Application-Layer Techniques for Data Communications over Deep Space Networks

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***Abstract* — The hazardous operative conditions experienced by deep space environments (very large latencies and frequent link disconnections) make the use of TCP-based transmission schemes inefficient. On the contrary, the use of erasure coding schemes and more appropriate Automatic Repeat reQuest (ARQ) schemes, available within the Packet Layer Coding-based and the Consultative Committee for Space Data Systems (CCSDS) protocol architectures respectively, assure better performance results. In this paper, the adoption of erasure codes within CCSDS protocol stack is considered and its effectiveness is evaluated with respect to ARQ-based transmission schemes available within the CCSDS File Delivery Protocol.**

I. Introduction

SINCE the end of eighties, the exploration of space and the proliferation of scientific experiments have shown, on the one hand, the necessity of reliable telecommunication infrastructures and, on the other hand, have revealed the shortcomings deriving from the use of TCP-based protocols. In particular, the large latencies experienced by typical deep space environments negatively affect the TCP performance because of its transmission paradigm based on a feedback scheme [1]. In this perspective, the features offered by the Consultative Committee for Space Data Systems (CCSDS) recommendations in terms of suspending and resuming capabilities are an effective resource to assure reliable data communication over space networks. Moreover, the support of highly efficient ARQ schemes available within the CCSDS File Delivery Protocol (CFDP) helps improve the overall data communication performance in terms of both throughput and loss recovery effectiveness. Although the use of CCSDS protocols has revealed its powerful abilities in recovering from consistent information losses and tolerating long disconnection periods, it is not completely able to properly exploit the channel bandwidth while recovery operations are performed. From this point of view, the adoption of erasure schemes and hence the Transport Layer Coding approach [2] would be beneficial for its recovery capabilities even in presence of bursty information losses. Starting from the aforementioned issues, this paper analyses the use of the Packet Layer Coding approach within the CFDP implementation and hence proposes a combined use of erasure coding and ARQ schemes for improving the overall performance.

The remainder of the paper is organized as follows. The state of the art and the related works carried out in the area of deep space communications are envisaged in Section II, while Section III addresses the peculiarities of such scenario by introducing the transmission channel model based on discrete Markov chains. The CCSDS protocol architecture, the Packet Layer Coding approach and the issues regarding the joint use of ARQ schemes and erasure codes are shown in Section IV. The investigation completes in Section V, where the performance analysis of the different CCSDS configurations is shown; in Section VI the conclusions are drawn.

II. Background

Over last years, the scientific community has made strong efforts for designing appropriate protocols and architectures able to guarantee reliable data communication over space networks. From the standardization point of view, relevant contributions have been provided by the CCSDS institution together with the Delay Tolerant Network [3] (formerly known as InterPlanetary Internet Project) working group within IRTF. In this perspective, it is worth mentioning the CCSDS File Delivery Protocol, which is able to tolerate long disconnection periods and to react properly to information losses thanks to suspending/resuming capabilities and efficient ARQ schemes, respectively.

Furthermore, the study of alternative mechanisms, based on erasure coding schemes and aimed at guaranteeing reliable communications deserves a particular attention. In particular, it is worth mentioning the work carried on within the Reliable Multicast Transport IETF working group, addressed to the design of protocol architectures able to support multicast communications over wireless links, by means of erasure codes implemented over the transport layer. From this standpoint, the advantages offered by the long erasure codes, and in particular by Low Density Parity Check codes (LDPC). Under this view their adoption over the transport layer is identified as Transport Layer Coding and proposed in [2]. Further considerations about the software complexity issues, arising from LDPC implementations, and the related performance are addressed in [4].

Beside the standardization activities performed within CCSDS and IETF, a special attention has to be paid to relevant protocol solutions, implemented at different layers of the OSI protocol stack, as proposed in [5]. In particular, TP-Planet

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protocol implemented at the transport layer, emerges as a promising solution.

Finally, this work takes the CCSDS File Delivery Protocol (CFDP) as reference and applies the Transport Layer Coding approach for improving the overall data communication performance over space networks.

