Joint Application of CCSDS File Delivery Protocol and Erasure Coding Schemes over Space Communications

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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 inapplicability of TCP/IP architectures 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, 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.**

Key words – CFDP, Erasure Coding, Transport layer, Satellite Communication.

I. INTRODUCTION

The integration of satellite and wireless network segments in the traditional internet has determined an increasing demand for communication technologies able to transport and deliver multimedia services to the final users. On the other hand, it has focused on the limits imposed by TCP/IP protocol architectures, when applied in hazardous environments characterized by long propagation delays, intermittent, and asymmetric links, frequent transmission errors. Taking the satellite technology as reference for its clear benefits concerning the wide area coverage and its inherent capability of broadcast/multicast communications, a protocol architecture alternative to TCP/IP has been designed by the Consultative Committee for Space Data Systems (CCSDS).

The goal of the paper is showing the efficiency of using CCSDS protocols, integrated with coding schemes implemented at the application layer, adopted over the highly asymmetric and intermittent link satellite environment mentioned above. In order to cope with the impairments introduced by such links, it is preferable to adopt erasure codes [1] implemented within CFDP (CCSDS File Delivery Protocol) specification, rather than Automatic Repeat reQuest (ARQ) schemes because the high propagation delays along with the intermittence of transmission links would imply very long recovery periods [2]. The trade-off is represented by the implementation cost and by the waste of network resources (namely channel bandwidth) because of the encoding operations. Both these aspects are investigated in the paper in terms of resource consumption, channel bandwidth exploitation and reliability of data communication.

In more detail, the adoption of the CFDP protocol combined with the use of erasure coding schemes is applied to data communication achieved between Earth and Moon satellite platforms. The whole analysis is performed taking the research activity carried on in the Cislunar Networking Working Group within CCSDS as reference.

The remainder of the paper is organized as follows. Section II presents the state of the art of erasure coding and focuses on the works related to protocol architectures for challenging satellite environments. Section III introduces the investigation carried on in the paper, focusing on the features offered by CFDP protocol integrated with promising erasure coding schemes. Section IV is devoted to the performance analysis, while Section V draws the conclusions emerged during the performed tests and gives an outlook of the future research directions.

II. STATE OF THE ART AND RELATED WORKS

One of the primary requirements of telecommunication infrastructures is to assure high reliability in order to transport multimedia data and services throughout the network. This task may be accomplished by means of Automatic Repeat reQuest (ARQ) acknowledgment based schemes, which react in presence of information loss and explicitly require the retransmission of missed data frames. Even though these mechanisms are widely adopted and implemented in the Internet, they are not suited for real-time multicast/broadcast services and, in particular, they can be hardly employed in hazardous environments composed of satellite and wireless links, where reliability is important. Alternatively, erasure coding techniques have been proposed since the end of eighties and communication architectures based on them have been standardized. In particular, a great effort has been carried out by IETF within the Reliable Multicast Transport (RMT) working group and has brought to the design of mechanisms, aimed at increasing service reliability, implemented at the

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higher layers (namely, application and transport ones) of the protocol stack. Asynchronous Layered Coding (ALC) and Layered Coding Transport (LCT), which work in conjunction with the File Delivery over Unidirectional Transport (FLUTE) protocol [3], assure a reliable data service through erasure codes. Transport Layer Coding is proposed in [4] and applied to satellite environments. Efforts have been produced, by ETSI and CCSDS institutions, to standardize and design MPE-FEC (Multi Protocol Encapsulation- Forward Error Control) within DVB-H (handheld) and "long erasure codes" for CCSDS protocols. The choice of proper robust encoding techniques implies the success of the proposed protocol solutions: it is worth remembering Low Density Parity Check (LDPC) and Reed Solomon (RS) codes [5], which are adopted also in this work and extensively investigated throughout the paper. A further approach, which is rapidly capturing the interest of the scientific community for its effectiveness, is represented by the Digital Fountain scheme [6] and, in general, by the rateless codes, such as Raptor, Tornado [7] and LT (Luby Transform) [8].

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.

