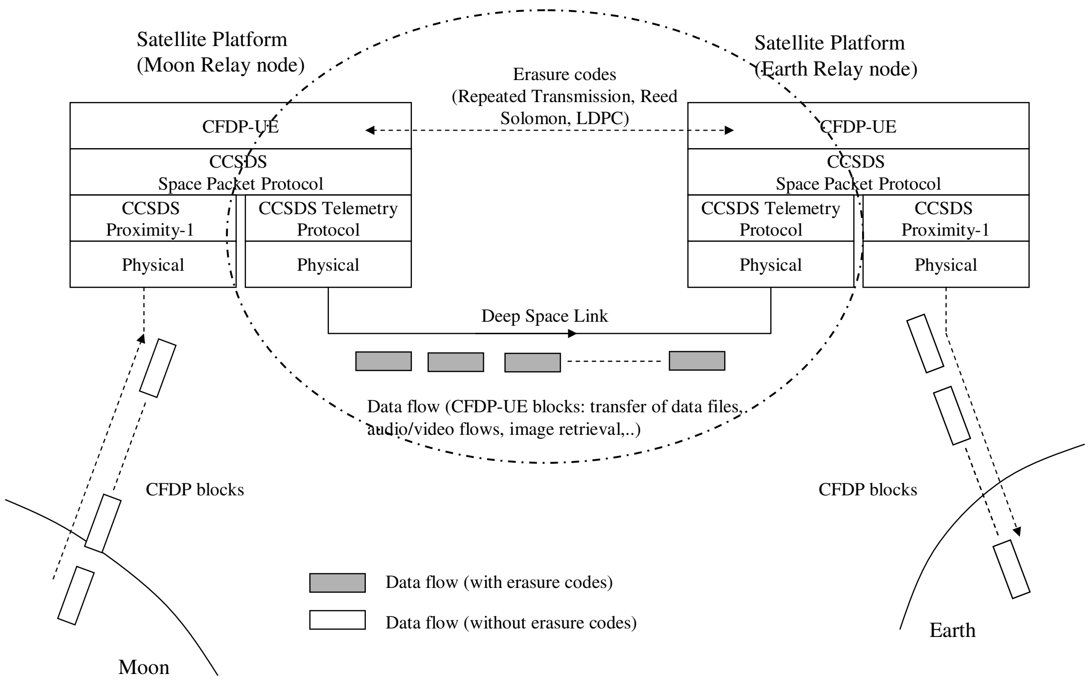

Fig. 4. The testbed and the CCSDS protocol architecture.

in Fig. 4. In more detail, the reliability of the deep space channel is characterized in terms of BER (Bit Error Ratio), assumed here as the values computed after the coding/decoding at the CCSDS Telemetry Protocol. In practice, BER is considered at the reception interface between CCSDS Space Packet and Telemetry Protocol. CCSDS Telemetry Protocol applies a Forward Error Correction (FEC) scheme on the transmission side to make the communication more robust; on the receiver side, when the corresponding frame is received, the decoding procedure works as follows: if the frame is received correctly or the FEC scheme is able to completely recover the errored bits, the frame is forwarded to upper layers. On the contrary, if the received frame carries a number of errored bits that cannot be recovered, the frame is anyway passed to the upper layer, where application of erasure codes should reconstruct the lost information. From this view, it is immediate to see that in the worst case, the frame will experience a number of corrupted bits, which can be thought as a result of *residual* BER. This value is the main factor accounting for channel degradation; this parameter referred in the following simply as BER.

Different configurations of CFDP-UE have been considered. CFDP-UE-LDPC has been tested by considering a Fec_ratio of 1.5, while CFDP-UE-RT has been evaluated in each test by varying the number of repeated transmissions, actually ranging from 1 up to 15. CFDP-UE-RSE has been configured with k fixed to 51 and the Fec_ratio varied between 1.5 and 5.

To fully characterize different possible operative conditions, BER values ranging from 10^{-2} to 10^{-8} are used: the values from 10^{-8} to 10^{-7} correspond to almost clear sky condition; from 10^{-6} to 10^{-4} to hard link intermittence; from 10^{-3} to 10^{-2} to deep-fading periods. A further element characterizing the overall performance and taken as reference in the tests is the length of the frame (referred as "Packet Size"), sent by the CCSDS Telemetry Protocol. Actually, the Packet Size has been varied within each test between 100 and 1500 bytes. The overall testbed configuration is reported in Table 1.

The test campaign test has been performed by using a proprietary tool, based on a mixed emulated–simulated framework. The emulation core served to reproduce the LDPC encoding/decoding operations, derived from the INRIA software [18], while the simulation core was responsible for evaluating the data transmission over the interplanetary

Table 1
TestBed configuration

Transmission Channel Configuration	
BER (Bit Error Ratio)	10^{-8}–10^{-7}, Almost clear sky
	10^{-6}–10^{-4}, Hard link intermittence
	10^{-3}–10^{-2}, Deep fading periods
Bandwidth (kbit/s)	256–2000
Propagation delay (s)	1.28
Protocol configuration (CFDP-UE-)	
LDPC	Fec_ratio: 1.5
	Packet size (bytes): 100–1500
RSE	Fec_ratio: 1.5–5
	Packet size (bytes): 100–1500
RT	Repeated transmissions: 1–15
	Packet size (bytes): 100–1500

scenario. The tests are accomplished (by considering a data transfer of 100 Mbytes), through 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 are imposed. The amount of transferred data is set to 100 Mbytes (800 Mbits, Transfer Size). The probability of missing a CFDP block, indicated as Loss Probability (P_{loss}) and defined as one minus the ratio among the transmitted and received blocks, neglecting the replications (if any as for CFDP-UE-RT), is the performance metric together with the real use of the channel, indicated as Effective Throughput. The latter is measured as the product of $(1 - P_{\text{loss}})$ and the ratio of the Transfer Size and the Elapsed Time between the reception of the first and the last bit. The product is normalized to the reference bandwidth employed in the test. Transfer Size is measured in [bit], Elapsed Time in [s] and Bandwidth in [bit/s].

