High Performance Communication and Navigation Systems for Interplanetary Networks

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***Abstract*—The increasing development of technologies enabling efficient space exploration and data communications has recently fostered a number of scientific missions, aimed at supporting the research in the field of geology and astronomy. To this end, the design of an effective telecommunication infrastructure is the challenge offered to research scientists and space engineers. In particular, the definition of a network architecture suitable to support both communication and navigation services is of paramount importance for future space missions. In this view, this paper reviews protocols and architectures presently used in space missions and proposes improved transmission strategies, relying upon a packet-layer coding approach, which is expected to improve the overall performance.**

***Index Terms*—Consultative Committee for Space Data Systems (CCSDS), interplanetary networks, low-density parity check (LDPC), navigation systems, packet layer coding, protocol architectures.**

I. Introduction

The increasing number of space missions, aimed at exploring space and at supporting scientific research in different fields, such as physics, chemistry, and geology, has encouraged the design and the study of effective telecommunication infrastructures. Having a network architecture able to support different services such as navigation and data communication is the primary goal in order to guarantee, on the one hand, efficient management and position control of spacecrafts and satellites, and, on the other hand, reliable and effective data transfers. The first aspects are partially matched by appropriate navigation systems, responsible to track the position of mobile units and control their motion accordingly to predefined trajectories. Concerning data transfer reliability and effectiveness, traffic flows injected into deep space networks present different characteristics which depend on the source application. From this point of view, typical applications are: retrieval of surface images, transmission of measures, data transfer for periodical location and navigation, and alert notifications. Hence, given the large heterogeneity of handled data flows, different quality-of-service (QoS) and reliability issues have to be matched. This often implies a management differentiation for each kind of flow. Besides, the design of a network architecture, able to take all the aforementioned issues under consideration, has to cope with hazardous environmental conditions, in terms of blocked line-of-sight transmission and fading events, which severely degrade the overall system performance. In this view, the Consultative Committee for Space Data Systems (CCSDS) has produced a relevant number of recommendations, concerning architectures and protocols to enable efficient navigation and communication services in space environments. In particular, CCSDS has defined a protocol stack that serves as effective communication support and it is alternative to the transmission control protocol/Internet Protocol (TCP/IP) suite that can seriously suffer from performance degradation in such environments. In addition, also specific navigation and control strategies have been designed in order to provide proper means to manage and control the position of the communication nodes.

This paper mainly focuses on the protocol architectures enabling efficient navigation and communication services in deep space networks and takes the CCSDS protocol stack as reference technology. Furthermore, this paper gives some insights related to advanced transmission strategies that will prove to be helpful to support and guarantee high performance communication in interplanetary networks.

The remainder of this paper is structured as follows. Section II presents the state of the art of proposals and solutions suited for data communication in space networks. Section III focuses on the CCSDS protocol stack and puts emphasis on both communication protocols and navigation solutions. Section IV introduces the reference deep space scenario. Section V addresses the protocol architecture used in this paper and presents the advanced protocol solutions, whose performance is evaluated in Section VI. Finally, Section VII draws some remarks and conclusions on the effectiveness of the proposals investigated in this paper and puts the basis for future extensions of this paper.

II. 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 over the years by the CCSDS in the study and design of protocols to transport data over interplanetary environments [1] efficiently. From this point of view,

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a number of CCSDS working groups have carried on tasks and proposed architectures and protocols suitable to transfer data in the deep space. It is worth mentioning the Cislunar and the CCSDS file delivery protocol (CFDP) working groups, whose activity is aimed at designing protocol architectures for Earth–Moon communications and beyond, and at studying file transfer protocols, respectively [6].

Also, the Internet engineering task force (IETF) and especially the Internet research task force (IRTF) provide big efforts to propose 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 interplanetary networks has also been highlighted in a special issue of Computer Networks on "Interplanetary Networks" [9], which describes recent space missions and focuses on interoperability issues between TCP/IP suite and space protocol stacks. The limitations of using the TCP protocol over deep space networks are one of the main problems. It is evidenced in [9] by proposing the implementation of automatic retransmission request (ARQ) schemes below additive increase, multiplicative decrease (AIMD)-oriented transport protocols [10]. In this direction, 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 can recognize link disruptions (i.e., blackout events) and tune transmission parameters efficiently.

Designing novel protocols that can provide satisfactory performance results has captured the interest of channel coding engineers too. Actually, in alternative to highly efficient ARQ schemes, the implementation of erasure coding schemes either at the transport or at the application layer can improve the reliability of communications and the overall performance. From this point of view, a solid framework is represented by the transport layer coding scheme [4] and, in general, by the asynchronous layered coding (ALC) [14]/layered coding transport (LCT) [15] architecture. It is defined to interwork with the file delivery over unidirectional transport (FLUTE) protocol [16] and it is conceived within the reliable multicast transport IETF working group. The basic idea behind all these approaches is to employ erasure coding schemes, which can limit packet losses in correspondence of strong link degradations directly at higher layers. Alternative coding algorithms include low density parity check (LDPC) [17], Reed–Solomon [18], and the recent digital fountain scheme [19] implemented through Luby transform (LT) [20], Tornado [21], and Raptor codes [22].

