

Consultative Committee for Space Data Systems

REPORT CONCERNING SPACE
DATA SYSTEM STANDARDS

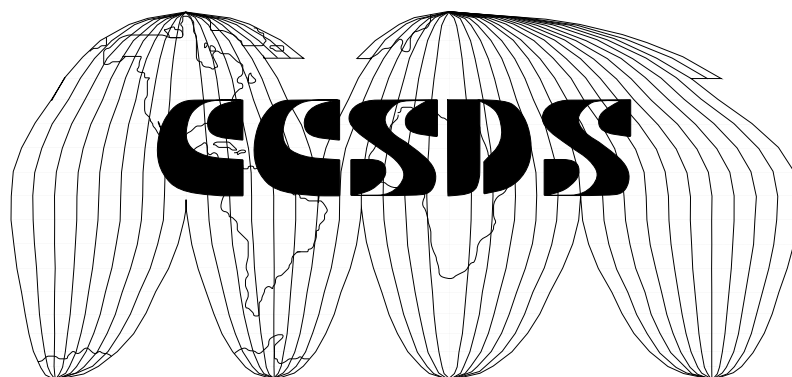
TELECOMMAND

SUMMARY OF
CONCEPT AND RATIONALE

CCSDS 200.0-G-6

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* * * * *

This Recommendation reflects the consensus technical agreement of the following member Agencies of the Consultative Committee for Space Data Systems (CCSDS):

- o Centre National D'Etudes Spatiales (CNES)/France.
- o Deutsche Forschungs-u. Versuchsanstalt fuer Luft und Raumfahrt e.V (DFVLR)/
West Germany.
- o European Space Agency (ESA)/Europe.
- o Indian Space Research Organization (ISRO)/India.
- o Instituto de Pesquisas Espaciais (INPE)/Brazil.
- o National Aeronautics and Space Administration (NASA)/USA.
- o National Space Development Agency of Japan (NASDA)/Japan.

The panel experts of the following observer Agencies also technically concur with this report:

- o British National Space Centre (BNSC)/United Kingdom.
- o Chinese Academy of Space Technology (CAST)/People's Republic of China.
- o Department of Communications, Communications Research Centre
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FOREWORD

This document is a CCSDS report which summarizes the principal concepts associated with the recommended CCSDS space mission telecommanding architecture. It is intended to orient technical personnel to these concepts, prior to reading the three main CCSDS architectural specifications, which are:

- o CCSDS Recommendation for Space Data System Standards. Telecommand, Part 1: Channel Service, Architectural Specification.
- o CCSDS Recommendation for Space Data System Standards. Telecommand, Part 2: Data Routing Service, Architectural Specification.
- o CCSDS Recommendation for Space Data System Standards. Telecommand, Part 3: Data Management Service, Architectural Definition.

A fourth specification is also under preparation by the CCSDS, containing the more detailed operational procedures which support the architecture defined in Part 2. This fourth document is:

- o CCSDS Recommendation for Space Data System Standards. Telecommand, Part 2.1: Command Operation Procedures, Detailed Specifications and State Matrices.

The current set of CCSDS Recommendations was developed to match a conventional mission environment, as characterized by the transmission of command data from a closed user community, at relatively low uplink data rates, to spacecraft of moderate complexity. The CCSDS is presently examining the extension of these Recommendations to a more complex future mission environment, including the transmission of multiple data types from a networked, more open user community at very high rates to space vehicles which include extensive onboard data networking capability.

Questions relative to the contents or status of this document should be addressed to the CCSDS Secretariat.

DOCUMENT CONTROL

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-	Telecommand Summary of Concept and Service, Issue 0	August 1984	Superseded
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- [1] "Procedures Manual for the Consultative Committee for Space Data Systems", Issue 1, Consultative Committee for Space Data Systems, August 1985 or later issue.
- [2] "Telecommand, Part 3: Data Management Service, Architectural Definition", Recommendation CCSDS 203.0-B-1, Issue 1, Blue Book, Consultative Committee for Space Data Systems, January 1987 or later issue.
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- [4] "Telecommand, Part 1: Channel Service, Architectural Specification", Recommendation CCSDS 201.0-B-1, Issue 1, Blue Book, Consultative Committee for Space Data Systems, January 1987 or later issue.
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- [6] "Packet Telemetry", Recommendation CCSDS 102.0-B-2, Issue 2, Blue Book, Consultative Committee for Space Data Systems, January 1987 or later issue.
- [7] "Telemetry Channel Coding", Recommendation CCSDS 101.0-B-2, Issue 2, Blue Book, Consultative Committee for Space Data Systems, January 1987 or later issue.
- [8] Miller, W.H., and Morakis, J.C., *Concatenated Coding Scheme for Telecommand Error Control*, GSFC X730-86-20, NASA Goddard Space Flight Center, December 1985.
- [9] "Standard Formatted Data Units -- Structure and Construction Rules", Document CCSDS 620.0-R-2, Red Book, Consultative Committee for Space Data Systems, February 1987 or later issue.
- [10] "CCSDS System Description, Volume 1: Recommended Interfaces and Service Access Points", Issue 0, Green Book, Consultative Committee for Space Data Systems, January 1986 or later issue.

The latest issues of CCSDS documents may be obtained from the CCSDS Secretariat at the address indicated on page i.