In fact:

$$P_{\text{loss}} = 1 - \frac{\text{Received Blocks}}{\text{Transmitted Blocks}},$$

$$\text{Effective Throughput} = (1 - P_{\text{loss}}) \cdot \frac{\text{Transfer Size}}{\text{Elapsed Time}} \cdot \frac{1}{\text{Bandwidth}}.$$

In order to consider also resource consumption, the "elapsed time" includes also the extra-delays incurred during encoding/decoding phase.

Handling Quality of Service issues is another goal of Cislunar Working Group. As a consequence, in order to characterize the different performance constraints of the traffic transported through CFDP blocks (namely: data file, audio–video broadcasting and medical–meteorological images), three classes characterized by a request of maximum P_{loss} are defined. Class A (e.g., transfer of data file) requires 100% of data delivery, and $P_{loss} = 0$. Class B (audio–video traffic) tolerates block loss up to 10^{-2}. Class C (transmission of medical–meteorological images) which, thanks to robust image encoding, may tolerate $P_{loss} \leqslant 10^{-1}$. Table 2 contains the details.

It is worth noting that no specific architectures supporting QoS issues have been adopted in this paper because current ones, relying on Diffserv-like paradigm, will be affected and impaired by frequent link degradations. The attempt is to satisfy QoS guarantees by means of erasure codes, implemented within the CFDP core.

5.3. Performance results

CFDP-UE assumes, respectively, the characteristics of CFDP-UE-LDPC, -RT, -RSE, in dependence of the algorithm used to extend the protocol features.

5.3.1. CFDP-UE-LDPC

The employment of LDPC codes, with Fec_ratio of 1.5, results to be powerful independently of the satellite channel conditions. The tests are performed by varying the packet size. The registered values of P_{loss} obtained by varying the BER from 10^{-2} up to 10^{-8}, are always "0". In this case, the distinction among class A, B, and C, in terms of effective throughput is redundant, since no information loss is registered. As the dimension of the packet increases, higher values of effective throughput are registered. Actually larger data units allow using the channel more effectively, since the information redundancy, caused by LDPC encoding and by the overhead of the headers added at the underlying layers, plays a minor role. Numerically, the maximum effective throughput registered (packet size of 1500 bytes) is about 0.62. A further consideration: the effective throughput is almost independent of the bandwidth availability. It is true also for CFDP-UE-RT and CFDP-UE-RSE. This is due to the definition of the "Effective Throughput", where, in practice, not being implemented congestion control mechanisms (e.g., TCP), the quantity "Elapsed Time" corresponds to the ratio of "Transfer Size" and "Bandwidth" with the addition of encoding/decoding latencies, so smoothing the role of "Bandwidth". In short, the only factors that affect the performance are the extra-latencies introduced by the encoding/decoding operations. Consequently, the channel bandwidth is not considered in the analysis of the other two approaches, since its setting does not affect the performance significantly.

Actually, the latencies incurred during LDPC encoding and decoding procedures impact only partially on the overall performance. Tests have pointed out that, in general, LDPC processing operations require a time, strictly dependent on the packet size, because smaller the packet is, higher the number of encoding/decoding operations is required for the same CFDP block. In practice, these latencies range between 8 and 20 s. On the other hand, time necessary to transmit all packets is in the order of hundreds of seconds. As a result, the introduction of LDPC engine impact only for less than 1% on the Effective Throughput measures, and, consequently, the benefits arising from using LDPC codes merely overcome the partial inefficiency due to processing latencies. Concerning resource consumption issues, it is immediate to argue, also on the basis of memory usage values provided in [18], that only a limited additional budget is required to perform the transmission of both information and redundancy packet.

Table 2
Classes of service configuration

Traffic class	Max P_{loss} requested
Class A (file transfer)	0
Class B (audio–video traffic)	10^{-1}
Class C (planet surface, meteorological images)	10^{-2}

5.3.2. CFDP-UE-RT

As far as the P_{loss} investigation is concerned: in presence of $BER = 10^{-2}$ all the CFDP blocks are lost and $P_{loss} = 1$. On the other hand, when BER values are lower than 10^{-6} (10^{-7} and 10^{-8}), all the transmitted blocks are received correctly, giving rise to $P_{loss} = 0$, independently of the number of performed transmissions. Particular attention must be reserved to the intermediate cases (i.e., BER varying from 10^{-3} to 10^{-6}): P_{loss} is shown versus the number of repeated transmissions and versus the packet size in Figs. 5–7, for "1 and 2", "3 and 5", "7, 10 and 15" transmissions, respectively.

