The CCSDS Next Generation Space Data Link Protocol (NGSLP)

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The CCSDS space link protocols i.e., Telemetry (TM)[1], Telecommand (TC)[2], Advanced Orbiting Systems (AOS)[3] were developed in the early growth period of the space program. They were designed to meet the needs of the early missions, be compatible with the available technology and focused on the specific link environments. Digital technology was in its infancy and spacecraft power and mass issues enforced severe constraints on flight implementations. Therefore the Telecommand protocol was designed around a simple Bose, Hocquenghem, Chaudhuri (BCH)[4] code that provided little coding gain and limited error detection but was relatively simple to decode on board. The infusion of the concatenated Convolutional and Reed-Solomon codes[5] for telemetry was a major milestone and transformed telemetry applications by providing them the ability to more efficiently utilize the telemetry link and its ability to deliver user data. The ability to significantly lower the error rates on the telemetry links enabled the use of packet telemetry and data compression. The infusion of the high performance codes for telemetry was enabled by the advent of digital processing, but it was limited to earth based systems supporting telemetry.

The latest CCSDS space link protocol, Proximity-1[6] was developed in early 2000 to meet the needs of short-range, bi-directional, fixed or mobile radio links characterized by short time delays, moderate but not weak signals, and short independent sessions. Proximity-1 has been successfully deployed on both NASA and ESA missions at Mars and is planned to be utilized by all Mars missions in development.

A new age has arisen, one that now provides the means to perform advanced digital processing in spacecraft systems enabling the use of improved transponders, digital correlators, and high performance forward error correcting codes for all communications links. Flight transponders utilizing digital technology have emerged and can efficiently provide the means to make the next leap in performance for space link communications. Field Programmable Gate Arrays (FPGAs) provide the capability to incorporate high performance forward error correcting codes implemented within software transponders providing improved performance in data transfer, ranging, link security, and time correlation. Given these synergistic technological breakthroughs, the time has come to take advantage of them in applying them to both on going (e.g., command, telemetry) and emerging (e.g., space link security, optical communication) space link applications. However one of the constraining factors within the Data Link Layer in realizing these performance gains is the lack of a generic transfer frame format and common supporting services amongst the existing CCSDS link layer protocols. Currently each of the four CCSDS link layer protocols (TM, TC, AOS, and Proximity-1) have unique formats and services which prohibits their reuse across the totality of all space link applications of CCSDS member space agencies. For example, Mars missions. These missions implement their proximity data link layer using the Proximity-1 frame format and the services it supports but is still required to support the direct from Earth (TC) protocols and the Direct To Earth (AOS/TM) protocols.

The prime purpose of this paper, is to describe a new general purpose CCSDS Data Link layer protocol, the NGSLP that will provide the required services along with a common transfer frame format for all the CCSDS space links (ground to/from space and space to space links) targeted for emerging missions after a CCSDS agency-wide coordinated date. This paper will also describe related options that can be included for the Coding and Synchronization sub-layer of the Data Link layer[4,5] to extend the capacities of the link and additionally provide an independence of the transfer frame sub-layer from the coding sublayer. This feature will provide missions the option of running either the currently performed synchronous coding and transfer frame data link or an asynchronous coding/frame data link, in which the transfer frame length is independent of the block size of the code. The benefits from the elimination of this constraint (frame synchronized to the code block) will simplify the interface between the transponder and the data handling

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equipment and reduce implementation costs and complexities. The benefits include: inclusion of encoders/decoders into transmitters and receivers without regard to data link protocols, providing the ability to insert latency sensitive messages into the link to support launch, landing/docking, telerobotics. and Variable Coded Modulation (VCM)[7]. In addition the ability to transfer different sized frames can provide a backup for delivering stored anomaly engineering data simultaneously with real time data, or relaying of frames from various sources onto a trunk line for delivery to Earth.