1 DOCUMENT PURPOSE AND ORGANIZATION

1.1 PURPOSE

This report is a high level technical summary describing architectural concepts for space mission telecommand systems. These concepts, and their associated telecommanding services, have been developed by the participating Agencies of the international Consultative Committee for Space Data Systems (CCSDS). The operating principles and procedures for the CCSDS are defined in Reference [1]. This report has been prepared to serve two major purposes:

- (1) To provide an overview that will introduce a new reader to the system concepts upon which the detailed CCSDS Telecommand Recommendations (References [2], [3], [4], and [5]) are based.
- (2) To summarize the technical content of the three main architectural Recommendations (References [2], [3], and [4]), and to describe their context within the framework of a layered architecture for space mission telecommanding.

This document is a CCSDS report that is intended for informational purposes, and as such it is not a part of the formal collection of CCSDS Telecommand Recommendations.

1.2 ORGANIZATION

This report contains two major sections, supported by four Annexes:

- (1) Section 2 presents an overview of the CCSDS Telecommand (TC) System and its associated concepts. This section describes the application of architectural layering techniques to achieve transparent and reliable commanding of scientific instruments or engineering subsystems aboard remote space vehicles.
- (2) Section 3 presents a summary of the service concepts that lie behind the three main CCSDS telecommand Recommendations. The overall service framework developed in the prior section is used to discuss the services and functions within each layer.
- (3) Annex A contains a Glossary in order to familiarize the reader with the terminology used throughout the discussion of the CCSDS Telecommand System.
- (4) Annex B contains a guideline for generating the Telecommand Transfer Frame error control polynomial which is specified in Reference [3].

- (5) Annex C describes a concept for the protection of Telecommand data sets so that security measures may be implemented if required by a particular mission.
- (6) Annex D contains some application notes which discuss the performance aspects of the telecommand system.

2 OVERVIEW OF THE CCSDS TELECOMMAND SYSTEM

2.1 INTRODUCTION

A telecommand system must reliably and transparently convey control information from an originating source (e.g., a human user) to a remotely located physical device or process. For a space mission telecommand system, the controlled devices and processes are scientific payload instruments or engineering subsystems onboard a spacecraft. Conventional space mission telecommand systems often display a centralized, mission-unique data handling architecture, with only a low level of data system standardization.

The introduction of more capable microprocessor-based spacecraft payloads and engineering subsystems will result in data systems with greater throughput needs, and in a corresponding increase in spacecraft autonomy and complexity. This technical environment, coupled with fiscal constraints, leads to a common space mission requirement for greater telecommanding capability and efficiency with reduced costs. The CCSDS telecommand concept addresses this requirement by recommending standardized approaches to space mission data handling: it is intended for use in conjunction with the standardized flow of telemetry data from instruments and subsystems to the user, in accordance with the CCSDS concept for "Packet Telemetry" (References [6] and [7]). Recognizing the need to cover a broad spectrum of mission needs, the new CCSDS telecommand concept is applicable to spacecraft and ground data system architectures which range from very simple and highly centralized to very complex and highly distributed.

For most past space missions, the telecommanding resources have been wholly contained within one cognizant space agency. With the exception of elements of the ground tracking networks, most of these telecommanding resources are completely dedicated and customized to the requirements of each mission. The lack of effective standardization among the various missions has forced the "multi-mission" elements of the tracking networks to implement a very low level of supporting command service, i.e., the transport of bitstreams. Higher level command services, oriented toward computer to computer transfers and typical of modern day commercial and military data networks, must presently be custom designed and implemented for space missions.

The CCSDS telecommanding architecture defines a comprehensive set of layered, standardized command services which are applicable to a very wide range of mission needs. This architecture will not only ease the transition towards the provision of more mission-independent command services within each individual space agency, but also will promote technical harmony among all space agencies that can result in greater cross-support opportunities and services. As more and more space missions look towards internationalization as the key to affordability, these standardized cross-support services will become increasingly important.

Figure 2-1 illustrates the recommended CCSDS Telecommand System architecture in terms of a layered set of telecommand services: the operations within each layer are detailed in