As shown in Fig. 5, in correspondence of BER values ranging from 10^{-3} to 10^{-6}, the employment of 1–2 transmissions offers meaningful results. In general, with $BER = 10^{-3}$, P_{loss} is higher than "0.1". So, no class can be satisfied by CFDP-UE-RT applied with 1 or 2 transmissions independently

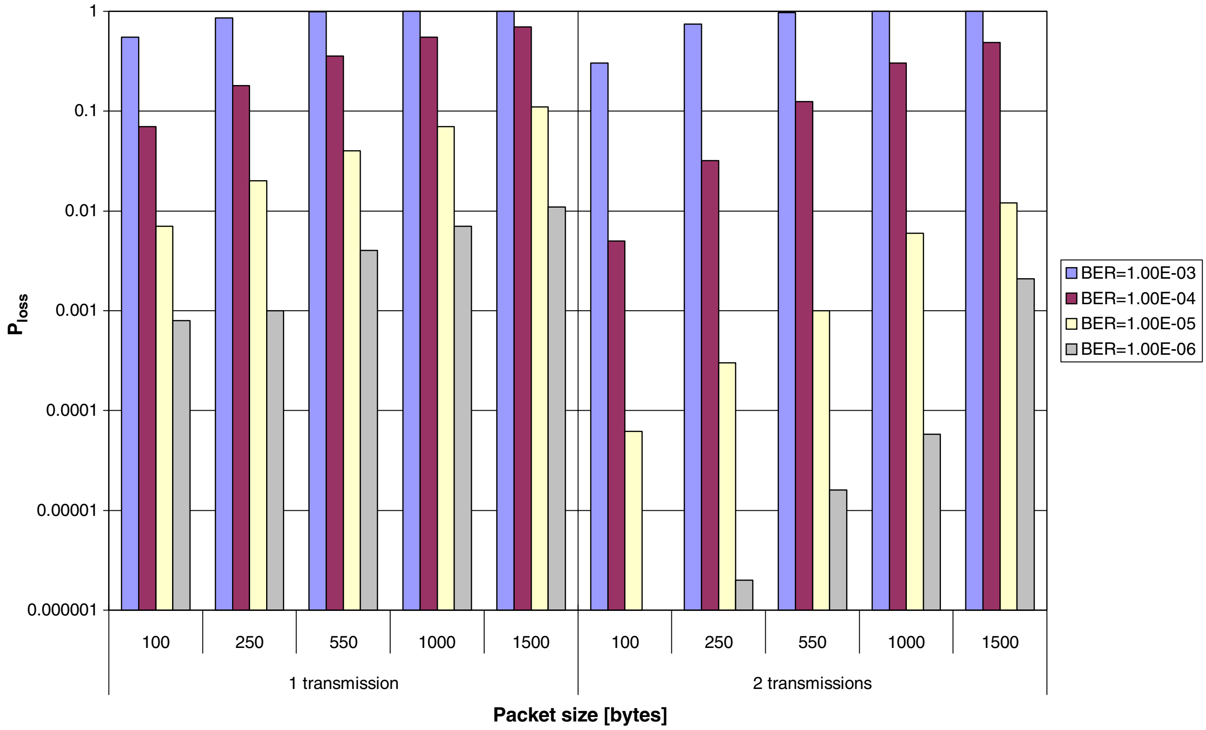

Fig. 5. P_{loss}, 1 and 2 transmissions, CFDP-UE-RT.

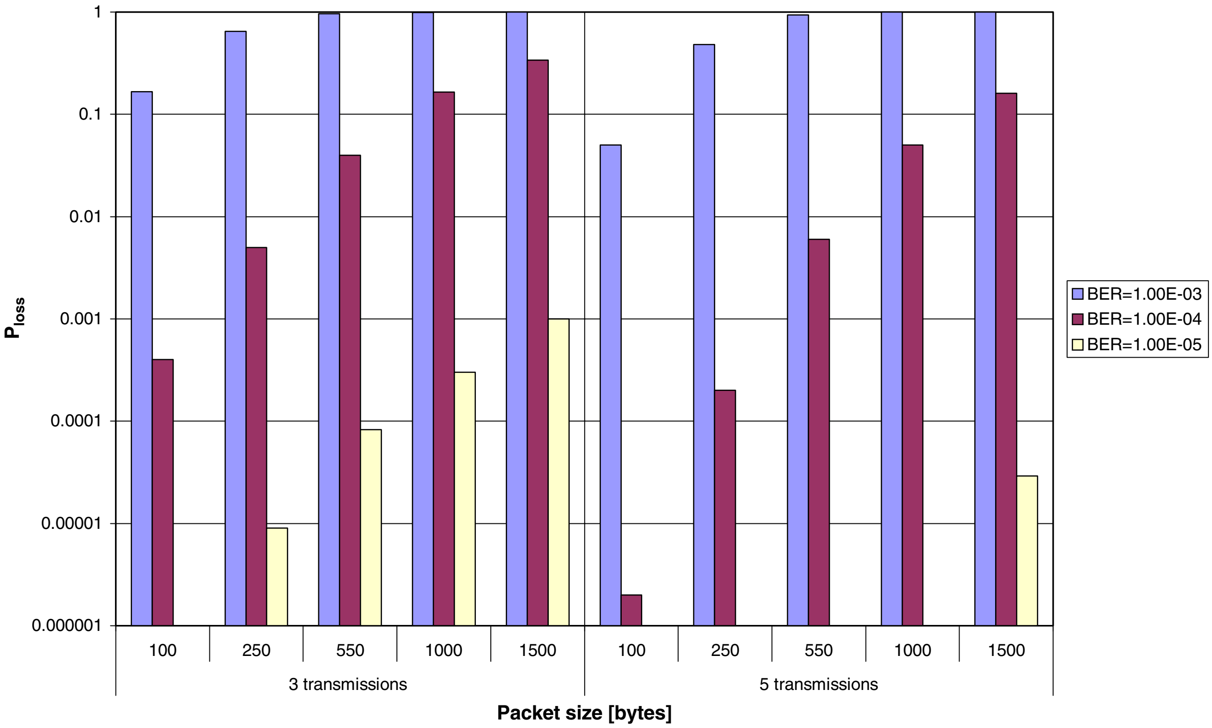

Fig. 6. P_{loss}, 3 and 5 transmissions, CFDP-UE-RT.