III. THE DEEP SPACE ENVIRONMENT

A. The Reference Scenario

To better capture the environment peculiarities and hence properly study protocol implementations able to counteract the hazardous conditions in which the data communication is achieved, the following scenario is assumed:

- Two remote stations, placed on the Earth and on a remote planet (e.g. Mars or Moon), communicating each other through specialised protocol stacks, based on the CCSDS protocol architecture and, in particular, implementing the CCSDS File Delivery Protocol (CFDP).
- Two satellites orbiting around Earth and the remote planet, respectively, guarantee the end-to-end path, by acting as relay nodes.
- The long-haul link connecting the two satellites is actually the deep space link, which is the focus of this work.

The whole scenario is depicted in Fig. 1.

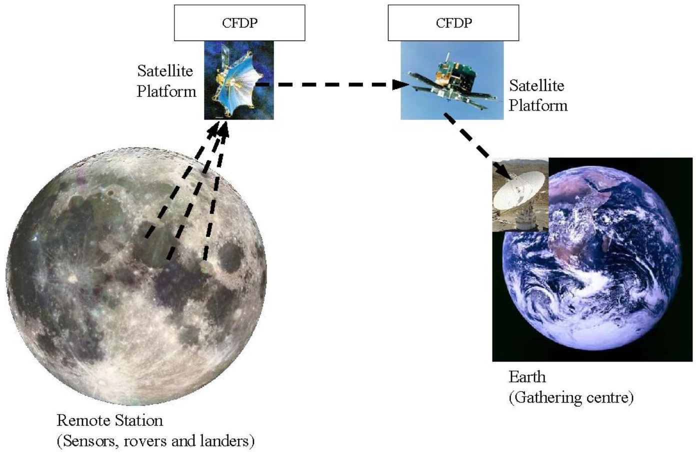

Fig.1. The Reference Scenario

B. The Deep Space Link

The strong impairments introduced by the deep space links, such as deep fading periods, blackout events and variable propagation delays, have to be properly taken into account while designing transmission schemes suited to the space environments. Under this view, the necessity of adopting a transmission channel model, able to capture the main peculiarities of the physical link, is hence straightforward. Given the high number of factors characterizing the transmission channel dynamics, some simplifications are introduced. Firstly, the propagation delay, whose variability is due to the relative motion of planets, is assumed constant. Secondly, the blackout events are neglected, since, in general, data communications in space scenarios are scheduled in advance, through ephemerides calculations.

On the basis of these considerations, the main aspects that have to be properly taken into account concern the relative motion of the satellite platforms, the multi-path fading effects due for instance to the solar flares and other hostile radiofrequency conditions. Hence, the adaptation of common models employed for characterizing the wireless transmission channel is an appropriate solution. In particular the use of Discrete-Time Markov Chains (DTMC) for representing the channel behaviour has been envisaged; in detail, the use of first order Markov chains with 4 states is proposed.

The transition between two arbitrary consecutive states, i and j, is ruled by the transition probability matrix $P = \{p_{i,j}\}$. On the other hand, the steady-state probability of being in the i[th] state is denoted as π_i, where $i \in \{0,1,2,3\}$. Each state accounts the channel reliability by means of the Bit Error Ratio (BER). In practice, a BER value equal to BER_i is assigned to the i[th] state; for consecutive states, the following inequality holds: $BER_i < BER_j \ \forall i,j \in \{0,1,2,3\}$, with $i < j$.

In particular, BER is the bit error rate measured at the receiver side, by taking into account the employment of forward error codes, applied at the lower layers.

Finally, under the hypothesis that the Markov chain is embedded at the start of each packet transmission, the mean permanence time τ_i within the i[th] state can be expressed as the bit duration time (i.e. the reciprocal of the channel bandwidth, here indicated as B_w) divided by one minus the probability of being in the same state, namely $(1-p_{ii})$. This yields:

$$\tau_i = \frac{1}{B_w \cdot (1-p_{ii})}$$

To fully evaluate the impact of corrupted bits on the transmission performance, it is also necessary to provide a statistical characterization of the packet loss process. Under this view, the use of the GAP error length model is promising. In practice, error and error-free gaps are defined as occurrences of consecutive successful and unsuccessful received packets respectively. It is immediate to realize that the length of error-free and error gaps differently affect the channel reliability.