III. THE CCSDS FILE DELIVERY PROTOCOL (CFDP)

A. Overview

CFDP protocol has been designed to run at the application layer of a full CCSDS protocol stack and to manage the transmission of data over satellite networks in space missions.

CFDP protocol splits the data to be sent into blocks (namely CFDP PDUs), composed of a payload, carrying a maximum information amount of 65536 bytes, and of a header whose length is assumed equal to 20 bytes. Furthermore, the protocol is responsible of segmenting the CFDP PDU into smaller data units if the maximum dimension of packets allowed in the network is lower than the size of the blocks.

The protocol works both in reliable and unreliable mode. Concerning the latter, the delivery of data has to be guaranteed by other entities, typically resident in underlying layers (e.g. transport and datalink layers), if necessary. Concerning the former, the reliability request of the communication is guaranteed by a recovery mechanism based on negative acknowledgment notification. Unfortunately, even if efficient, acknowledgment-based schemes are not always feasible in real environment and need to be substituted by alternatives that, on one hand, improves the communication reliability but, on the other hand, require no explicit requests of retransmissions.

B. Integration of Erasure Codes

The aim of this proposal is to integrate erasure coding schemes into the CFDP entity, when working in unreliable mode. The entity with extended integrated features is called CFDP-UE (where UE stands for Unreliable Extended). Three different mechanisms are adopted to extend the CFDP features: Repeated Transmission (RT), Reed Solomon Encoding (RSE) and Low Density Parity Check (LDPC). The RT is based on heuristics of automatic repeated transmissions, which may help guarantee the delivery of most sent data. From the protocol implementation point of view, CFDP entity splits the information into blocks, and takes care of transmitting the same CFDP PDU for N times consecutively, where the number of repetitions (N-1) is set at the beginning of the transaction. Concerning RSE, it is based on the adoption of Reed Solomon codes. In this case, once a full CFDP PDU (i.e. carrying a payload of 65536 bytes) is built by the entity, it is split into k data packets and encoded into n packets, of which (n-k) are redundancy packets. It is straightforward that an important role is played by the ratio between the "n" encoded and the "k" original packets. This parameter is referred as Fec_ratio in the remainder of the paper. Taking the work in [9] as reference, k=51 is set and Fec_ratio varies from 1.5 up to 5, corresponding to a maximum value n=255.

The third solution is based on LDPC codes, whose main peculiarity is to present a sparse parity check matrix. This encoding scheme allows very robust communication when very long codewords are applied. The drawback is due to the very high encoding/decoding times, which make its employment critic in practice. For this purpose, a subclass of LDPC codes defined in [9] and indicated in the following as LDGM is investigated in this paper. Even in this case, an important role is played by the Fec_ratio value, set to 1.5. At CFDP data block building phase, the protocol entity assembles different data blocks into only one bit vector (operation necessary since LDPC codes perform well in presence of very long codewords) and encodes it accordingly to the LDGM scheme.

The first approach is referred as CFDP-UE-RT (UE - Unreliable Extended) and the other two schemes as CFDP-UE-RSE and CFDP-UE-LDPC, respectively.

IV. PERFORMANCE ANALYSIS

A. Testbed Configuration

The investigated scenario is derived from the activity developed within CCSDS Cislunar Networking Working Group, aimed at individuating novel protocol solutions, to guarantee reliable data communication over space links. Under this view, the reference environment considered in this paper, is composed of:

- Sensors, rovers and landers: placed on the Moon's surface, responsible of taking measures 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. One of them orbits around the Moon and receives the data (e.g. images and measures) that arrive from the sensors, landers and rovers placed on the Moon's surface. The other one orbits around the Earth and collects the data arriving from the Moon orbit satellite and works as a relay node towards the gathering centre.

The photos in the lower part of Fig. 1 show the data path from the Moon to the gathering centre.