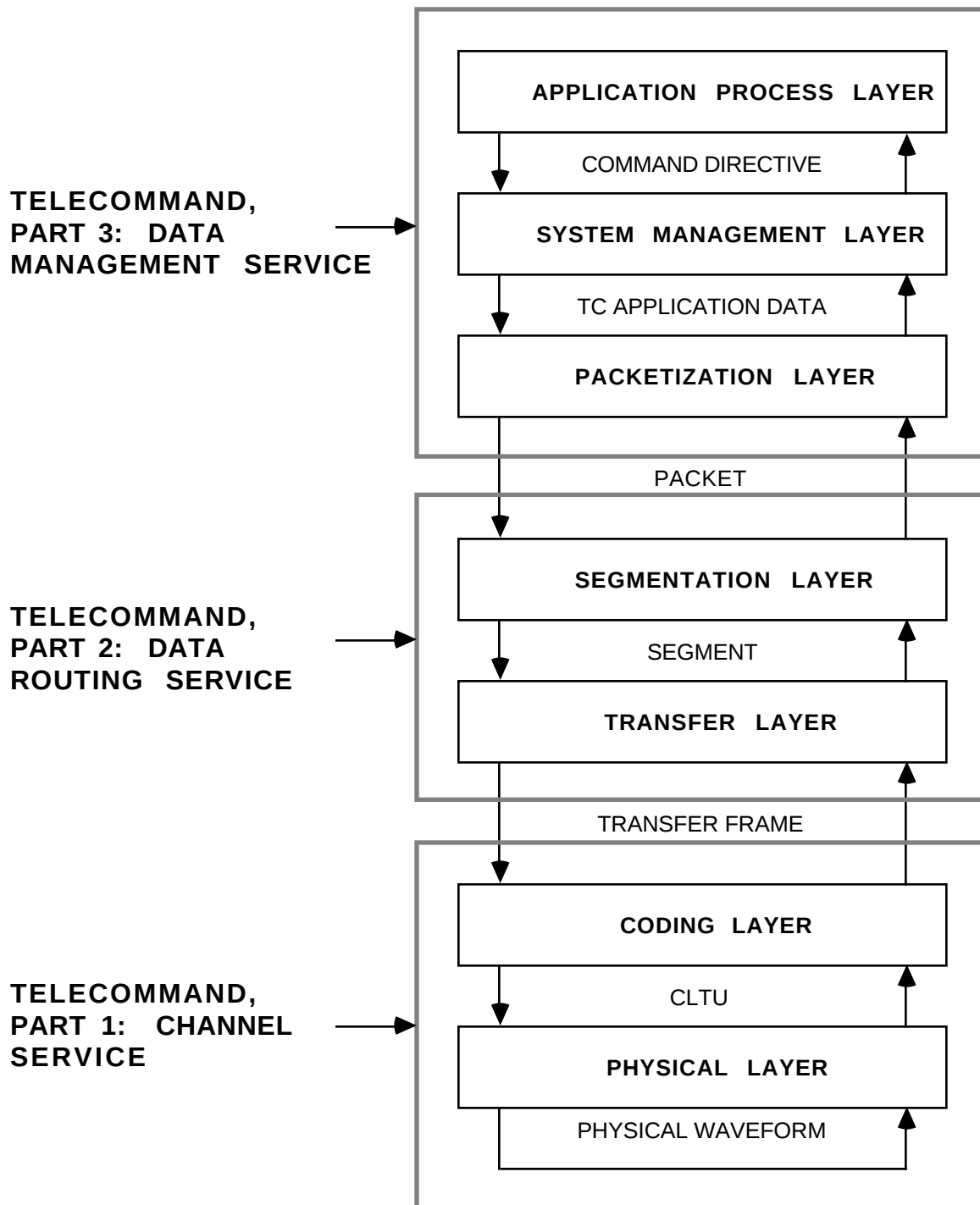


Figure 2-1: CCSDS Telecommand System

Figure 2-2. The layers of TC service are functionally grouped into a "Data Management Service", a "Data Routing Service", and a "Channel Service". Each of these three major architectural components of service is separately specified in its own CCSDS technical Recommendation, i.e., References [2], [3], and [4]. The detailed retransmission protocols associated with the Data Routing Service are contained in Reference [5]. Taken as a whole, these four Recommendations (three architectural specifications and one detailed specification) form a system which provides the user with reliable and transparent delivery of telecommand information.

The three main architectural components of service reflect increasing sophistication in terms of telecommand delivery. The Channel Service provides and controls a single reliable physical connection to the spacecraft. The Data Routing Service may be overlayed on the Channel Service to provide channel multiplexing capabilities, and to ensure the reliable delivery of buffers of telecommand data. The Data Management Service may be overlayed on the Data Routing Service to supply individually addressed end-to-end transportable command data units to each user, and to provide overall TC System coordination, integration, and management. Since each layer is independent of the layers above, individual missions may make their own decisions concerning how "high" in the layered hierarchy they wish to be compatible.

2.2 TELECOMMAND SERVICE CONCEPT

The system design technique of layering is a key tool for transforming service concepts into sets of operational and data formatting procedures. Layering (the strategy of "dividing and conquering") allows a complex procedure such as spacecraft commanding to be decomposed into sets of relatively simple peer functions residing in common architectural strata. Within each layer, the functions exchange information using standard data formatting techniques and standard procedural rules or "protocols".

Each layer of the TC System draws upon a well defined set of services provided by the layer below, and provides a similarly well defined set of services to the layer above. As long as these service boundaries are preserved, the internal operations within an individual layer are unconstrained. Consequently, an entire layer within a system may be removed and replaced as needed by user or technological requirements without destroying the integrity of the rest of the system. Further, as long as the appropriate interface protocol is satisfied, a customer (user) can conceptually interact with the system/service at any of its component layers. Layering is therefore a powerful tool for designing structured, user-responsive data systems which may easily change owing to the evolution of requirements or technology.