In this work, the values of permanence times τ_0 and τ_3, as well as the steady state probabilities π_2 and π_3 have been fixed within each tests; the lengths of error-free and error gaps have then been evaluated through MATLAB™.

The whole channel model is sketched in Fig. 2.

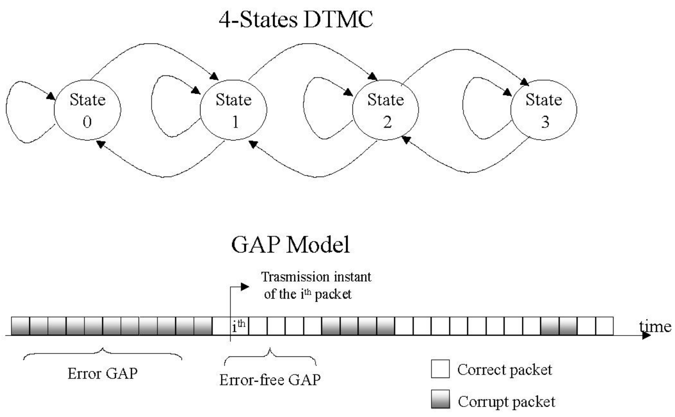

Fig. 2. The 4-states DTMC and the GAP model

IV. THE PROPOSED PROTOCOL ARCHITECTURE

A. The CCSDS File Delivery Protocol (CFDP)

The CCSDS File Delivery Protocol supports file transfer operations in space environments. In facts, CFDP transmitting entity assembles data into PDUs, identified in the following as CFDP blocks, whose payload can carry up to 65536 bytes, while the header length is assumed here of 20 bytes. Once the data transmission is completed, an End-of-File notification (EOF PDU) is transmitted to the other side, which will be responsible of issuing an ACK PDU to acknowledge the receipt of the EOF PDU. The reliability issues are addressed by the CFDP entity in dependence of the operating mode in which it is configured, either acknowledged or unacknowledged. In the latter, no specific options for assuring the communication reliability are implemented: protocols acting in the lower layers are responsible for that (if necessary). On the other hand, when CFDP operates in acknowledged mode, the communication reliability is assured my means of negative acknowledgments (NAK, issued by the receiving CFDP entity) and requiring the retransmission of the missed data PDUs. Once the loss of a data block is detected, the recovery mechanism is ruled by four different algorithms: immediate, prompted, asynchronous and deferred. In this work, the attention has been paid to the last one.

Finally, a particular note has to be dedicated to the suspending and resuming features provided by CFDP. In particular, when the protocol entity is configured for operating in "extended operations", it is able to suspend the transmission on the basis of the notifications, indicating the unavailability of the transmission medium, issued by the lower layer protocols. Afterwards, the data blocks are temporally stored in the local CFDP buffer; the transmission is resumed again once positive notifications about the channel availability are provided.

B. Proposed CFDP improvements

In this work, CFDP working in both acknowledged and unacknowledged modes is investigated. The proposed CFDP improvements regard the use of erasure coding schemes, aimed at guaranteeing reliable exchange of data also when the communication is achieved in very hazardous conditions. In practice, two protocol proposals have been conceived, namely "CLDGM" and "CLDGM-deferred", whose description follows.

CLDGM. It concerns the integration of erasure coding schemes into CFDP protocol when running in unacknowledged mode, by applying the Transport Layer Coding approach as shown in [2]and [6]. In practice, the adoption of LDGM codes, derived from the Low Density Parity Check codes, is envisaged for their ability of protecting the communication against bursty data losses. In facts, the integrated scheme works as follows: CFDP aggregates different data blocks, split them into k information "packets", and hence encode them into n packets, exploiting a LDGM generator matrix. The necessity of merging several CFDP PDUs is that LDGM performance strictly depends on the number of information packets (k): higher is k, more effective is the encoding procedure. Moreover, it is straightforward that the LDGM performance strictly depends on the ratio among the number of encoded packets and the total number of generated packets, referred in the following as code-rate. In particular, in this work, code-rate values ranging from 0.125 up to 0.875 have been considered and, for the sake of the completeness, block and packet sizes varying from 1024 to 65536 bytes and 128 to 1024 bytes, respectively have been considered in order to characterize the impact of link errors on the overall performance. In the following this approach will be referred as *CLDGM* (which stands for CFDP with LDGM codes).