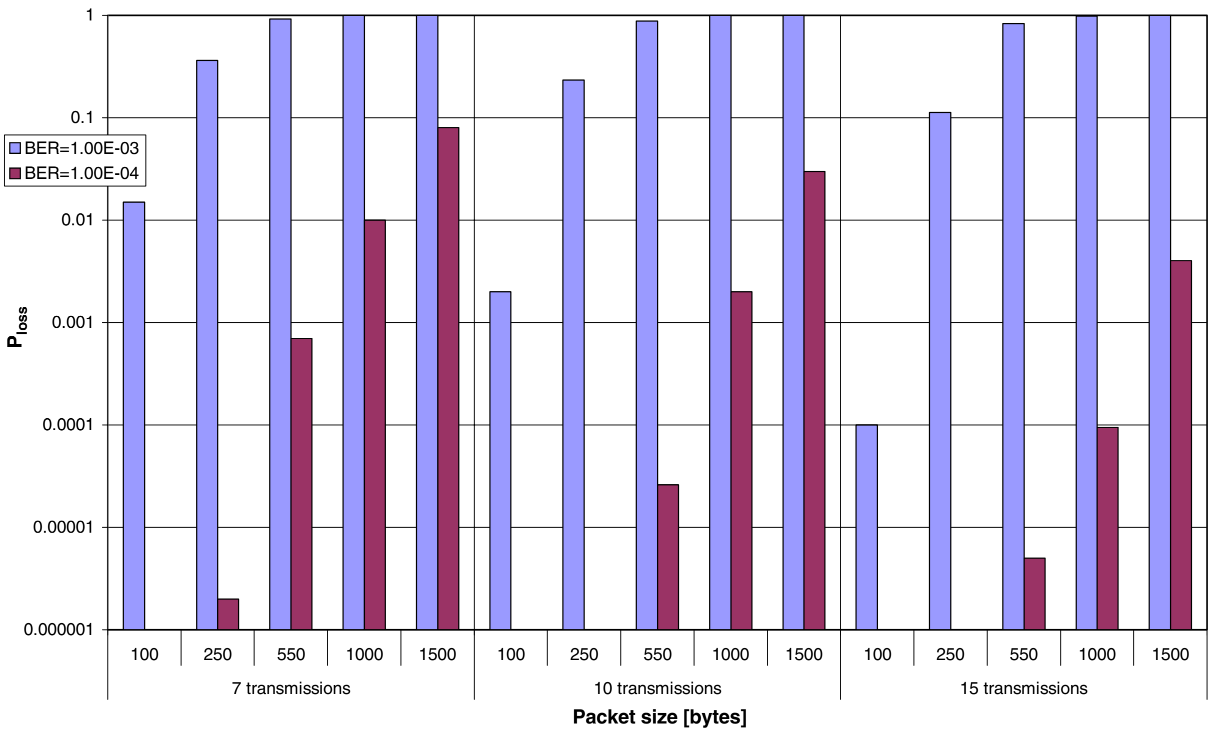

Fig. 7. P_{loss}, 7, 10 and 15 transmissions, CFDP-UE-RT.

of the packet size, even if smaller the packet size is, better performance is registered. This behaviour is confirmed when BER decreases and, in this case, packet size is fundamental to match the performance constraint of each class, given the BER value. It is straightforward that increasing the number of transmissions, from 1 to 2, the probability of CFDP data blocks delivery definitely increases, even if at cost of the effective throughput, as pointed out in the following.

If the number of transmissions is further increased, from 3 to 5 (Fig. 6), when $\mathrm{BER} = 10^{-6}$, $P_{\mathrm{loss}} = 0$ (not shown in Fig. 6). If BER ranges from 10^{-3} to 10^{-5}, the performance is still strictly dependent on the packet size and on the number of performed transmissions. As highlighted in the previous case, best results are provided with minimum packet size (i.e., 100 bytes) and by performing 5 transmissions. In this case $P_{\mathrm{loss}} = 0.05$, 2×10^{-6} and 0 is measured for $\mathrm{BER} = 10^{-3}$, 10^{-4} and 10^{-5}, respectively. Matching the result with the performance requests of the classes is immediate. When there is a higher number of transmissions (from to 7 to 15, as shown in Fig. 7), only $\mathrm{BER} = 10^{-3}$ and 10^{-4} determine $P_{\mathrm{loss}} \neq 0$. The same comments reported for Figs. 2 and 3 can be applied. It is worth noting that 10 and 15 transmissions with packet size 100 bytes assure the requirements of Class B and C, even for $\mathrm{BER} = 10^{-3}$, obviously at cost of channel bandwidth utilization.

The Effective Throughput is shown in Fig. 8 versus the number of transmissions structured for traffic class and versus the BER value. In more detail, the figure contains the effective throughput values of the configuration assuring the lowest P_{loss} among the ones that guarantee the performance request of a specific class. For example, considering Class B ($P_{\mathrm{loss}} \leqslant 0.01$) and 5 transmissions, there are three configurations that satisfy the request for $\mathrm{BER} = 10^{-4}$: packet size 100, 250, and 550. The first one assures the minimum loss probability and it is used to compute the throughput value in Fig. 8, corresponding to Class B, 5 transmissions, $\mathrm{BER} = 10^{-4}$.