As shown in the service model (Figure 2-2), the CCSDS TC System contains the following seven distinct layers:

- (1) TC Application Process layer
- (2) TC System Management layer

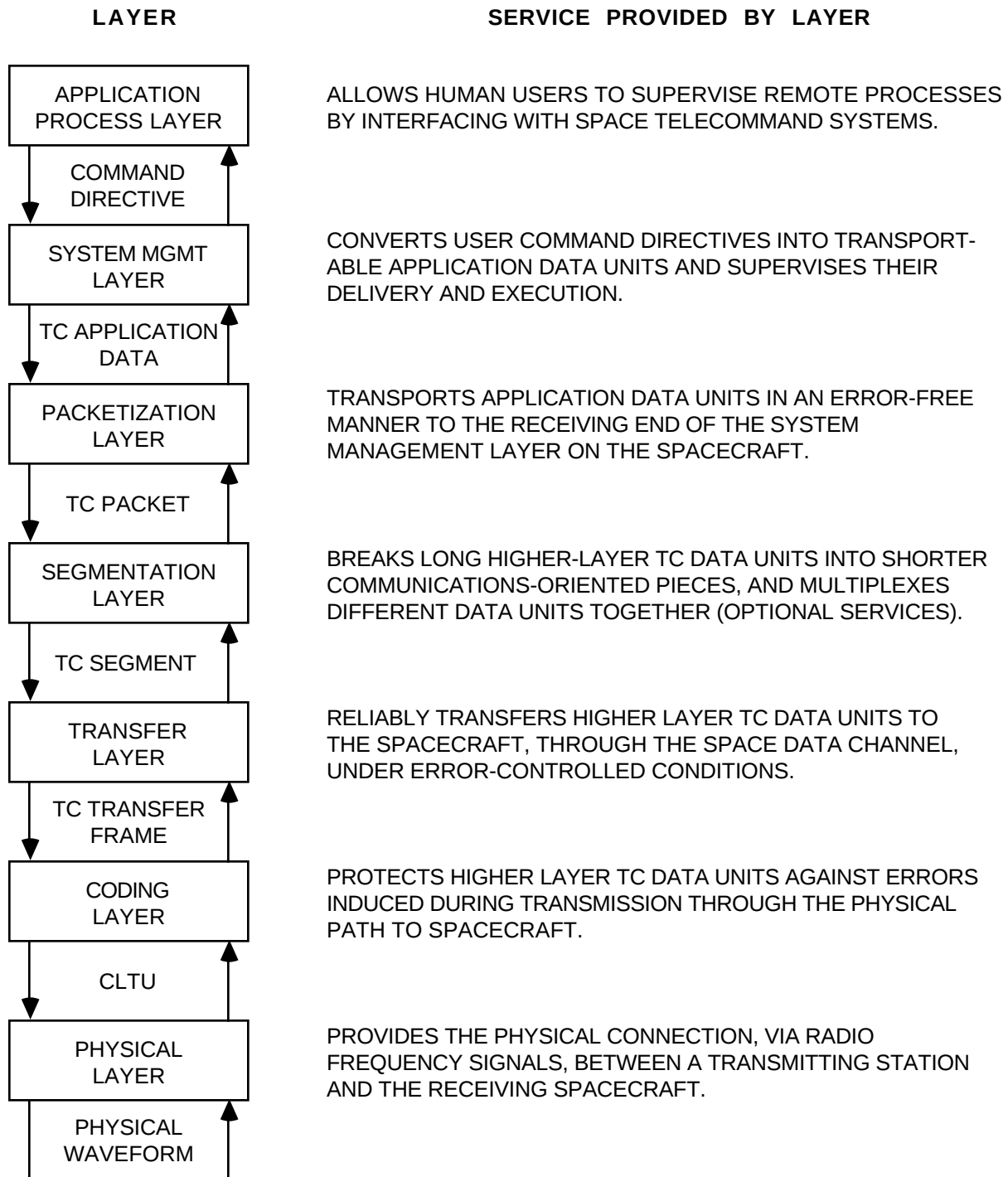


Figure 2-2: Layered Telecommand Service Model

- (3) TC Packetization layer
- (4) TC Segmentation layer
- (5) TC Transfer layer
- (6) TC Coding layer
- (7) TC Physical layer

The **TC DATA MANAGEMENT SERVICE**, containing the top three layers, provides command data delivery and management services for the user.

- (1) The **TC Application Process layer** provides the first-level interface between the user and the TC System, by insulating the user from the physical aspects of the command delivery processes. The Application Process layer translates the user requests into high-level command directives which are interpretable by the underlying System Management layer.
- (2) The **TC System Management layer** translates the high-level command directives into process-interpretable TC application data, plus control instructions to lower layers which establish the parameters for their transport to the spacecraft. The System Management layer draws upon services provided by the underlying Packetization layer in order to initiate the data transport process.
- (3) The **TC Packetization layer** formats TC application data into end-to-end transportable data units called TC Packets. A TC Packet is a basic user data unit that is transported "up" to the spacecraft by the TC System: it is virtually identical to a Telemetry Packet, which is the basic user measurement data unit that is transferred "down" to the user through the CCSDS Telemetry System. The Packetization layer utilizes the underlying services of the TC Data Routing Service to accomplish its functions.

The **TC DATA ROUTING SERVICE** contains the intermediate two layers: the TC Segmentation layer and the TC Transfer layer. The Data Routing Service supports the error-controlled transmission and retransmission of standard TC Packets or TC Segments through the data link to the spacecraft, or other user data structures from non-standard higher layers.

- (1) The **TC Segmentation layer** provides flow control services. Recognizing that user data units from the layer above may be too long for efficient handling by lower layer processes, the Segmentation layer is available to break them into smaller communications-oriented pieces (TC Segments) for transfer through the space data channel. It also provides "Multiplexer Access Points" (MAPs) which allow different user data units to be multiplexed together for data flow control purposes. TC Segments are of proper size for placement into the data unit of the next lower layer, the TC Transfer Frame. If the user data units are already short enough to be

compatible with insertion into the TC Transfer Frame, and the MAP feature is not required, the entire Segmentation layer may be bypassed.