CLDGM-deferred. The second approach combines the use of NAK PDUs with LDGM codes in order to allow data retransmission when LDGM effectiveness is not sufficient. On the other hand, the design of this scheme has taken into account the necessity of aggregating several CFDP blocks as well as the time spent in retransmitting the aggregated CFDP blocks, that can get lost. In practice, the integration of LDGM codes within CFDP follows the implementation adopted in the CLDGM proposal. In particular, the number of encoding packets (k) has been fixed to 1000 in order to avoid the retransmission of too big CFDP aggregated blocks. The deferred issuance of NAK PDUs, on the other hand, conforms the CFDP specification. Code-rate and packet sizes have been varied, during the tests, within the same intervals as CLDGM. This proposal will be referred in the following as *CLDGM-deferred.* For the sake of the completeness, the two proposals have been compared with CFDP working in the following configurations:

- acknowledged mode, with deferred NAK. This scheme is indicated in the performance analysis as *CFDP-deferred*;
- unacknowledged mode, with extended operations. In this case, the *a priori knowledge* of the transmission medium availability help achieve reliable communications without necessity of either data retransmissions or employment of erasure codes. This solution is actually an "ideal solution" and has been taken into account in order to assess the effectiveness of the other solutions. This scheme is indicated in the following as *CFDP-extended.*

V. THE PERFORMANCE ANALYSIS

A. The testbed

The investigation has been focused on the transfer of data between two remote peers, implementing a full CCSDS stack. For the sake of the analysis, the transfer of 100 Mbytes has been considered. The tests are accomplished 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 has been imposed.

As far as the deep space transmission medium is concerned, the forward-link bandwidth is set to 1Mbit/s, while the reverse link has availability for 1Kbit/s. The propagation delays in the reverse and forward directions are equal and ranging from 0.250s to 200s for each experiment. The states within the DTMC model assume BER values equal to 10^{-8}, 10^{-6}, 10^{-4} and 10^{-2}, for states 0, 1, 2, and 3 respectively (Fig. 2). Moreover, the steady state probability π_2 and π_3 has been fixed together with the average permanence times τ_0 and τ_3 within states 0 and 3 in order to evaluate the effectiveness of the proposals. In particular four case studies have been identified, in dependence of τ_0 and τ_3 values, in order to show the different impact of bursty losses on the communication reliability:

- Scenario 1: τ_0=20s and τ_3=5s, Scenario 2: τ_0=60s and τ_3=5s
- Scenario 3: τ_0=5s and τ_3=20s, Scenario 4: τ_0=5s and τ_3=60s

B. The metrics

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, 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 Transfer Time evaluated as the time elapsed from the transmission of the first bit and the reception of the last one. Transfer Size is measured in [bit], Transfer Time in [s] and Bandwidth in [bit/s].

In facts:

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

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

C. The results

Scenario 1 (τ_0=20s, τ_3=5s)

In this configuration, since the average time spent in state 0 is much longer than state 3, the error gaps have a moderate length.

In general, it is possible to see that CFDP-extended, which represents an ideal protocol solution, outperforms the other proposals because of its capabilities of transmitting data when the channel is reliable. On the other hand, it is immediate to recognise that CLDGM assures better performance in terms of effective throughput if compared with CFDP-deferred and CLDGM-deferred, because the only use of erasure codes is sufficient to guarantee a minimal loss probability. As regards CLDGM-deferred (effective throughput ranging from 0.5 to 0.36)and CFDP-deferred (results vary from 0.51 to 0.285), they present similar performance results.

Scenario 2 (τ_0=60s, τ_3=5s)

In this study case, the effect of link errors on the overall performance is even more limited since the mean time spent in state 0 is much longer than in state 3; consequently, the mean length of error gaps is reduced with respect to scenario 1.

In facts, CFDP-extended guarantees the highest effective-throughput values, ranging from 0.988 to 0.673 as the propagation delay is varied from 0.25s to 200s. On the other hand, the other three solutions provide very similar results ranging from a maximum of 0.86 to a minimum of 0.35. In this case, it is worth remarkable that CLDGM (0.495-0.27) presents lower results (0.495-0.27) with respect to CFDP-deferred (0.86-0.31) and CLGM-deferred (0.5-0.3) because the very stringent constraint on the loss probability cannot be matched without increasing the code-rate and accordingly the transfer time.