The distance between Moon and Earth, about 384000 km, implies a round trip time of 2.56s that imposes severe limitations to the performance of TCP-based protocols. On the other hand, improving the reliability of the overall communication and of the interplanetary portion in particular is important. For these reasons, the CFDP-UE proposal, which does not rely on feedback mechanisms, integrated with algorithms that can assure relevant reliability improvement, is considered in this paper as a viable solution for the described environment and is deeply analyzed. A propagation delay of 2.45 s is assumed and available bandwidth values of 2.048 Mbit/s, 1.024 Mbit/s, 0.512 Mbit/s and 0.256 Mbit/s are considered in different tests. Such a transmission channel is modeled as a AWGN (Additive White Gaussian Noise): corrupted bits are assumed uniformly and identically distributed within each frame (i.i.d model).

The protocol stack mounted on the two satellites is fully CCSDS-based: it implements CFDP-UE layer on the top layer, as defined in Section III; below, in cascade, there are the CCSDS Space Packet Protocol responsible of routing and addressing tasks and the CCSDS Telemetry Protocol, which deals with framing, robust channel coding and modulation operations (Fig. 1). The reliability of the satellite 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.

To fully characterize different possible operative conditions, BER values ranging from 10^{-2} to 10^{-8} are considered: 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. The tests are accomplished (by considering a data transfer of 100Mbytes), through a simulation tool designed for the aim. 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 $(1-P_{loss})$ and the ratio of the Transfer Size and the Elapsed Time between the reception of the first and the last bit, 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 facts:

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

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

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 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 $P_{loss} \le 10^{-1}$.

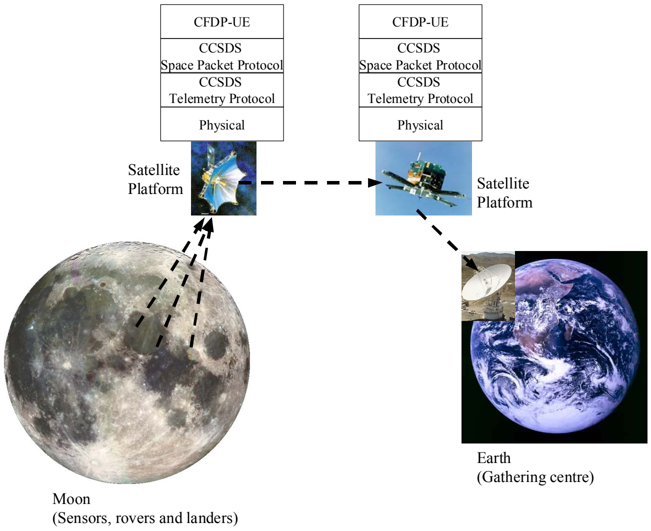

Fig. 1. Testbed configuration and CCSDS protocol architecture

B. *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.

CFDP-UE-LDPC. The employment of LDGM 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 the 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.

CFDP-UE-RT. As far as the P_{loss} investigation is concerned: in presence of BER=10^{-2} all the blocks are lost and $P_{\text{loss}} = 1$. On the other hand, when BER values are lower than 10^{-6} (from 10^{-7} down to 10^{-8}), all the transmitted blocks are received correctly, giving rise to $P_{\text{loss}} = 0$, 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 of packet size in Fig. 2, Fig. 3 and Fig. 4, for “1 and 2”, “3 and 5”, “7, 10 and 15” transmissions, respectively.

As shown in Fig. 2, 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 of the packet size, even if smaller the packet size is, better performance are registered. This behavior 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 data blocks delivery definitely increases, even if at cost of the effective throughput, as pointed out in the following.