In addition to communication reliability, the interest of deep space scientists is also moving towards QoS issues, which may include service differentiation through the notion of traffic class, resource reservation and allocation mechanisms, scheduling algorithms, and routing policies. At present, the limited number of nodes and hops in interplanetary networks 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 as well as resource reservation mechanisms will be necessary to meet specific QoS constraints. Some proposals are 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 likely that the IP signaling flow, carrying QoS information, will suffer from link disruption. A similar observation may be done for any flow that carries control information.

Attention should 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 by NASA. They are aimed at providing communication systems for satellite tracking and data acquisition. Reference [24] shows some experiments conducted during 2002 and 2003 to investigate the effectiveness of geographic information networks for planetary exploration.

A special note must be dedicated to the CFDP. It is 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 this paper. The use of ARQ mechanisms along with the adoption of the transport layer coding approach are the focus of this work.

III. CCSDS Protocol Architecture

A. Protocol Stack

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

- *Physical Layer:* CCSDS recommendations on RF and modulation systems provide viable and effective indications on the most suitable transmission schemes to be adopted in space missions, where either long haul-links (long range and bidirectional) established to allow communication between spacecrafts and satellites very far from each other or proximity links (short range and bidirectional), generally used to communicate among landers, rovers, orbiting constellations, and orbiting relays, are employed.
- *Datalink Layer:* CCSDS has developed four protocols: telemetry (TM) space data link protocol [25]; telecommand (TC) space data link protocol [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 the protocol data units (PDUs) that come from the network layer and to transmit them to the physical layer as transfer frames of fixed or variable length. In more detail, TM and TC space data link protocols must send, respectively, TM information from a spacecraft to a ground station and control commands from a ground station to a spacecraft. AOS space data

link protocol has been designed to allow two-way data transmissions on both forward and reverse directions as in the case of real-time communications. Proximity-1 link protocol is designed for proximity links. Synchronization and channel coding functions are performed along with encapsulation and framing operations. 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], [30], [31].

- *Network Layer:* Two protocols have been proposed: the Space Packet Protocol and the Space Communication Protocol Specification-Network Protocol (SCPS-NP). Both of them take care of addressing and routing operations, by means of path, end system address, and other specific identifiers [32], [33].
- *Transport Layer:* CCSDS has developed the Space Communications Protocol Specification-Transport Protocol (SCPS-TP) [34] to provide end-to-end reliable communication. SCPS-TP uses congestion avoidance and flow control mechanisms inherited from TCP and improved for deep space environments. Anyway, even though recommendations for the transport layer have been produced within CCSDS, the use of transport protocols is not mandatory in the CCSDS protocol stacks. In practice, most applications, such as CCSDS file delivery protocol (CFDP), do not require to run over a transport protocol, but they can work directly over the network layer. This is the choice followed in this paper. SCPS-TP is considered operating over a lower layer protocol such as the SCPS-security protocol (SCPS-SP), the SCPS-network protocol (SCPS-NP), or the IP [34]. Even if the interoperability with the IP 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 as the network protocol working below SCPS-TP.
- *Application Layer:* CFDP is designed to get reliable file transfers. It follows an FTP-like paradigm. Its implementation spans over application and transport layers. Being CFDP is an essential part of this paper, its detailed description is postponed to the next session. In addition to file transfer, also the event-driven asynchronous message exchange should be provided in future deep space communications. They will be used to establish a dialogue among spacecrafts and remote stations. In this perspective, CCSDS within the space internetworking service area (SIS) has developed the asynchronous message service (AMS) [35]. It is thought to provide a messaging layer over which the protocol messages of the mission operation services [36] can be carried. Consequently, AMS can be effective for engineering (housekeeping) data streaming, for real-time commands and for continuous collaborative operations among robotic crafts.

Recently, also issues about the interoperability with TCP/IP suite have been considered. Encapsulation procedures have been designed to include CFDP in TCP segments and IP datagrams in CCSDS space link protocols frames [33], [37]. 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 robust header compression (ROHC) recommendation [38], applied to UDP-IP datagrams, might be used to reduce the overhead introduced by the space packet protocol from 6 B to about 2–4 B. Actually, these solutions are still experimental. They are not yet part of the CCSDS recommendations. Being this paper completely based on a homogenous CCSDS protocol stack, the possibility to address spacecrafts through IPv4/IPv6 mechanisms, even though it is attractive and may represent an interesting solution for future space communications, is not considered here.