Fig. 8 has a double function: it allows having a global vision about the performance request satisfaction by means of CFDP-UE-RT and understanding the drawback of the RT strategy. Low values of P_{loss} are paid in terms of bandwidth consumption. Fig. 8 allows getting a precise quantification of it. For example, CFDP-UE-RT can guarantee the performance requirement of Class A

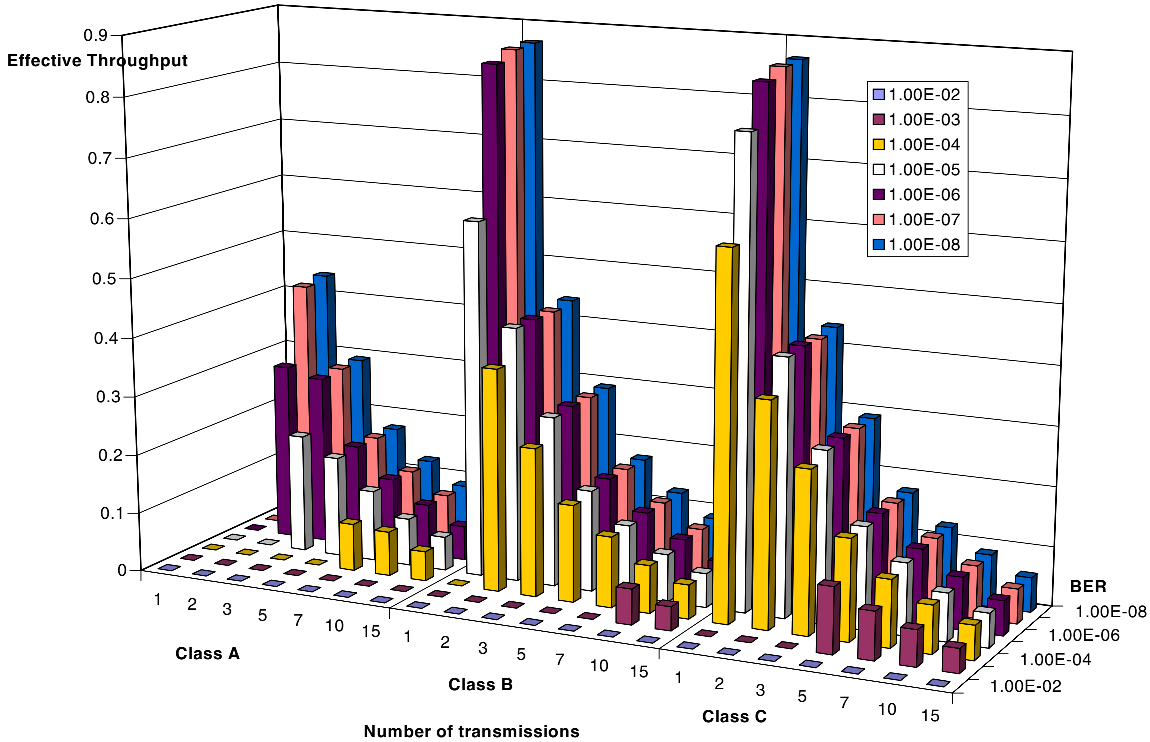

Fig. 8. Effective Throughput for different traffic classes, CFDP-UE-RT.

even for BER $= 10^{-4}$ by setting either 7, 10 or 15 transmissions but it implies an effective throughput below "0.1". It means that less than 10% of the overall bandwidth is used.

As regards resource consumption issues, times required to perform encoding and decoding operations are really limited in this configuration. Actually they are less than 1 s. CFDP-UE-RT works by replicating the same PDU, and consequently no relevant latencies have been registered since processing operations are really simple. On the other hand, some issues about implementation have arisen.

5.3.3. CFDP-UE-RSE

In this approach, as indicated previously, a full CFDP block is split into k packets, and then encoded into n packets; k is set to 51. The tests are performed by varying the Fec_ratio and the size of the k packets, in order to show how the performance changes in correspondence of different BER and bandwidth values. As emerged for the other encoding schemes, the impact of channel bandwidth is almost negligible for the motivations previously said. As a consequence, P_{loss} and Effective Throughput values are simply ruled by Fec_ratio and packet length. As far as P_{loss} analysis is concerned, independently of the Fec_ratio configurations, for BER of 10^{-2}, $P_{\text{loss}} = 1$ is obtained, while for BER of 10^{-6}–10^{-8} P_{loss} falls down to 0. Concerning the other cases, two sets of Fec_ratio values are considered: 1.5 and 2, representing low FEC, and 3 and 5, for strong FEC. P_{loss} values by varying the BER and the packet size are shown in Tables 3 and 4, for the two FEC sets, respectively. In Table 3: if BER $= 10^{-3}$, the results are poor, since a limited number of redundancy packets is not able to recover a large number of errors, as exhibited for such BER. If BER equals 10^{-4} and 10^{-5}, the results are more encouraging: P_{loss} decreases down to 0 in both cases, by employing a Fec_ratio of 2 and setting the packet size to 100 bytes. The role of "Packet Size" is outstanding. It is clear also in Table 4, where the increased redundancy allows getting much more satisfying P_{loss} results: if BER $= 10^{-5}$, P_{loss} is always "0" and it is not shown. If BER $= 10^{-4}$, properly setting Packet Size, even Class A may be satisfied, while, if BER $= 10^{-3}$, only Fec_ratio 4 and 5, associated with Packet-Size $= 100$ bytes, allows getting acceptable results, at least for Class C and Class B (and C), respectively.