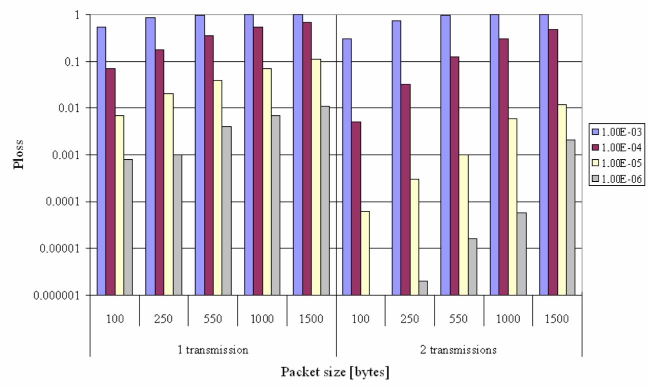

Fig. 2. P_{loss}, 1 and 2 transmissions, CFDP-UE-RT

If the number of transmissions is further increased, from 3 to 5 (Fig. 3), when BER=10^{-6}, $P_{\text{loss}} = 0$ (not shown in Fig. 3). If BER ranges from 10^{-3} to 10^{-5}, the performance is still strictly dependent on the packet size and on the number of transmissions performed. 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 $P_{\text{loss}} = 0.05$, $2 \cdot 10^{-6}$ and 0 is measured for BER=10^{-3}, 10^{-4} and 10^{-5}, respectively. Matching operation with the performance constraints of the classes is immediate. When there is a higher number of transmissions (from to 7 to 15, as shown in Fig. 4), only BER=10^{-3} and 10^{-4} determine $P_{\text{loss}} \neq 0$. 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 BER=10^{-3}, obviously at cost of channel bandwidth utilization.

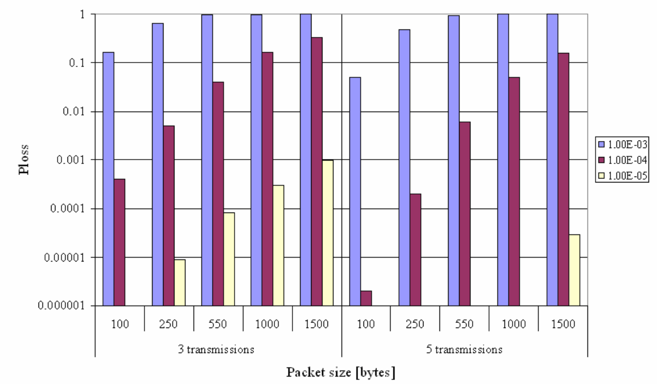

Fig. 3. P_{loss}, 3 and 5 transmissions, CFDP-UE-RT

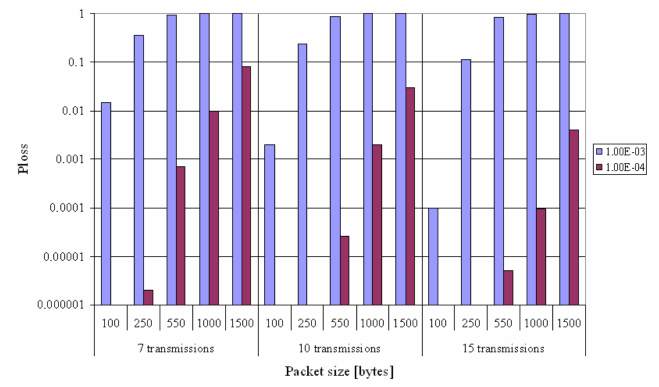

Fig. 4. P_{loss}, 7, 10 and 15 transmissions, CFDP-UE-RT

The Effective Throughput is shown in Fig. 5 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 constraint of a specific class. For example, considering Class B ($P_{\text{loss}} \le 0.01$) and 5 transmissions, there are three configurations that satisfy the constraint for $\text{BER} = 10^{-4}$: 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. 5, corresponding to Class B, 5 transmissions, $\text{BER} = 10^{-4}$.

Fig. 5 has a double function: it allows having a global vision about the performance constraint satisfaction by means of CFDP-UE-RT and to understand the drawback of the RT strategy. Low values of P_{loss} are paid in terms of bandwidth consumption. Fig. 5 allows getting a precise quantification of it. For example, CFDP-UE-RT can guarantee the performance requirement of Class A even for $\text{BER} = 10^{-4}$ 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.