B. CCSDS File Delivery Protocol

The CFDP transmitting entity encapsulates data into PDUs identified as CFDP blocks in the following. The payload of the CFDP blocks can carry up to 65 536 B, while the header length is set to 20 B. The actions taken by the CFDP entity to guarantee communication reliability depend upon the used CFDP operating mode. Both acknowledged and unacknowledged modes can be applied. The latter contains no specific options to assure communication reliability. On the other hand, when CFDP operates in acknowledged mode, communication reliability is guaranteed through negative acknowledgments (NAK), issued by the receiving CFDP entity. In more detail, once the loss of a data block is detected, the recovery mechanism can be ruled by four alternative algorithms: immediate, prompted, asynchronous, and deferred. In particular when the deferred option is set, the receiver checks if CFDP blocks are missing only at the end of the data communication. When missing blocks are detected, the recovery phase is invoked at the receiver side by sending NAK blocks to the sender, which will retransmit the missing blocks.

Finally, a particular note must be dedicated to CFDP suspending and resuming features. If the protocol entity is configured to operate in "extended operations," it is able to suspend the transmission on the basis of notifications issued by lower layer protocols, which signal the unavailability of the transmission medium. In this case, data blocks are temporarily stored in a local CFDP buffer and the transmission is resumed again once positive notifications about channel availability are issued by lower layers.

C. Navigation Communication Framework

Navigation aspects deserve a particular attention in space missions as hazardous networking conditions as well as large propagation delays may affect, on the one hand, the measure of parameters involved in the spacecraft orbit determination, and, on the other hand, the transfer of these measures to the tracking stations, responsible for guidance and monitoring operations. In order to provide a solid framework to develop navigation and monitoring systems, CCSDS has created a specific research area, called Mission Operations & Information Management (MOIMS). It is aimed at devising procedures for data navigation management and interfaces for spacecraft monitoring and control, which should allow a seamless guidance data transfer between space stations and tracking centers. In practice, the

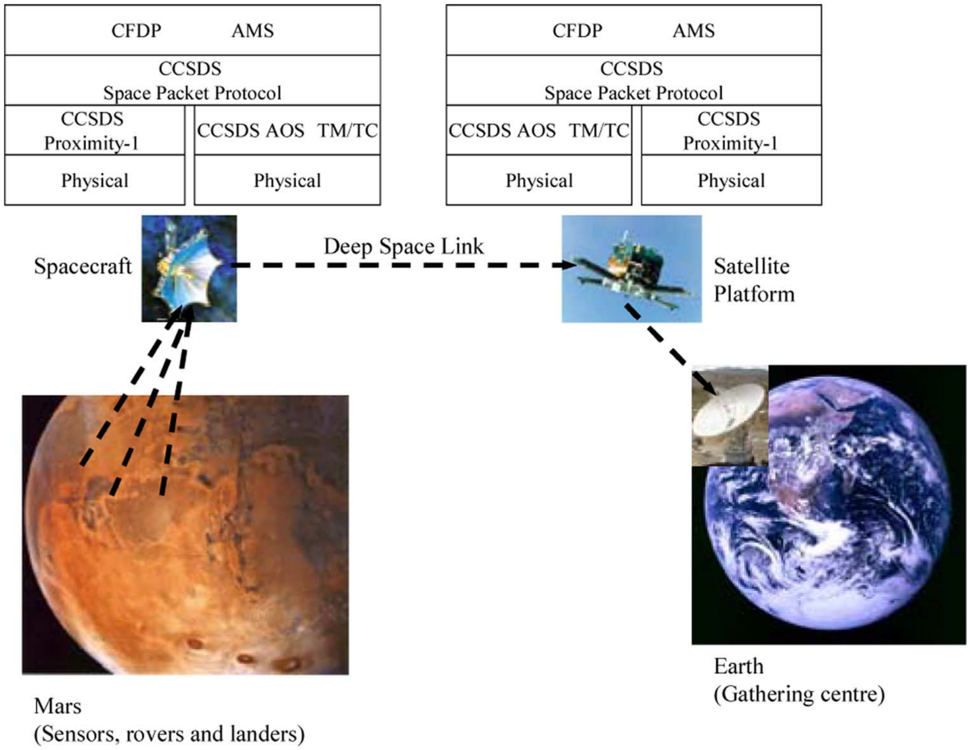

Fig. 1. Reference scenario.

navigation process estimates the spacecraft trajectory and the related physical parameters given a set of tracking data. Afterwards, the guidance phase will compute the optimal maneuvers and the commands needed to address the spacecraft to the desired target. From this point of view, two main aspects are covered by CCSDS recommendations: the definition of the navigation data and of a service oriented architecture suited to interface navigation and communication modules. As far as navigation data are concerned, [39] defines: orbit data messages (ODM, including orbit parameter and ephemeris) [40], attitude data messages (ADM) [41], and tracking data messages (TDM) [42], which are encoded into XML "Schemas" [43] processed by tracking centers. On the other hand, [44] defines a framework for mission operation services. They rely upon the use of the asynchronous messaging service, which acts as interface between application source and communication protocols. In particular, navigation and guidance data are exchanged between spacecrafts and control stations by means of the CCSDS telemetry and the CCSDS telecommand protocols, respectively.