Table 3
P_{loss} evaluation for Fec_ratio of 1.5 and 2, for CFDP-UE-RSE

Fec_ratio	Packet size	BER		
		10^{-5}	10^{-4}	10^{-3}
1.5	100	0	10^{-6}	0.997
	250	0	0.231	1
	550	2×10^{-6}	0.998	1
	1076	0.0002	1	1
	1285	0.011	1	1
2	100	0	0	0.834
	250	0	0.0028	1
	550	0	0.957	1
	1076	0	1	1
	1285	2×10^{-6}	1	1

Table 4
P_{loss} evaluation for Fec_ratio of 3, 4 and 5, for CFDP-UE-RSE

Fec_ratio	Packet size	BER	
		10^{-4}	10^{-3}
3	100	0	0.317
	250	0	1
	550	0.413	1
	1076	1	1
	1285	1	1
4	100	0	0.045
	250	0	1
	550	0.080	1
	1076	1	1
	1285	1	1
5	100	0	0.002
	250	0	1
	550	0.007	1
	1076	1	1
	1285	1	1

Concerning Effective Throughput: is structured as Fig. 9. Again, the effect of redundancy, now due to the $(n-k)$ redundant packets, is clear and directly measurable.

As far as encoding/decoding times are concerned, even in the case of Reed Solomon encoding, tests have shown a limited impact of processing operations on the overall performance (Effective Throughput). The latencies varied between 8 and 42 s, in dependence of both packet size and Fec_ratio values. As a consequence, the overall Effective Throughput is only partially affected by the processing times, which impact only on the 2% in the worst configuration (Fec_ratio of 5 and Packet Size of 100 bytes).

5.4. Performance comparison

All the considerations emerged about the effectiveness of proposed protocols are summarized now. For the sake of the clarity, for each configuration, only the maximum values of Effective Throughput are considered. As shown in Table 5, CFDP-UE-LDPC offers a constant performance result, equal to 0.62, that is always better than the results of the other configurations, independently of the traffic class, for BER higher than 10^{-4}. On the other hand, CFDP-UE-RT offers the best absolute results, with a maximum of 0.868 for BER equal to 10^{-8} and Class C (1 transmission). Considering Class per Class:

- Class A: CFDP-UE-RT is the less efficient, while CFDP-UE-RSE offers results progressively more satisfying as BER decreases and, for BER $\leqslant 10^{-6}$, it equals CFDP-UE-LDPC.
- Class B: CFDP-UE-LDPC is again very efficient; there is advantage using CFDP-UE-RSE instead of CFDP-UE-RT for BER $\geqslant 10^{-5}$. For lower BER values, CFDP-UE-RT overcomes the other solutions because the relaxed constraint on P_{loss} (Class B: $P_{loss} \leqslant 0.01$) allows avoiding redundant retransmissions.
- Class C: comments are similar to Class B case. Even more relaxed P_{loss} request "anticipates" the advantage of CFDP-UE-RT up to 10^{-4}.

Finally, considerations about complexity and implementation cost arise. CFDP-UE-RT presents a very simple implementation without particular cost in terms of memory, CPU consumption and extra processing latencies. On the contrary, according to [17,18], Reed Solomon encoding is characterized by high memory usage along with very long processing times, up to tens of seconds. LDPC codes present limited memory consumption because of the employment of sparse parity check matrix, while the processing time, even if lower than Reed Solomon one, is not negligible and may raise up to 20 s.

From this picture it is possible to see which advantages derive from the use of erasure codes within CFDP protocol. Firstly, adopting error control schemes, implemented at higher layers, helps improve the overall performance by reducing the impact of residual link errors, not detected by FEC techniques, acting at the datalink layer. In this view, the use of erasure codes is really promising if

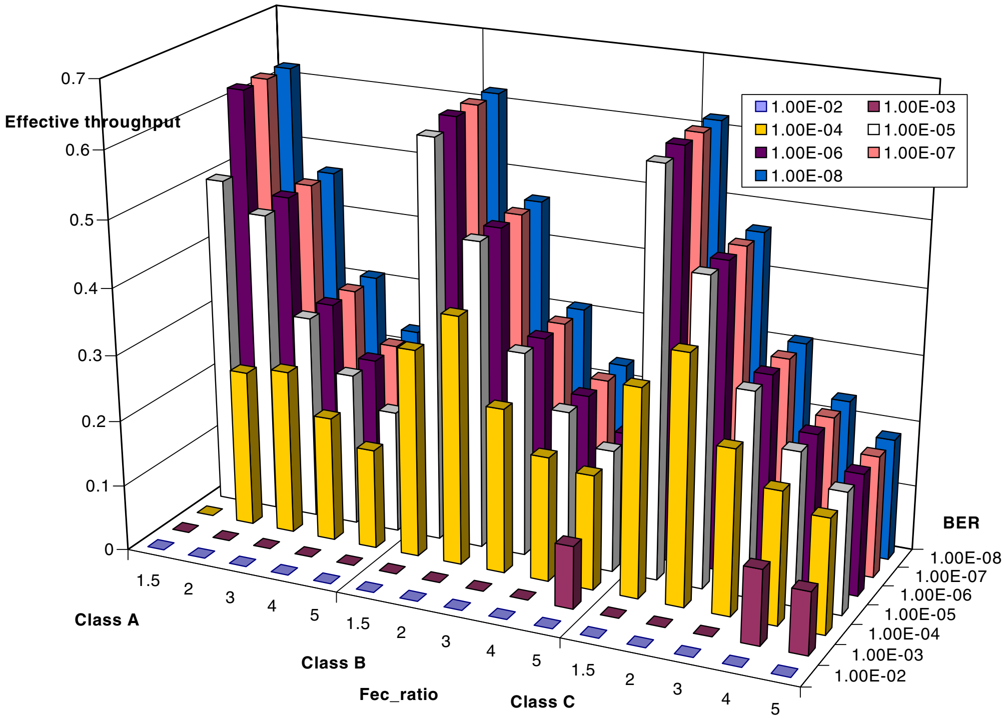

Fig. 9. Effective Throughput for different traffic classes, CFDP-UE-RSE.