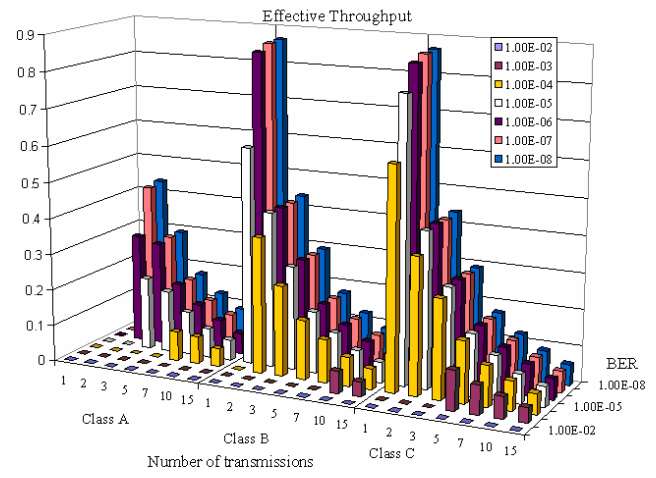

Fig. 5. Effective Throughput for different traffic classes, CFDP-UE-RT

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 $10^{-6} \div 10^{-8}$ 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 I and II, for the two FEC sets, respectively. In Table I: 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 II, where the increased redundancy allows getting much more satisfying P_{loss} results: if $\text{BER} = 10^{-5}$, P_{loss} is always "0" and it is not shown. If $\text{BER} = 10^{-4}$, properly setting Packet Size, even Class A may be satisfied, while, if $\text{BER} = 10^{-3}$, 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 I
P_{LOSS} EVALUATION FOR FEC_RATIO OF 1.5 AND 2

		BER		
Fec_ratio	**Packet Size**	**10^{-5}**	**10^{-4}**	**10^{-3}**
1.5	100	0	10^{-6}	0.997
	250	0	0.231	1
	550	$2 \cdot 10^{-6}$	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	$2 \cdot 10^{-6}$	1	1

TABLE II
P_{LOSS} EVALUATION FOR FEC_RATIO OF 3,4 AND 5

		BER	
Fec_ratio	**Packet Size**	**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: Fig. 6 is structured as Fig. 5. Again, the effect of redundancy, now due to the (n-k) redundant packets, is clear and directly measurable.

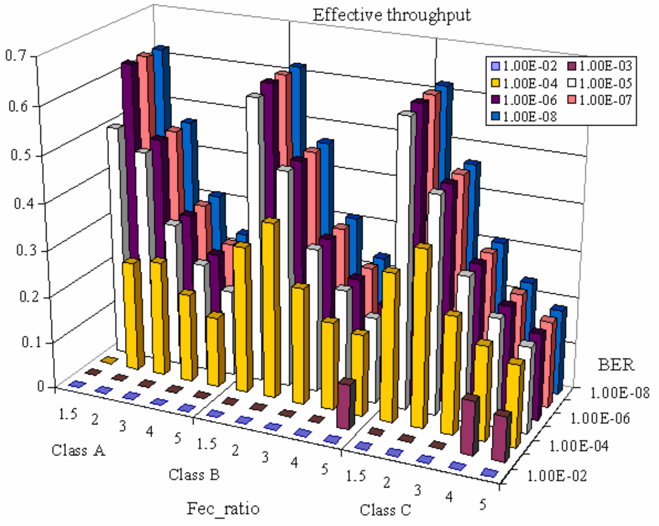

Fig. 6. Effective Throughput for different traffic classes, CFDP-UE-RSE

C. 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 III, 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 $\mathrm{BER} \leq 10^{-6}$, 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 $\geq 10^{-5}$. For lower BER values, CFDP-UE-RT overcomes the other solutions because the relaxed constraint on P_{loss} (Class B: $P_{\mathrm{loss}} \leq 0.01$) allows avoiding redundant retransmissions.
- Class C: comments are similar to Class B case. Even more relaxed P_{loss} constraint "anticipates" the advantage of CFDP-UE-RT up to 10^{-4}.

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 [9], Reed Solomon encoding is characterized by high memory usage along with very long processing times, up to tens of seconds. LDGM 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 5 seconds.

TABLE III
PERFORMANCE COMPARISON: EFFECTIVE THROUGHPUT

		BER						
Class	CFDP-UE	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

V. CONCLUSIONS AND FUTURE WORK

The problem of assuring reliability to space "cislunar" 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 (Repeated Transmission RT, Reed Solomon Encoding RSE and Low Density Parity Check LDPC) implemented within a CFDP protocol core, whose extended features compose CFDP-UE. 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 constraints 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 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.

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