IV. Deep Space Environment

A. Reference Scenario

Two remote stations, one located on the Earth and the other on a remote planet (e.g., Mars or the Moon), communicate by means of the following:

1) two satellite links that connect two satellite platforms or, alternatively, spacecrafts, orbiting around the Earth and the remote planet;
2) a deep space link established between the two satellite platforms or spacecrafts.

All the network nodes implement a full CCSDS protocol stack, and, in particular, the CCSDS file delivery protocol (CFDP) and the AMS at the upper layers. The lower layers implement the CCSDS Proximity-1 Datalink Protocol on the proximity links. The CSCDS TM/TC datalink layer protocol and the CCSDS AOS Protocol are used to transfer navigation data and files, respectively, on the long-haul link.

The whole scenario is depicted in Fig. 1, by using a satellite platform and a spacecraft.

B. Deep Space Link

The strong impairments introduced by 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 for space environments. In this view, the adaptation of common models employed to characterize wireless transmission channels seems an appropriate solution. In particular, the use of a first-order discrete-time Markov chains (DTMC) with four states has been assumed here to represent the channel behavior.

The transition between two arbitrary consecutive states, i and j, is ruled by the transition probability matrix $P = \{p_{i,j}\}$. 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 "represents" a different channel reliability by means of the bit error ratio (BER), evaluated at the receiver side after the channel decoding procedures. In other words, each i^{th} state is characterized by a specific BER, called BER_i. The following inequality holds for consecutive states: $\text{BER}_i < \text{BER}_j$, with $i, j \in \{0, 1, 2, 3\}$, and $i < j$. A relevant parameter that influences the link behavior is the mean

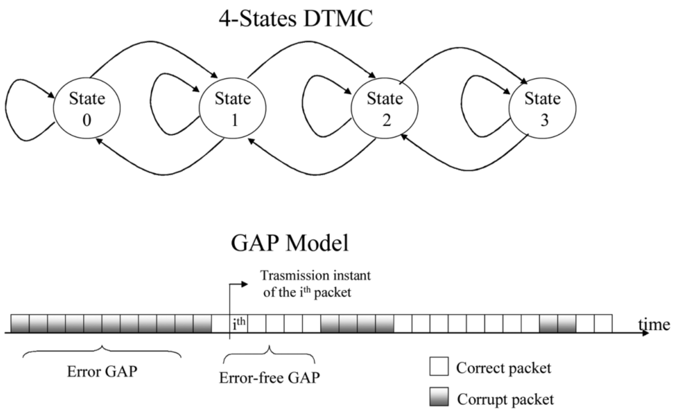

Fig. 2. Four-states/GAP channel model.

permanence time within the i^{th} state, indicated as τ_i in the following. Finally, 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. The use of the GAP error length model is promising. In practice, error-free and error gaps are defined as occurrences of consecutive successful and unsuccessful received packets, respectively. The channel model is graphically shown in Fig. 2.

V. Reference Protocol Architecture

A. Architecture Layout

Previous sections have pointed out how AMS and CFDP protocols may be effective in handling data through space links, by providing the proper protocol interfaces to efficiently manage file transfer and navigation data, respectively. In addition, many networking and communication problems arise in deep space environment because of the hazardous conditions in which a message exchange has to be performed. In order to alleviate the impact of the environment peculiarities on the overall system performance, the adoption of the transport layer coding approach seems to be promising. Basically, the use of erasure codes is expected to be effective in making data communication more robust against link disruptions, by operating efficient encoding techniques on information packets. Hereafter, Transport Layer Coding and Packet Layer Coding terms will be used interchangeably, as they refer to packet erasure coding strategies implemented at the transport layer.

As a result, the overall architecture layout can be conceived as composed of three main parts: High layer, Medium Layer, and Low Layer, which implement the functionalities described at the beginning of Section III. The whole protocol architecture taken as reference in this paper is shown in Fig. 3.

In more detail, we show the following layers.

- *High Layer—Consumer and Provider Applications:* In this layer, the services to be supported by the interplanetary architecture are implemented mission operation services, which include message exchange, file transfer, and mail. The different services are then mapped onto different space internetworking services, in particular CFDP and AMS. The CFDP entity will take care of file transfer sessions established among remote stations and, where necessary, of performing forwarding operations in case of relay nodes, such as spacecrafts and other intermediate nodes. AMS, which supports asynchronous message exchange, allows sending navigation data as well as control and monitoring notifications.