I. Introduction

The prime purpose of this paper is to introduce the initial release of the new general-purpose CCSDS Data Link layer protocol i.e., the Next Generation Space Link layer Protocol (NGSLP). Its goal is to provide the required CCSDS member agency mission services for all the CCSDS space links (ground to/from space and space to space links). The Protocol will be targeted for the emerging missions, both human and robotic, moreover it will need to support the escalating data rates, identify the ever growing number of new space vehicles, support the needs to deliver low latency data by, intentionally decoupling the transfer frame from the code blocks, and providing the capability to insert real-time messages. The protocol builds upon the Virtual Channel concept. It provides the means to share a physical channel with separately definable and routable data streams. It does this by incorporating multiple individually addressable Virtual Sub Channel (VCS) within a single Virtual Channel. In so doing it provides the means to utilize the VC's Security Association[8] and its sequence control mechanisms. NGSLP utilizes the proven features of the existing CCSDS protocols and adds options that enable users to configure their communication links to meet their emerging needs. In addition this paper references channel coding configurations currently under investigation by CCSDS that offer significant performance gains for communications links that terminate in space vehicles.

II. Key Technical Features and Benefits

The four existing CCSDS link layer protocols each have limitations and changes should be made to handle even higher data rates, increasing space vehicle populations, and to remove the key constraint of forced alignment between the transfer frame and the code block. This constraint has already been removed for the proximity environments. Once this constraint is removed for both DFE and DTE links, it will be no longer be necessary to maintain distinct link layer formats for forward and return links.

A. One CCSDS Link Protocol for all Space Data Links

Currently each distinct space link (DFE, DTE, and proximity links) has its own unique protocols, largely due to the historical evolution of the protocols and the incremental nature of emerging mission needs. For example, when it was apparent that a new type of space vehicle was to be developed e.g., the International Space Station (ISS), the CCSDS developed a new protocol (AOS) to handle higher data rates and provide more Virtual Channels. When relay orbiters were being planned for Mars exploration a new, adaptive data rate protocol Proximity-1 was developed to address the needs of the in-situ environment. Differences between the forward and return links were mandated in part by typical asymmetrical data rates, and also by the simple on-board processors in the landed entities at the time. However some missions, particularly those for human space flight, require higher bi-directional data rates. Furthermore the use of optical communications will drive these rates even higher. Powerful on-board processors, FPGAs, and large memories enable much more capable protocols than were possible decades ago.

While there are significant costs in developing and deploying this new unified link protocol we anticipate future agency savings in terms of less end-to-end link testing as well as reduced implementation and operations costs due to the consolidation of four link layer protocols into one. As the performance of the current implementations become inadequate or the technology becomes obsolete it would be cost effective to add the NGSLP protocol for those high performance needs and the eventual decommissioning of the current protocols.

B. Increased Variable Length Frame Size, Frame Sequence Counter for Higher Rate Links

There are numerous missions in the planning phase that require significantly higher rates, including Earth Science missions planning to use Ka, Ku band, more advanced coding schemes and optical downlinks. It is anticipated that Observatory Class missions in this decade will exceed the 400 Mbps downlinks supporting the LandSat mission. Plans are already in the planning for 600 Mbps links with Optical Links easily exceeding 1000 Mbps. Part of the problem with today's ground systems is that they are currently incapable of processing the data

received at rates that are close to 1 Gbps. Thus operational equipment needs to be developed to handle those very high rates, and these developments need to start soon enough to ensure mission success.

NGSLP proposes a maximum frame size of 65,536 bytes. This enlarged frame would provide for frame sizes 32 times larger than the current set of standards. A larger maximum CCSDS frame size would reduce frame data processing and delivery switching requirements for very high rate missions and the increased size of the VC sequence counter would provide the desired link layer accountability.

NGSLP offers a variable length transfer frame on all links. A variable length frame accommodates the insertion of a data driven Insert Zone. The Insert Zone may carry real time data or messages signaled in the transfer frame header. The aperiodic insertion of real time data on demand is not possible using a fixed frame approach. Additional flexibility is available to a mission, even when it has decided to maintain the dependency between the frame and the code block. Namely, variable length frames may utilize an integer number of smaller code words to form the desired code block (similar to that accommodated by the DFE (TC) protocol). In so doing, one code word size can be utilized for an entire mission with little degradation of coding gain performance while allowing the frames to be sized to meet the need and demands of the link.