Table 5
Performance comparison: effective throughput for the best protocol configurations

Class	CFDP-UE	BER						
		10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}
A	LDPC	0.62	0.62	0.62	0.62	0.62	0.62	0.62
	RSE	0	0	0.25	0.5	0.62	0.62	0.62
	RT	0	0	0.08	0.2	0.3	0.429	0.436
B	LDPC	0.62	0.62	0.62	0.62	0.62	0.62	0.62
	RSE	0	0.095	0.377	0.607	0.62	0.62	0.62
	RT	0	0.06	0.375	0.6	0.849	0.864	0.868
C	LDPC	0.62	0.62	0.62	0.62	0.62	0.62	0.62
	RSE	0	0.114	0.377	0.612	0.619	0.619	0.619
	RT	0	0.11	0.61	0.78	0.849	0.8647	0.868

compared with performance degradation that typical ARQ-based schemes might suffer, in correspondence of long retransmission cycles. Besides, erasure codes allow achieving satisfactory performance results at a limited cost in terms of resource consumption, as observed above. This result has a direct connection to implementation on real satellite systems, where the limited power budget usually represents a limitation for the maximum achievable performance. On the contrary, using CFDP-UE variants allows matching specific QoS requests with limited resource consumption.

6. Conclusions and future work

The problem of assuring reliability to space "cis-lunar" communications achieved in various conditions, namely "almost clear sky" (tolerable BER values ranging from 10^{-8} to 10^{-7}), "hard link intermittence" (experiencing BER values ranging from 10^{-6} to 10^{-4}) and "deep-fading periods" (characterized by BER values of 10^{-2} and 10^{-3}), is investigated in this paper. The proposed approach is based on the adoption of erasure codes schemes (Reed Solomon Encoding RSE and Low Density

Parity Check LDPC) and of a Repeated Transmission (RT) scheme implemented within a CFDP protocol core, whose extended features are defined as CFDP-UE-RSE, -LDPC, -RT, respectively. Three classes of data traffic are assumed, namely Class A for data file transmission, Class B for audio/video broadcasting and Class C for medical/meteorological images transfer. They are characterized by different requests on the maximum probability of data loss (0 for Class A, 10^{-2} for Class B, 10^{-1} for Class C). In the case of "deep-fading periods" CFDP-UE-LDPC offers the best results, thanks to the very robust coding technique adopted. In the case of "hard link intermittence", also CFDP-UE-RSE offers encouraging results, while CFDP-UE-RT gives less satisfying performance. On the other hand, CFDP-UE-RT employment is really promising when applied to "almost clear sky" conditions. As next steps of this research: the investigation of adaptive code solutions based on monitoring current C/N values (carrier to noise power ratio) and consequent evaluation of BER values, in order to tune: choice of encoding scheme, redundancy weight and suitable packet sizes.

References

[1] Consultative Committee for Space Data Systems website: <http://www.ccsds.org>.

[2] D.C. Lee, W.B. Baek, Expected file-delivery time of deferred NAK ARQ in CCSDS file-delivery protocol, IEEE Transactions on Communications 52 (8) (2004) 1408–1416.

[3] CCSDS File Delivery Protocol, Recommendation for Space Data System Standards, CCSDS 727.0-B-3., Blue Book, Issue 3, Washington, DC, CCSDS, June 2005.

[4] H. Ernst, L. Sartorello, S. Scalise, Transport layer coding for the land mobile satellite channel, in: 59th IEEE Vehicular Technology Conference (VTC'04), Milan, Italy, May 2004.

[5] L. Rizzo, Effective erasure codes for reliable computer communication protocols, ACM Computer Communication Review 27 (2) (1997) 24–36.

[6] Cislunar Working Group website: <http://www.ccsds.org/docu/dscgi/ds.py/View/Collection-527>.

[7] K. Fall, A Delay-Tolerant Network Architecture for Challenged Internets, in: ACM Sigcomm 2003, Karlsruhe, Germany, August 2003, pp. 27–34.

[8] 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 41 (6) (2003) 128–136.

[9] K.B. Bhasin, Interplanetary Internet, Computer Networks 47 (5) (2005) 599–783, Special issue.

[10] C. Liu, E. Modiano, On the performance of additive increase multiplicative decrease (AIMD) protocols in hybrid space-terrestrial networks, Computer Networks 47 (5) (2005) 661–678.

[11] J. Fang, Ö.B. Akan, Performance of multimedia rate control protocols in InterPlaNetary Internet, IEEE Communications Letters 8 (8) (2004) 488–490.

[12] Ö.B. Akan, J. Fang, I.F. Akyildiz, Performance of TCP protocols in deep space communication networks, IEEE Communications Letters 6 (11) (2002) 478–480.

[13] Ö.B. Akan, J. Fang, I.F. Akyildiz, TP-Planet: a reliable transport protocol for interplanetary Internet, IEEE Journal on Selected Areas in Communications 22 (2) (2004) 348–361.

[14] Luby, J. Gemmell, L. Vicisano, L. Rizzo, J. Crowcroft, Asynchronous Layered Coding (ALC) Protocol Instantiation, IETF, RFC 3450, December 2002.