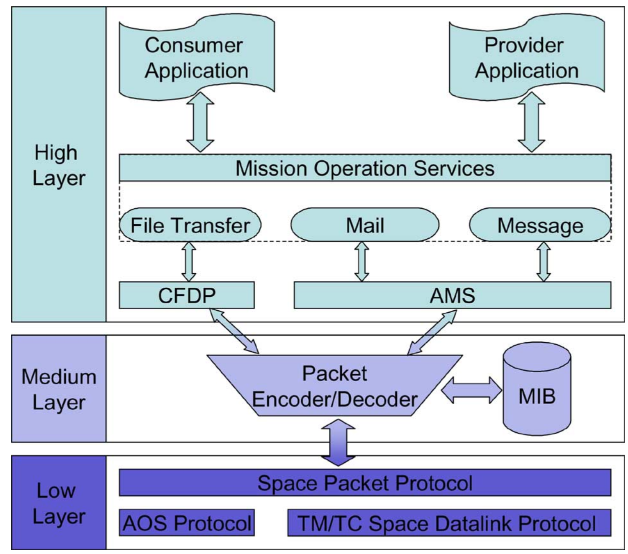

Fig. 3. Reference protocol architecture.

- *Medium Layer—Packet Coding Layer:* This layer includes the protocol entities necessary to perform the encoding/decoding operations and the related management procedures, required to select the most appropriate coding strategies in dependence on traffic characteristics and QoS requirements (e.g., reliability and delivery time). These procedures are handled by a specific management information base (MIB) entity. An optimized class of LDPC codes, called LDGM, is used here. The packet layer coding approach is applied in this paper by aggregating the PDUs coming from AMS and CFDP protocol entities into a unique SDU, which handles at least 1 MB in order to match the effectiveness constraints imposed by the LDGM code specifics. Afterwards, each SDU is then split into smaller "packets" subject to the LDGM encoding procedure, which generates a number of information and redundancy packets, conformant to the code rate set by the layer management module. The general scheme of the packet coding core is depicted in Fig. 4.
- *Lower Layer—Communication Layer:* It includes the transmission protocols operating at network, datalink, and physical layer responsible for transporting the data service over a deep space link. As outlined in Section IV, the reference network layer used here is the CCSDS space packet protocol, while the choice of datalink/physical protocol relies upon the transported specific service. The file transfer data flow will be directed onto the AOS protocol interface, while the navigation flow will be forwarded

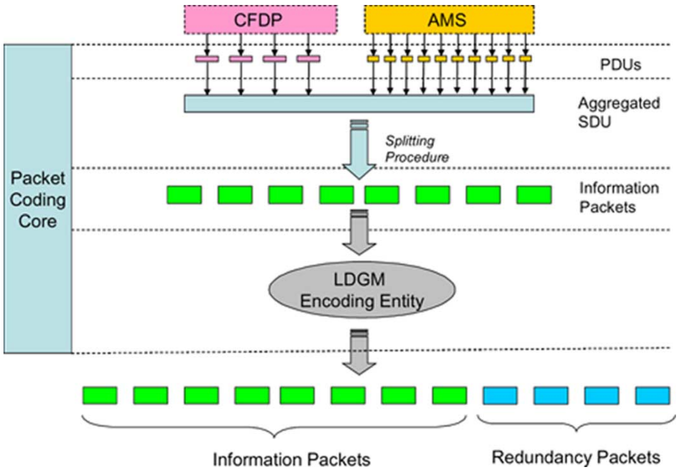

Fig. 4. Packet coding core.

into the TC/TM protocol interfaces depending on whether navigation or guidance data are being transferred.

B. Advanced Transmission Protocols

CFDP, working in both acknowledged and unacknowledged modes, is taken as reference for file transfer services in this paper, while the exchange of navigation data is dealt with by the AMS protocol.

The introduction of a coding layer (medium layer) that implements effective erasure codes aimed at guaranteeing reliable data communication, allows defining two protocol proposals, namely "CLDGM" and "CLDGM-deferred," whose description follows.

CLDGM concerns the integration of erasure coding schemes both into CFDP protocol when it runs in unacknowledged mode, and the AMS protocol, by applying the transport layer coding approach as shown in [2] and [6]. In practice, LDGM codes, derived from the LDPC codes, are adopted here for their capacity of protecting data communication against bursty data losses.

The integrated scheme works as follows. Different data blocks coming from CFDP and AMS entities are aggregated together, split into k information "packets," and encoded into n packets by means of the LDGM generator matrix. It is straightforward that 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 paper, "k" is set to 1000, code rate values ranging from 0.125 up to 0.875 are considered block and packet sizes varying from 1024 to 65 536 B and from 128 to 1024 B, respectively, are taken into account in order to evaluate the impact of link errors on the overall performance. Hereafter, this approach will be referred to as CLDGM (which stands for CCSDS with LDGM codes).