Agency data accountability services depend upon a suitable frame sequence counter, one whose frame sequence count does not return to zero over short periods of time. CCSDS agencies currently utilize this type of counter as the primary means of uniquely identifying and ordering telemetry frames. At a 10 Gbps downlink rate and using the current maximum transfer frame size of 2048 bytes, the AOS extended frame sequence counter recycles in approximately 7 minutes. Such a short sequence counter cycle time is clearly unacceptable for mission operations data accountability. In the proposed NGSLP protocol this counter is easily extendable to larger sizes, which could take years to overflow the counter.

Thus it is imperative to increase the frame size and frame sequence counter to reduce the impact on future link communications service implementations both on the ground and on-board.

C. Increased Spacecraft ID (SCID) Name Space

The number of available Spacecraft IDs available to future missions is limited and current missions consume 75% of the available Version 1 SCIDs and 63% of the Version 2 SCIDs, based upon the CCSDS SANA SCID registry.[10] Currently there are two sets of SCIDs, one for the TC and TM recommendations (Version 1) up to 1024 SCIDs, and one for AOS that supports 256 SCIDs. As a result, if a spacecraft uses TC on the forward link and the AOS on the return link, it must be assigned two SCIDs, one for the TC (V=1) and the other for the AOS (V=2). Another factor that leads to the rapid consumption of SCIDs is multiple assignments per spacecraft. Currently most missions require multiple SCID assignments in order to differentiate the data based upon mission phase (i.e., System Test vs. Mission Operations).

Another driver for an increased number of SCIDs is increased agency activities in developing cubesat/microsats and the future expectation of internetworking in space. For NGSLP, we propose a larger SCID field, along with the addition of an associated field signaling how the SCID will be used, providing the means for a single unified SCID to be used for all mission phases and on all links.

D. Accommodation of Space Data Link Security (SDLS) Protocol and New Implementations to Incorporate Security

The addition of the CCSDS SDLS Protocol[8] to the existing space data link layer protocols will cause changes in both ground and spacecraft implementations in the near future. SDLS is another important driver for the timeliness of this activity. The redesign of the uplink processing required for SDLS could also accommodate the changes in the NGSLP link formats and thereby extend the life of the new equipment and the compatibility with future mission needs. This will only be possible if the new NGSLP protocol is matured in a timely way.

A proposed key capability in the NGSLP is the creation of VC sub-channels within a given VC. VC sub-channels replace the MAP and Port ID approaches used in TC and Prox-1 with a common method that provides the sub addressing of frame data associated with a single Virtual Channel (VC). This technique is perfectly suited to the COP-1[9] and especially useful when trying to provide security for multiple Virtual Channels utilizing a single Security Association (SA)[8]. The use of VC sub-channels allows the COP-1 to be executed on a single VC instead of requiring that these services be provided across multiple VCs. This technique also enables a single SA to use the existing VC sequence counter to provide the required uniqueness to block command replay for many years using a single key, which simplifies key management security design. Since this technique also allows the VC sequence

counter to be used for anti-reply attacks it eliminates the need to include a separate counter in the security header reducing overhead.

Currently Prox-1 cannot support SDLS because there is no VCID in the protocol and SDLS is based upon the use of VCs. The NASA Mars Program is concerned that CCSDS SDLS security services do not apply to Proximity-1. Since the NGSLP provides VCs, SDLS protocol would be applicable for proximate environments wherever they are deployed.

E. Allows for Data-Driven Master Channel Services

The proposed NGSLP signals the presence/absence of different Master Channel fields so that computers can make run-time decisions on how to process the data as it arrives. When the frame length is allowed to vary, this data driven approach provides the ability to insert low latency messages into the link to provide rapid indication of actions that are taking place onboard a vehicle or actions that need urgently attention by the receiving entity. Thus the Insert Zone (IZ) may be used as needed to provide synchronous, periodic or transient insertion of data as required by the mission.