- (2) The **TC Transfer layer** uses its own data structure, the TC Transfer Frame, to reliably transport TC Packets, TC Segments or other higher layer user data structures through the telecommand channel to the receiving spacecraft. As the heart of the CCSDS Telecommand System, the Transfer layer offers a range of delivery service options designed to satisfy various mission needs. It contains the retransmission procedures required to reliably deliver TC Transfer Frames to the spacecraft, plus the facility to multiplex these frames together into "Virtual Channels" (VCs). The Transfer layer uses the underlying TC Channel Service to accomplish its role.

The **TC CHANNEL SERVICE** contains the bottom two layers: the TC Coding layer and the TC Physical layer. The Channel Service supports the radiation of telecommand information through the physical uplink path to the spacecraft.

- (1) The **TC Coding layer** satisfies the TC System requirement for the error-free delivery of commands to the spacecraft, by encoding the TC user data from the layer above to protect them against noise-induced errors during transmission through the underlying ground-to-spacecraft radio frequency (rf) channel. The basic protocol data unit of the Coding layer is the TC Codeblock, which appends a small block of information bits with parity bits that provide error detection and (optionally) correction capability. Strings of TC Codeblocks, conveying the information bits representing one or more TC Transfer Frames in the form of parity-protected channel symbols, are encapsulated within a Command Link Transmission Unit (CLTU) before being passed to the layer below. Any errors that occur in the encoded information bits as a result of the physical transmission process may be detected or corrected at the spacecraft receiving end of the Coding layer.
- (2) The **TC Physical layer** modulates the CLTUs onto the rf carrier, and provides the procedures necessary to activate and deactivate the channel.

Reflecting an evolutionary philosophy, the CCSDS has focussed its attention on the Channel Service and the Data Routing Service and, with the exception of the Packetization layer, has at present left many of the functions within the Data Management Service for future specification. (Note: this is the reason why the Part 3 Recommendation is called an "architectural definition" whereas the other two Parts are called "architectural specifications".) A more complete specification of the upper layer functions and data structures may be performed once more operational experience is gained with the lower layer services.

Full advantage of the CCSDS TC System architecture would be realized if a space project organization complied with all of its fully specified layers of protocol: at present, this effectively means the Packetization, Segmentation, Transfer, Coding, and Physical layers. However, a project organization can conceptually interface at any layer of the TC System,

provided that all lower layers are used, as long as it conforms to the interface data structures that are defined in the three main CCSDS TC Recommendations (References [2], [3], and [4]). In such cases, only a reduced set of standard services may be made available to the project.

2.2.1 TELECOMMAND/TELEMETRY SYSTEMS RELATIONSHIP

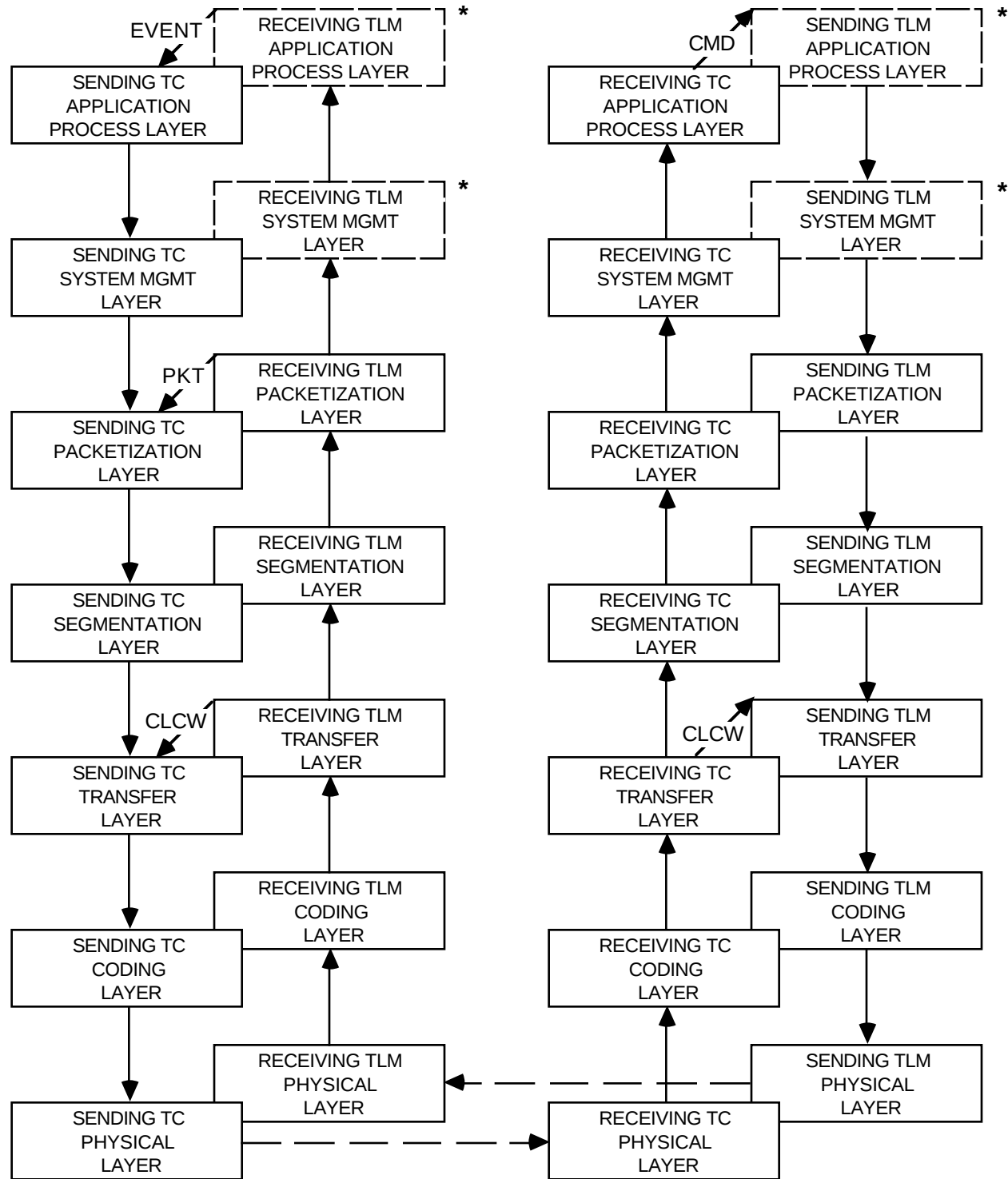
The Telecommand System is balanced by a return link Telemetry (TLM) System. Figure 2-3 shows the conceptual relationship, in an operational environment, between the TC System (which allows users to control remote instruments or subsystems) and the TLM System (which returns measurement data from those instruments or subsystems back to the user). As far as the flow of telecommands is concerned, the two systems work hand-in-hand to assure the transfer of data from the sending end to the receiving end of the TC System.