CLDGM-deferred is the second approach, which combines the use of NAK PDUs with LDGM codes in order to allow data retransmission when the LDGM code alone is not sufficient to get a satisfying reliability. The integration of LDGM codes within CFDP and AMS follows the implementation adopted in the CLDGM proposal. Even in this case, the number of encoding packets (k) is set to 1000. The deferred issuance of NAK PDUs conforms the CFDP specification. Code rate and packet sizes were varied, during the tests, within the same intervals used for CLDGM. This proposal will be referred to in the following as CLDGM-deferred.

For the sake of completeness, the two proposals have been compared with CFDP working under 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 helps achieve reliable communications without the necessity of either data retransmissions or erasure codes. The transmission of new data blocks is scheduled once the channel is in state 0. This solution is actually an "ideal solution" and is taken into account in order to assess the effectiveness of the other solutions. This scheme is indicated in the following as CFDP-extended.

In the previously reported configuration (CFDP-deferred and CFDP-extended), the navigation data are assumed collected in batches and sent as files to the tracking centres, by means only of the CFDP protocol.

Finally, for the sake of the clarity, only the configurations in terms of code rate, CFDP/AMS block and packet size, providing the highest performance results have been considered, as reported in Section VI.

VI. Performance Analysis

A. Testbed

The investigation is focused on the transfer of data between two remote peers, which implement a full CCSDS stack. A transfer of 100 MB has been considered. 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 is imposed.

As far as the deep space transmission medium is concerned, the forward-link bandwidth is set to 1 Mb/s, and the reverse link to 1 kb/s. The propagation delays in the reverse and forward directions are equal and range from 0.250 to 200 s 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. The steady-state probability π_2 and π_3 has been fixed along 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, two case studies have been identified (A and B), in dependence on τ_0 and τ_3 values, in order to show the different impact of bursty losses on the communication reliability.

B. 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 along with the real use of the channel, indicated as effective throughput. The latter is measured as the product (divided for bandwidth) of $(1-P_{\text{loss}})$ and the ratio of the transfer size and the

TABLE I
CLASSES OF SERVICE AND RELATED PERFORMANCE CONSTRAINTS

Class of Service	Delivery Time	Loss Probability
A: spacecraft location data and classes of telemetry data updates.	$< T_1 = 2\ T_{min}$	$< P_{loss\_2}$
B: critical instrument status notification or urgent remote control commands.	$< T_1 = 2\ T_{min}$	$< P_{loss\_3}$
C: measurements, planet's surface images.	$< T_2 = 4\ T_{min}$	$< P_{loss\_3}$
D: periodic notifications bulks of data sent on a best-effort basis.	$< T_2 = 4\ T_{min}$	$< P_{loss\_2}$
E: other file transfers.	any	$< P_{loss\_1}$

transfer time evaluated as the time elapsed from the transmission of the first bit and the reception of the last one. In short

$$P_{\text{loss}} = 1 - \left(\frac{\text{Received Blocks}}{\text{Transmitted Blocks}}\right)$$

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

In order to characterize the different performance constraints of the traffic transported through the CFDP blocks, five classes of service are introduced: A, B, C, D, and E. They have different constraints in terms of the maximum P_{loss} and transfer time acceptable. Actually, three thresholds for P_{loss}, namely $P_{\text{loss\_1}}$, $P_{\text{loss\_2}}$, $P_{\text{loss\_3}}$, and equal to 0.025, 0.05, and 0.15, respectively, are chosen. As regards the constraints on the transfer time, taking as reference the minimum time, $T_{\min}$, required to accomplish the whole transfer of data (equal to the ratio between the transfer size and the bandwidth, plus twice the propagation delay), two thresholds T_1 and T_2 are set. The whole classification is shown in Table I.

C. Results

1) Case Study A ($\tau_0 = 20$ s, $\tau_3 = 5$ s): Since the average time spent in state 0 is much longer than time spent in state 3, the error gaps have a moderate length. Consequently, the loss probability requirement has no great impact on all the tests. In particular, the values of loss probability obtained during the simulation campaigns resulted lower or equal to 0.05 for classes A, B, C, and D, so matching the constraints on the maximum tolerable information loss (i.e., $0.05 \leq P_{\text{loss\_2}} < P_{\text{loss\_3}}$), as evident from Table I. In this light, the investigation (reported in Fig. 5) is limited, without loss of generality, to the performance offered by classes A, D, and E; actually, class B performance is overlapped to class A one, being $0.05 \leq P_{\text{loss\_2}} < P_{\text{loss\_3}}$ and class D results are the same as class C ones for the same motivation.