III. Data Link Services Protocol Sub-Layer

A. Overview

The NGSLP provides a flexible transfer frame structure that may be optimized for the specific needs of all space link types and constraints. The transfer frame structure provides sufficient data within the frame header to enable the receive side link layer frame processing: delimit the transfer frame, separate and route Master and/or Virtual Channel (VC) frames without requiring knowledge of the management details associated with the VC nor the security encoding incorporated within them. The tailoring of the frames functionality is accommodated within the Transfer Frame Data Field (TFDF). The details of the TFDF data structure will be explained in a subsequent section of this Paper. An attached synchronization marker (ASM) is required and is pre-pended to the frame. The exact size and code for the marker is dependent upon the channel error characteristics. The ASM and the application of Forward Error Correction (FEC) are discussed in a later section of this paper.

In order to provide extra useful capabilities, Virtual Channel Sub-Channels (VCS) have been introduced. The VCS is a multiplexing feature that allows a VC to deliver up to 32 independent sub channels one at a time over the same VC. The capability to include multiple distinct VCS SDUs within a Virtual Channel allows for the capability to utilize a single Security Association to delivery those independent VCS SDUs that share the same VC. This capability enables a single VC to provide reliable delivery of the various VCS-SDUs sharing that VC using the "Go-Back-N" protocols for that VC as currently defined in Telecommand and Proximity Links. This capability may be used, for example, for the operational control facilities to provide their unique security coding on those data streams that it controls within a single SA, while the data traffic to/from equipment in other agency elements can use their own VC and SA.

The current Telecommand Protocol relies on a segmentation process to allow large packets to be carried within smaller frames, while the TM and AOS protocols provide this capability by a process identified in this paper as "streaming". In the "streaming" process, packets are allowed to flow across frame boundaries. The streaming process has been identified by NGSLP for use on all links to provide this functionality.

B. NGSLP Transfer Frame Format

The Transfer Frame Structure is shown in Fig. 1 below:

NGSLP Transfer Frame

Transfer Frame Header	Transfer Frame Insert Zone	VC Security Header	Transfer Frame Data Field (TFDF)	VC Security Trailer	Transfer Frame Operational Control Field	Transfer Frame Error Control Field
6-11 Octets Mandatory	Variable Optional	Variable Optional	Variable Optional	Variable Optional	4 Octets Optional	Variable Optional

Figure 1. NGSLP Transfer Frame

The Transfer Frame shall have a mandatory frame header followed by up to six optional fields, positioned contiguously, in the following sequence:

1) Transfer Frame Header (mandatory, fixed format per VC, difference is signaled]
2) Insert Zone (IZ)
3) Virtual Channel Security Header (optional, managed)
4) Transfer Frame Data Field (optional, variable)
5) Virtual Channel Security Trailer (optional, managed)
6) Operational Control Field (OCF is optional, managed by VC, required to support ARQ protocols)
7) Frame Error Control Field (FECF which is optional, managed and signaled by the Master Channel)

Note: Only one FECF algorithm is allowed per Physical Channel and inclusion is signaled in the Frame Header. This field is often referred to as the Cyclic Redundancy Check (CRC). Coding is managed for a link (only 1 Attached Synchronization Marker, code type and code word size per link session is allowed).

NGSLP Transfer Frame Header

Version Number	FECF Size	VC Count size	Frame Length	Source or Destination ID	SCID Use	Spacecraft ID	Insert Zone Flag	OCF Flag	Virtual Channel ID	VC Count
3 bits	2 bits	3 bits	16 Bits	1 bit	2 Bits	13 bits	1 bit	1 bit	6 Bits	0-56 Bits

Figure 2. NGSLP Transfer Frame Header Structure

The first field in the Transfer Frame is the Transfer Frame Header in Fig. 2 above that contains eleven possible fields with only the VC Count Size field being optional. The functions associated with each field are described below:

1) The Version Number field is compatible with the current CCSDS Version Number field and when it contains the value "110" it identifies the frame as being a NGSLP Frame.
2) The FECF Size field identifies whether a FECF is contained in the frame and its size (the FEC algorithm is related to its size and will be describe in the Coding and Sync Specification).
3) The VC Count Size field identifies whether a VC Count Field is contained in the frame and its size. The VC Count can be 0 to 7 bytes in length.
4) Frame Length field provides for a frame size up to 65,536 bytes in length.
5) Source or Destination ID signals whether the SCID identifies either the spacecraft which generated the frame (source) or the destination of the frame to which the frame is being addressed.
6) SCID Use Field is provided for the mission developers to identify during what phase of the mission's development the frame was created. The post-launch phase will be identified by the value "11".
7) The SCID provides for 8192 SC IDs, which is 8 times the number currently available.
8) Insert Zone flag signals the presents or absence of an Insert Zone.
9) The OCF flag signals the presents or absence of an OCF Field.
10) The VCID field can identify up to 64 VCs.
11) The VC Count field is an incrementing sequence counter for a given VC. The size of this field is identified by the VC Count Size field.

TRANSFER FRAME INSERT ZONE (IZ): The second field in the Transfer Frame is the Transfer Frame Insert Zone in Fig. 3 below. The presence or absence of the IZ is signaled by the Insert Zone Flag in the Transfer Frame Header. In order for all Master Frame Services to be data driven, an Insert zone header is required that identifies at a minimum its length. The IZ header contains the source spacecraft ID (SCID), if the frame is to be relayed to another Spacecraft and a User Defined Type, which describes the contents of the IZ. The maximum Insert Zone size is 255 bytes. Larger data contents could be accommodated by insertion of a frame dedicated to the information to be transferred.

Insert Zone Length	User Defined Type	Source SCID Included Flag	Source SCID
8 bits	7 bits	1 bit	16 bits (Optional)

Figure 3. NGSLP Transfer Frame Insert Zone Header

The Security Fields: The third and fifth fields in the frame (VC Security Header and Trailer) are considered part of the VC's contents and is managed. The contents of these fields will abide by the SDLS protocol.

The Transfer Frame Data Field: The fourth field is the Transfer Frame Data Field whose structure is shown in Fig. 4 and contains three optional fields.

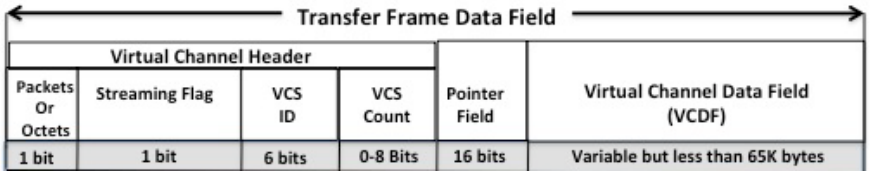

Figure 4. NGSLP Transfer Frame Data Field

1) The Virtual Channel Header is used to identify an included VC Sub Channel and supporting fields:
   a. The Packets or Octets Flag identifies the type of data contained within the Virtual Channel Data Field (VCDF).
   b. The Streaming Flag identifies the rules concerning how the data is transferred. When streaming is signaled, packets can flow across boundaries and user octets need not fill the VCDF.
   c. VC Sub channel ID field identifies the contained VC Sub channel.
   d. VC Count field will contain an 8-bit incrementing sequence counter used to verify continuity of the VC Sub channel data stream.
2) The Pointer field is used to point to the first byte of the first complete packet header when packets are specific or points to the last user provided octet in the VCDF.
3) The VCDF will contain the user's data to be transferred within the VC.

Operational Control Field: the sixth field that is used for reporting on bi-directional traffic supporting the Go-Back-N frame retransmission protocol. This field is optional and is a fixed 4-byte field that is compliant with all current CCSDS Link specifications.

Frame Error Control Field: the seventh field that is optional and is used to check that the received frame has not been corrupted in transit. The FECF Size Field identifies this field's length as 0, 16, 24 or 32 bits in length. The 16 and 32 bit FEC algorithms are specified in the CCSDS Synchronization and Channel Coding specifications.[4, 5]

C. Tailoring the Frame to the Operational Requirements of the Link

Figure 5 highlights the four basic frame constructs that can be formed to provide the required services for a link. Note that inclusion of an Insert Zone field, Security Header Fields, an OCF and/or a FECF can be accommodated in all the basic forms but these fields are not shown in the figure to reduce drawing complexity.