CCSDS recommendations for the standardization of the Packet Telemetry and Telemetry Channel Coding data structures and procedures are contained in References [6] and [7]. It should be noted that these two TLM Recommendations were written before the CCSDS telecommand work was mature, and therefore the TLM System does not contain the same formal layering hierarchy as the TC System. However, these same layers are implicit in the telemetry documentation, and hence Figure 2-3 synthesizes the equivalent TLM System layers for the purpose of illustration.

As shown in Figure 2-3, there are two possible protocol mechanisms inherent to the TC System for reporting command transfer status and verification information to the sending end via the TLM System. The primary mechanism is the Command Link Control Word (CLCW), which contains key information concerning the status of receipt of TC Transfer Frames by the receiving end of the TC Transfer layer. The CLCW is periodically sampled by the TLM System, and is returned to the sending end of the TC Transfer layer via the CLCW word in the trailer of the standard CCSDS TLM Transfer Frame. The information conveyed in the CLCW is used by the sending end of the TC Transfer layer to continue, retransmit or otherwise modify the transmission of the stream of TC Transfer Frames.

Reliable, mission-independent operations within the TC Transfer layer form the cornerstone of the CCSDS telecommanding concept. The closed-loop retransmission protocols between the sending and receiving ends of the TC Transfer layer (using the CLCW reporting services of the TLM Transfer layer) are specified in Reference [5].

A second reporting loop conceptually exists within the higher Packetization layer, where TLM Packets may be prepared by the receiving end of the layer to acknowledge receipt or indicate problems with the TC Packets it received from the TC Segmentation layer. These reporting TLM Packets may then be sent back to the sending end of the TC Packetization layer via the TLM System. However, at present the CCSDS has made no attempt to standardize any reporting procedures within the Packetization layer, since these are likely to involve mission-unique processes. The TC Packetization layer therefore relies fully on the standardized, guaranteed service provided by the Transfer layer.



* THESE LAYERS DO NOT EXIST IN REFERENCE [5].

Figure 2-3: Telecommand/Telemetry System Orientation

The final verification of proper command delivery and execution is, of course, provided when the user observes the effect of the command via measurement data received from the TLM System.

2.2.2 TELECOMMAND DATA STRUCTURES

Figure 2-4 illustrates how the various TC data structures within the Packetization, Segmentation, Transfer, and Coding layers map into one another. As previously noted, there is presently no attempt by the CCSDS to define the data structures of the top two layers of the TC System, i.e., the Application Process layer and System Management layer.