[15] M. Luby, J. Gemmell, L. Vicisano, L. Rizzo, M. Handley, J. Crowcroft, Layered Coding Transport (LCT) Building Block, IETF, RFC 3451, December 2002.

[16] T. Paila, M. Luby, R. Lehtonen, V. Roca, R. Walsh, FLUTE – File Delivery over Unidirectional Transport, IETF, RFC 3926, October 2004.

[17] C. Neumann, V. Roca, R. Walsh, Large scale content distribution protocols, ACM SIGCOMM Computer Communication Review 2005 35 (5) (2005) 85–92.

[18] V. Roca, Design, Evaluation and comparison of four large block FEC Codecs, LDPC, LDGM Staircase and LDGM Triangle, plus a Reed Solomon Small Block FEC Codec, INRIA, Rapport de Recherche, June 2004, <http://www.inrialpes.fr/planete>.

[19] J.W. Byers, M. Luby, M. Mitzenmacher, A digital fountain approach to asynchronous reliable multicast, IEEE Journal on Selected Areas in Communications 20 (8) (2002) 1528–1540.

[20] M. Luby, L.T. Codes, in: Proceedings of the 43rd Symposium on Foundations of Computer Science, IEEE Computer Society, Vancouver, 2002.

[21] J.W. Byers, M. Luby, M. Mitzenmacher, Accessing multiple mirror sites in parallel: Using tornado codes to speed up downloads, in: IEEE INFOCOM 1999, New York, March 1999, pp. 275–283.

[22] A. Shokrollahi, Raptor codes, IEEE Transactions on Information Theory 52 (6) (2006) 2551–2567.

[23] Next Generation Space Internet—End-to-end resource provisioning for orbiting missions, research and development for space data system standards, CCSDS 732.5-O-1, Orange Book, Issue 1, Matera, Italy, CCSDS, April 2003.

[24] R.A. Beck, R.K. Vincent, D.W. Watts, M.A. Seibert, D.P. Pleva, M.A. Cauley, C.T. Ramos, T.M. Scott, D.W. Harter, M. Vickerman, et al., A space-based end-to-end prototype geographic information network for lunar and planetary exploration and emergency response (2002 and 2003 field experiments), Computer Networks 47 (5) (2005) 765–783.

[25] TM Space Data Link Protocol. Recommendation for Space Data System Standards, CCSDS 132.0-B-1., Blue Book, Issue 1, Washington, DC, CCSDS, September 2003.

[26] TC Space Data Link Protocol. Recommendation for Space Data System Standards, CCSDS 232.0-B-1., Blue Book, Issue 1. Washington, DC, CCSDS, September 2003.

[27] AOS Space Data Link Protocol. Recommendation for Space Data System Standards, CCSDS 732.0-B-1., Blue Book, Issue 1. Washington, DC, CCSDS, September 2003.

[28] Proximity-1 Space Link Protocol—Data Link Layer, Recommendation for Space Data System Standards, CCSDS 211.0-B-3., Blue Book, Issue 3, Washington, DC, CCSDS, May 2004.

[29] TM Synchronization and Channel Coding. Recommendation for Space Data System Standards, CCSDS 131.0-B-1., Blue Book, Issue 1, Washington, DC, CCSDS, September 2003.
[30] TC Synchronization and Channel Coding. Recommendation for Space Data System Standards, CCSDS 231.0-B-1., Blue Book, Issue 1. Washington, DC, CCSDS, September 2003.
[31] Proximity-1 Space Link Protocol—Coding and Synchronization Sublayer, Recommendation for Space Data System Standards, CCSDS 211.2-B-1. Blue Book, Issue 1, Washington, DC, CCSDS, April 2003.
[32] Space Packet Protocol. Recommendation for Space Data System Standards, CCSDS 133.0-B-1., Blue Book, Issue 1, Washington, DC, CCSDS, September 2003.
[33] Overview of Space Link Protocols, Report Concerning Space Data System Standards, CCSDS 130.0-G-1, Green Book, Issue 1, Oxfordshire, UK, CCSDS, June 2001.
[34] Space Communications Protocol Specification (SCPS)—Transport Protocol (SCPS-TP), CCSDS 714.0-B-1, Blue Book, Issue 1, Newport Beach, CA, May 1999.
[35] K. Hogie, E. Criscuolo, R. Parise, Using standard Internet Protocols and applications in space, Computer Networks 47 (5) (2005) 603–650.
[36] C. Bormann, C. Burmeister, M. Degermark, H. Fukushima, H. Hannu, L-E. Jonsson, R. Hakenberg, T. Koren, K. Le, Z. Liu, A. Martensson, A. Miyazaki, K. Svanbro, T. Wiebke, T. Yoshimura, H. Zheng, RObust Header Compression (ROHC): Framework and four profiles, IETF, RFC 3095, July 2001.
[37] I.S. Reed, G. Solomon, Polynomial codes over certain finite fields, Journal of the Society for Industrial and Applied Mathematics (SIAM) 8 (2) (1960) 300–304.
[38] R.G. Gallager, Low density parity check codes, IRE Transactions on Information Theory (1962).
[39] D. MacKay, R. Neal, Near shannon limit performance of low density parity check codes, Electronic Letters 32 (18) (1996) 1645–1646.
[40] D. MacKay, Good error correcting codes based on very sparse matrices, IEEE Transaction on Information Theory 45 (1999) 399–431.
[41] M. Luby, M. Mitzenmacher, M.A. Shokrollahi, D.A. Spielman, Efficient erasure correcting codes, IEEE Transactions on Information Theory 47 (2) (2001) 569–584.

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