Scenario 3 (τ_0=5s, τ_3=20s)

An increased length of error gaps is exhibited in this configuration because of the longer mean permanence time in state 3 (20s). As a consequence, less effective results are expected. For instance, CLDGM performs poorly. Alternatively CFDP-deferred and CLDG-deferred implement more performant recovery mechanisms and hence allow achieving effective throughput values ranging from a maximum of 0.691 down to a minimum of 0.38.

Scenario 4 (τ_0=5s, τ_3=60s)

In this configuration, the transmission channel presents a very high mean permanence time in state 3 (60s) and, accordingly, very long error gaps. In particular, it is possible to realize that, apart from CFDP-extended that behaves almost ideally, CFDP-deferred and CLDGM-deferred completely outperform CLDGM, since the long error runs cannot be only counteracted by the erasure code efficiency.

The main result emerging from this investigation is that for moderate propagation delays, the effective throughput offered, by CFDP-deferred is slightly better than CLDGM-deferred; instead as the propagation delays increases the trend inverts and CLDGM-deferred achieves the most satisfactory results. In facts, CFDP-deferred effective throughput ranges from a maximum of 0.86 down to a minimum of 0.251, while CLDGM-deferred from a maximum of 0.69 down to a minimum of 0.4.

D. Comparison

In order to assess more deeply the performance and the effectiveness provided by the investigated results, CFDP-deferred, CLDGM and CLDGM-deferred are compared with CFDP-extended, by introducing the Efficiency (%), expressed at the ratio between the effective throughput achieved by the above solutions (indicated as CFDP variants) and CFDP-extended one:

$$Efficiency(\%) = \frac{\text{Effective Throughput (CFDP variants)}}{\text{Effective Throughput (CFDP-extended)}} \cdot 100$$

From Fig. 3, it is possible to see that CLDGM-deferred offers the best efficiency results when strong impairments (scenarios 4 and 3) are introduced by the channel. Actually, the combined use of erasure codes and retransmissions allows achieving the highest performance results, corresponding to 72.30% and 62.87% for scenarios 4 and 3 respectively. On the other hand, when minor losses are exhibited, it is LDGM that offers the most satisfactory efficiency results, equal to 88.5% and 90.06% for scenarios 2 and 1 respectively.

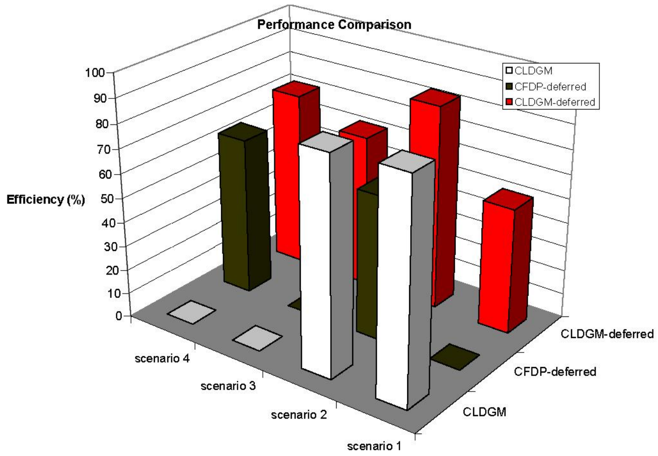

Fig. 3. Performance comparison (Efficiency %)

VI. CONCLUSIONS

This work has been devoted to the design of novel protocol solutions, based on the CCSDS File Delivery Protocol (CFDP), for achieving data communications over long-delay networks. Two proposals CLDGM and CLDGM-deferred have been introduced in this work and deeply investigated with respect to CFDP-deferred and CFDP-extended. The performance analysis, carried out for different scenario configurations, has identified CLDGM together with CLDGM-deferred as promising solutions. In particular, CLDGM, thanks to the powerful LDGM erasure codes, offers very satisfactory results in scenarios 1 and 2, where moderate losses are experienced. On the other hand, the adoption of CLDGM-deferred is beneficial when "almost reliable" data communications have to be carried out in very hazardous conditions, such as in scenarios 3 and 4.

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