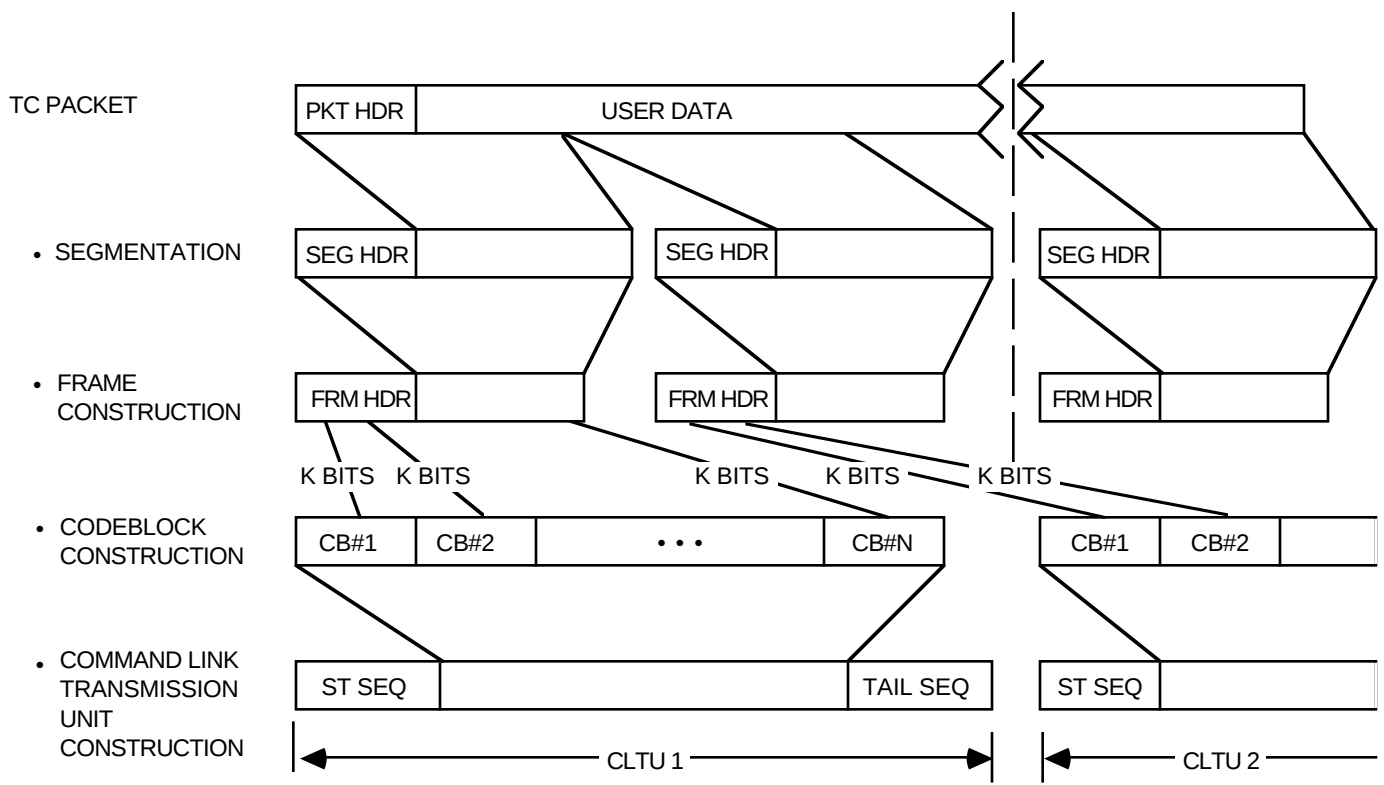
TC Packets which are longer than the data field of a TC Transfer Frame are broken into suitable-sized pieces and placed into the data field of TC Segments. A TC Segment can only contain a portion of one TC Packet, i.e., if a string of Packets is input to the Segmentation layer, new Segments must begin at each Packet boundary. A very long TC Packet will be broken into "n" TC Segments, where the length of segments (1) through (n-1) will match the maximum length of the TC Frame data field, and segment (n) will be of a length that corresponds to the residue of data from the Packet. TC Segments are, on a one-to-one basis, placed into the data fields of individual TC Transfer Frames and are encapsulated by the frame header and (optionally) the trailing Frame Error Control code.

NOTE

As specified in Reference [3], the Transfer Frame Error Control field may be needed in order to meet certain mission-defined Transfer layer performance requirements. A guideline which describes the recommended encoding/decoding procedure for the Frame Error Control field is contained in Annex B of this report. Reference [8] discusses the performance of this code in more detail.

Each TC Transfer Frame is piecewise-encoded into a series of short, fixed length TC Codeblocks which provide error detection or correction capabilities. Successive blocks of information bits from each TC Frame are placed into the data space of each codeblock, to which computed parity bits are appended.

The resulting string of TC Codeblocks is encapsulated within a "Command Link Transmission Unit" (CLTU) data structure. **Note that each CLTU may contain the encoded representation of one or more TC Frames**, i.e., several frames may be placed back-to-back, encoded and inserted into one CLTU. Each CLTU contains a Start Sequence and ends with a Tail Sequence. It is these delimited CLTUs which are modulated onto the rf carrier and physically radiated to the receiving spacecraft.



NOTE: THE DATA FIELD OF EACH CLTU CONTAINS THE ENCODED REPRESENTATION OF ONE OR MORE TRANSFER FRAMES.

Figure 2-4: Telecommand Data Structures

2.2.3 COMMUNICATIONS SECURITY/DATA PROTECTION CONCEPT

For many missions there is a requirement to prevent any intentional or accidental attempts to manipulate or control the spacecraft by an unauthorized party, including efforts to deny access to authorized users. Some missions may also have requirements to render the contents of telecommand messages unintelligible to unauthorized users. The CCSDS has developed a telecommand data protection concept, which is described in Annex C of this report, that permits authentication and encryption measures to be implemented when required by a particular mission.

2.2.4 TELECOMMAND SYSTEM PERFORMANCE

Performance considerations associated with the CCSDS TC System are discussed in Annex D of this report.

3 TELECOMMAND SERVICES

This section summarizes the services, functions, inputs, and outputs characterizing each layer of the Telecommand System. The component layers are discussed for both the sending end (where the user resides) and the receiving end (where the control actions are effected).

3.1 TC DATA MANAGEMENT SERVICE

The Data Management Service, Reference [2], provides the primary user interface with the TC System. This service enables user requests for command activity to be generated, integrated, aggregated, translated, and scheduled for delivery to a spacecraft.