It is possible to see that CFDP-extended, which represents an ideal protocol solution, outperforms the other proposals because of the *a priori* knowledge of the channel state, which allows exploiting the available bandwidth. In more detail, CFDP-extended achieves effective throughput values ranging from 0.999 down to 0.666, as the propagation delay varies from 0.25 to 200 s, respectively. Finally, it is worth noticing that the performance offered by this solution is independent of the traffic class to which data transported over the deep space belong. This behavior is due to the CFDP-extended

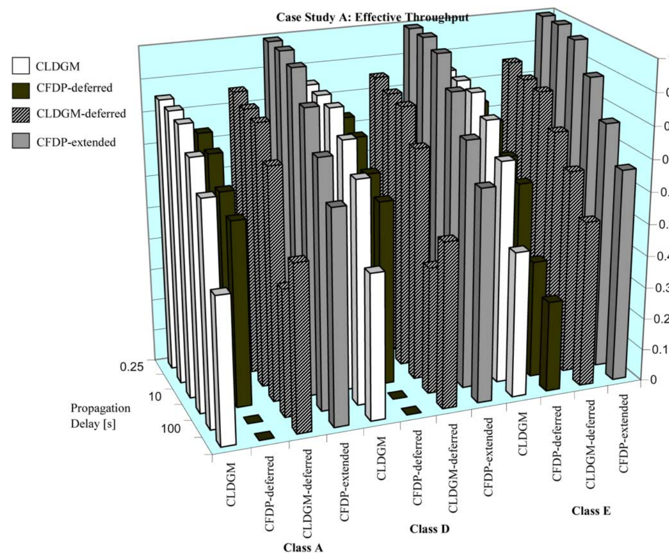

Fig. 5. Case study A: the overall performance.

implementation that, relying upon the perfect knowledge of the channel state, schedules data transmissions only in case of error-free gaps, and avoids long retransmission phases that would severely impair the overall performance.

On the other hand, the performance offered by the other solutions (i.e., CLDGM, CLDGM-deferred, and CFDP-deferred) is ruled by the specific service class considered, as argued in the following. In more detail, as far as class A is concerned, CLDGM achieves the best performance results independently of the propagation delays (except for 200 s). The effective throughput measured for CLDGM ranges from 0.85 to 0.45, when the propagation delays vary from 0.25 to 200 s. In particular, the effective throughput is 0.78 for a propagation delay of 50 s.

The performance of CLDGM-deferred is similar for delays ranging from 0.25 to 50 s, where the effective throughput values range from 0.85 down to 0.72. CLDGM-deferred throughput is much lower than CLDGM one for a propagation delay of 100 s, but it raises up for 200 s, where it is higher than CLDGM one. The full comprehension of the CLDGM-deferred behaviour as well as of the comparison with CLDGM is not so simple. On the one hand, the higher CLDGM throughput for propagation delay ranging from 0.25 to 100 s is due to the number of "useless" retransmissions, i.e., to the retransmission provided by CLDGM-deferred also when the loss probability is under threshold (i.e., below 0.05). On the other hand, throughput values heavily depend also on the combined effect of code rate and packet size, which is variable because the best results obtained are selected and shown here. The mentioned combination is particularly meaningful for the propagation delay of 200 s and is the cause of the trend inversion between the results got for propagation delays of 100 and 200 s.

CFDP-deferred shows limited performance, and, when the propagation delay is 100 and 200 s, it cannot match the performance requirements, since very large delays without any protection coding give rise to long and repeated retransmission operations, thus degrading the overall performance.

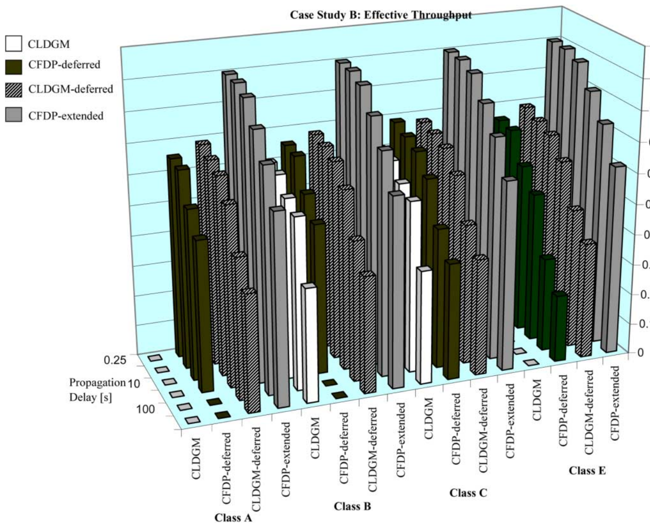

Fig. 6. Case Study B: the overall performance.