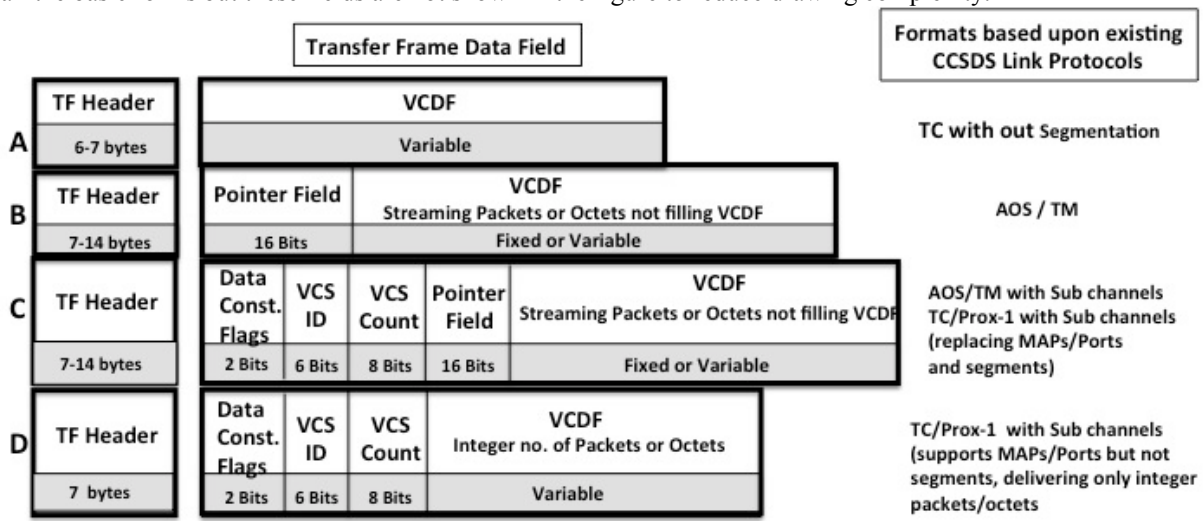

Figure 5. Basic NGSLP Frame Constructs

The first format, A is tailored for message transfers that support variable length frames as currently supported by Telecommand and Proximity-1 exclusive of segmentation and ports (these features are included in the third format described below). In the formation of hardware commands, for example, the sequence count field can be set to zero length and thus the required frame header would be just 6 bytes in length, and the rest of the frame could contain the user's complete message (control commands, packets or octets).

The second format, B is derived and consistent with the current TM and AOS protocols but could be considered for used for all links. If the frame and code block are not coupled than variable length frames are accommodated by this format. This form allows the frame's message contents to cross frame boundaries eliminating the need for segmentation as currently available with the TC protocol. Thus when segmentation is required to provide a means to share link transport time then the second and third forms presented in Fig. 5 may be used.

The third format, C provides for VC Sub channels and allows messages to cross frame boundaries. By using VC Sub channels, messages can be directed at a particular element within the receiving system. This methodology allows for using a single VC for operational control (i.e. go-back-n protocol) and security processing before contents extraction and delivery to the designated element.

The fourth format, D provides for VC Sub channels but limits the content of the frame to be an integer number of packets or constrains the frame to deliver the complete set of user provided octets. This methodology allows for using a single VC for operational control (i.e., go-back-n protocol) and security processing before contents extraction and delivery to the designated element.

IV. Conclusion

The applications we foresee for the future use of the NGSLP protocol are:

1) *Frame Relaying for LEO to GEO to Earth links*. The same transfer frame format can be relayed from multiple spacecraft, because the same frame structure is transferred across all operational links.