As far as class D is concerned, CLDGM provides effective throughput results ranging from 0.855 to 0.69 as delay varies from 0.25 to 100 s. As the delay raises up to 200 s, CLDGM-deferred gives more satisfactory results for the same reasons explained before. CLDGM-deferred effective throughput is 0.52 for 200 s, while CLDGM does not come over 0.45. Finally, concerning class E, given the total relaxation of the delay constraint combined with the severe loss constraint and with the limited length of the error gaps, CLDGM and CLDGM-deferred provide very similar results for all propagation delays, including 200 s. The effective throughput ranges from 0.85 to 0.45, and from 0.85 to 0.52, in the two cases, respectively. CFDP-deferred can match the performance requirements for all propagation delays, in this case, because there are no constraints about the delivery time and the retransmission recovery phase can take place with no time limitation.

2) Case Study B ($\tau_0 = 5$ s, $\tau_3 = 20$ s): The longer permanence in state 3, if compared to state 0, implies an increased length of error gaps. Less effective results are expected. For the sake of simplicity, the investigation does not take class D into account, since it does not add information with respect to class C evaluation. In practice, CFDP-extended exhibits the most satisfactory results, showing effective throughput ranging from 0.90 to 0.602. The other three solutions show performance results strictly dependent on the service classes, as shown in Fig. 6. For class A, CLDGM-deferred achieves the best average performance results and never fails to match performance constraints. The effective throughput varies from 0.69 to 0.38. The only application of erasure codes is not sufficient: CLDGM never matches performance constraints. CFDP-deferred is efficient for short propagation delays but fails to match the requested reliability for delay of 100 and 200 s.

Concerning class B, CLDGM-deferred again provides the best results (0.68–0.59) as delay ranges from 0.25 to 50 s. Once the delay increases, CLDGM performs better and achieves effective throughput of 0.56 and 0.37 for 100 and 200 s, respectively. Class C results show that CLDGM-deferred and CFDP-deferred are very efficient, achieving performance ranging from 0.69 to 0.38 in both cases. Also, CLDGM is quite efficient: its performance is below CLDGM-deferred and CFDP-deferred one for propagation delay from 0.25 to 50 s, but it is above for delay of 100 s. CLDGM results are the same as the other two schemes for delay of 200 s. The strict constraint on loss probability of class E can be efficiently matched by CLDGM-deferred, which achieves performance from 0.69 to 0.38. CFDP-deferred can always match the performance constraint but its performance is reduced with respect to CLDGM-deferred, because it does not implement protection codes and must use multiple retransmissions. CLDGM never matches the hard loss probability constraint: the mere protection code is not sufficient to guarantee the desired requirement.

Comparing the effective throughput values achieved in Case Study A with those collected in Case Study B (see Figs. 5 and 6), it is straightforward to see that, except for CFDP-extended that performs ideally independently of the channel state and of the service class, the other protocol solutions attain effective throughput results that are a function of the link reliability, which, in this paper, is considered through the GAP model presented in Section IV-B. In practice, it is immediate to see that in the first reported scenario (Case Study A), the only use of erasure codes (solution CLDGM) is sufficient to ensure satisfactory results owing to the powerful corrective capabilities of the error control codes therein implemented. On the contrary, the implementation of only erasure codes is not sufficient in Case Study B, where longer occurrences of error gaps are experienced. In this case, the combined use of ARQ and coding strategies is more efficient, as it is able to tackle the information loss effectively.

VII. Conclusion

This paper is focused on the design of efficient protocol architectures for handling navigation and data communications in deep space environments. To this end, the CCSDS protocol architecture is taken as reference, by pointing out advantages offered by CFDP and AMS protocols, for their ability to support file transfer and navigation services effectively. In addition, in order to devise a novel protocol architecture able to counteract performance degradations due to the hazardous environments peculiarities, the use of erasures codes, as implemented within a dedicated packet/transport layer coding is considered. This layer design choice has driven to conceive two novel protocol solutions, CLDGM and CLDGM-deferred that have proven to be effective to ensure reliable communications in long delays and lossy networks. The solutions is investigated also with respect to CFDP-deferred and CFDP-extended, in order to clearly state the advantages offered by the new solutions if compared to the basic features available from the CCSDS protocol stack.

In particular, the performance analysis, carried out for two different case studies, identifies CLDGM together with CLDGM-deferred as promising solutions, able to match the specific constraints of five classes of service. In particular, CLDGM, owing to the powerful LDGM erasure codes, offers very satisfactory results in case study A, where moderate losses are experienced. CLDGM-deferred, in this case, is less efficient even if its behavior is very satisfying. On the other hand, the adoption of CLDGM-deferred is immediate when "almost reliable" data communications have to be carried out in very hazardous conditions, such as in case study B.

Future extensions of this paper should consider proper mechanisms to address congestion events, which are likely to occur in future space missions for the complex network topologies envisaged in NASA programs, and evaluate the advantages that could be offered by the delay tolerant network architecture in such environments.

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