2) *Frame Relaying for Proximity Mars to/from Earth links.* Currently, and envisioned through 2020 on the telemetry link, landed assets format their telemetry in DTE transfer frames that are then reliably tunneled via the Proximity-1 protocol to an orbiter. These DTE frames are stored in the orbiter's data system as orbiter packets and then downlinked to Earth in Orbiter transfer frames. NGSLP enables both transfer frames (generated by a landed asset and orbiter self-generated) to be prioritized and downlinked over the same physical channel without any intermediate processing (packetizing the lander's frame for inclusion in the Orbiters frame) of the landed assets telemetry. Note that frame relaying and consistent handling of frames could also apply to the command (forward) link.

3) The Human Exploration Program has very ambitious goals that include clusters of vehicles, very high data rates, and link security and relay services. The ISS already has link configurations in which a single uplink is used to serve multiple on-board entities that are essentially autonomous. Similar configurations exist on the downlink as well. *The combination of the NGSLP and the emerging CCSDS CSTS Forward Frame service would permit each of these user communities to create and manage their own secured virtual channels between their mission operations ground system and their on-board environment.* The NGSLP is designed to facilitate this sort of deployment. The NGSLP requires standardization and needs to be matured in time for this program to utilize it.

4) *Utilization of the CCSDS FCLTU-SLE service for all DFE communications can be accommodated when the frame length is independent of the codeblock length.* The ground stations can accommodate the needs of both low rate and high rate missions by continuously encoding the data stream provided by the current SLE-CLTU service using the selected LDPC code. In this mode the frame and the codeblock are independent of one another and the continuous stream of codeblocks are separated by the Codeblock Synchronization Marker (CSM). In this case, the C&S sublayer provides a virtual error free uplink upon which the CCSDS link layer frames reside. This method provides the decoding process with fixed length codeblocks thus simplifying the decoding process and ensures that the transfer frame delimiting process will be performed in a virtual error free environment. When synchronous frame delivery is not required then the current SLE-CLTU service can be used to create the data stream that will be encoded and uplinked. Idle data can be inserted when ground delivery transients disrupt continuous frame delivery to the stations thereby incurring minimum added latency on those occasions.

Appendix A
Acronym List

AOS	Advanced Orbiting Systems
ARQ	Automatic Repeat ReQuest
ASM	Attached Synchronization Marker
BCH	Bose-Chaudhuri-Hocquenghem
C&S	Coding and Synchronization
CRC	Cyclic Redundancy Check
CSM	Codeblock Synchronization Marker
CCSDS	Consultative Committee for Space Data Systems
CLTU	Command Link Transmission Unit
COP-1	Communications Operations Procedure 1
CRC	Cyclic Redundancy Check
CSTS	Cross Support Transfer Services
DFE	Direct From Earth
DTE	Direct to Earth
ESA	European Space Agency
FCLTU	Forward Command Link Transmission Unit
FEC	Forward Error Correction
FECF	Frame Error Control Field
FPGA	Field Programmable Gate Array
GEO	Geosynchronous Earth Orbiter
ISS	International Space Station
IZ	Insert Zone
JWST	James Webb Space Telescope
LEO	Low Earth Orbiter
LDPC	Low-Density Parity Check
MAP	Multiplexer Access Point
NASA	National Aeronautics and Space Administration
NGSLP	Next Generation Space Link Protocol
OCF	Operational Control Field
PDU	Protocol Data Unit
SA	Security Association
SCID	Spacecraft ID
SDLS	Space Data Link Security
SDU	Service Data Unit
TC	Telecommand
TESS	Transiting Exoplanet Survey Satellite
TF	Transfer Frame
TFDF	Transfer Frame Data Field
TM	Telemetry
VC	Virtual Channel
VCDF	Virtual Channel Data Field
VCID	Virtual Channel Identifier
VCM	Variable Coded Modulation
VCS	Virtual Channel Sub-channel

Appendix B
Glossary

Acknowledge Repeat ReQuest	An error-control method for data transmission that uses acknowledgements and timeouts to achieve reliable data transmission over an unreliable service.
CCSDS	An organization of Space Agencies that produces space data standards mainly for flight and ground systems and their interface to space systems.
Low-Density Parity Check Codes	A linear error correcting code: a method of transmitting a message over a noisy transmission channel, and is constructed using a sparse bipartite graph.

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