3.1.1 TC APPLICATION PROCESS LAYER

The basic service of the Application Process layer is to provide users with a method by which they can formulate instructions to control a remote device in space, and to interface those instructions with the systems which provide the physical delivery of telecommands. Figure 3-1 depicts the activities and interfaces of the Application Process layer.

Inputs to the sending end of the layer take the form of user requests for specific command actions, plus associated requests concerning any desired overall delivery and execution conditions. The user command requests are translated into corresponding machine interpretable "command directives" which are passed to the layer below, along with control instructions to lower layers that specify the overall configuration of the TC System required for their delivery. Control instructions are also sent ACROSS the layer (to the peer application process in space) to define the overall conditions which must exist within that process at the time of execution of the command directives.

At the receiving end of the Application Process layer, named sets of command directives, and their associated delivery status information, are received from the System Management layer. The receiving application process executes the command directives when specified operational conditions are satisfied: the resulting executed command actions cause changes in the state of spacecraft instruments or subsystems, which may be observed and confirmed by the user via telemetered measurements.

APPLICATION PROCESS LAYER

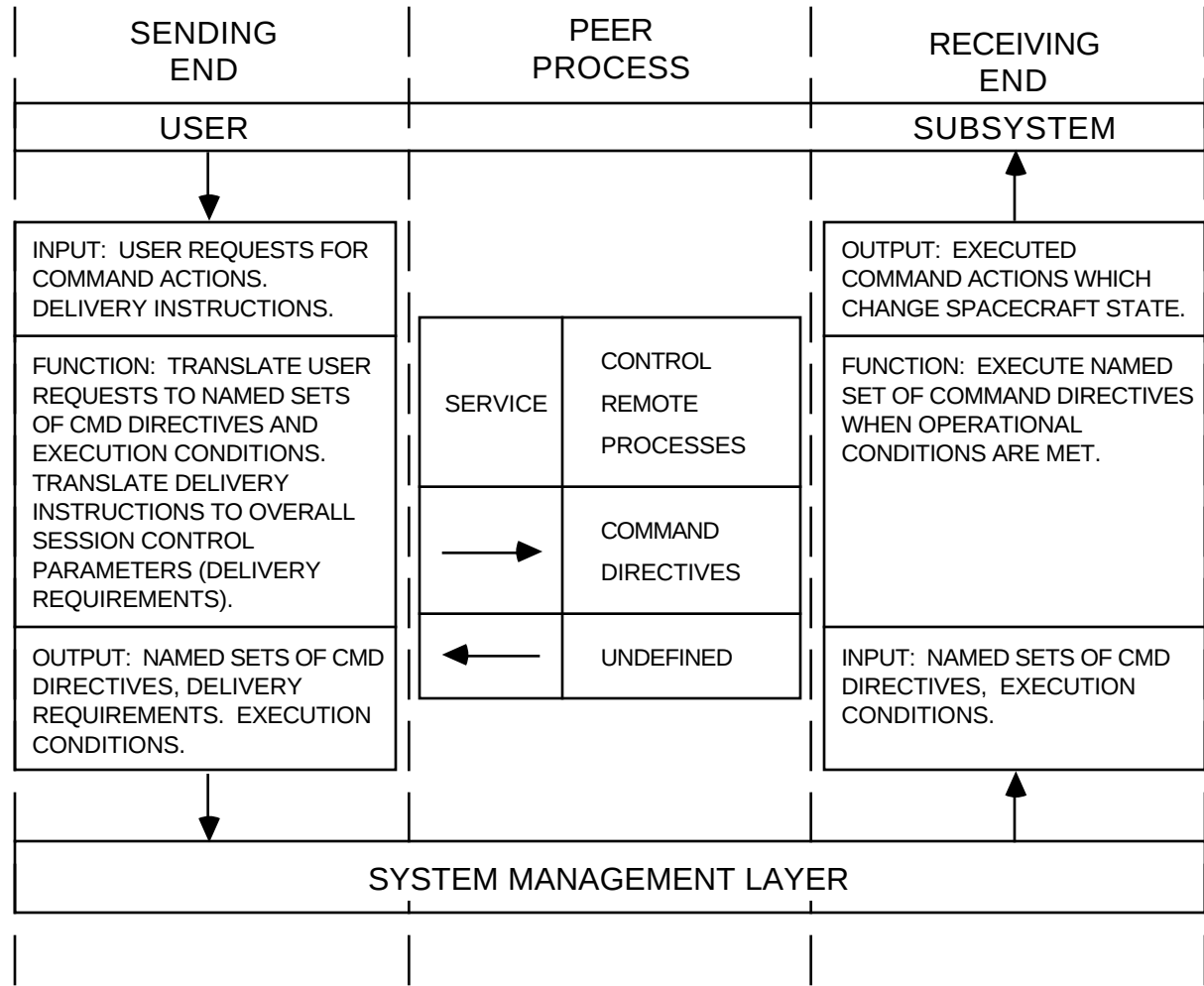


Figure 3-1: TC Application Process Layer

3.1.2 TC SYSTEM MANAGEMENT LAYER

The basic service of the TC System Management layer is to provide translation of command directives into transportable telecommand application data units, supervise their delivery to the receiving end of the layer, and to translate the application data back into command directives (if required) prior to delivery to the receiving application process. Figure 3-2 depicts the activities and interfaces of the TC System Management layer.

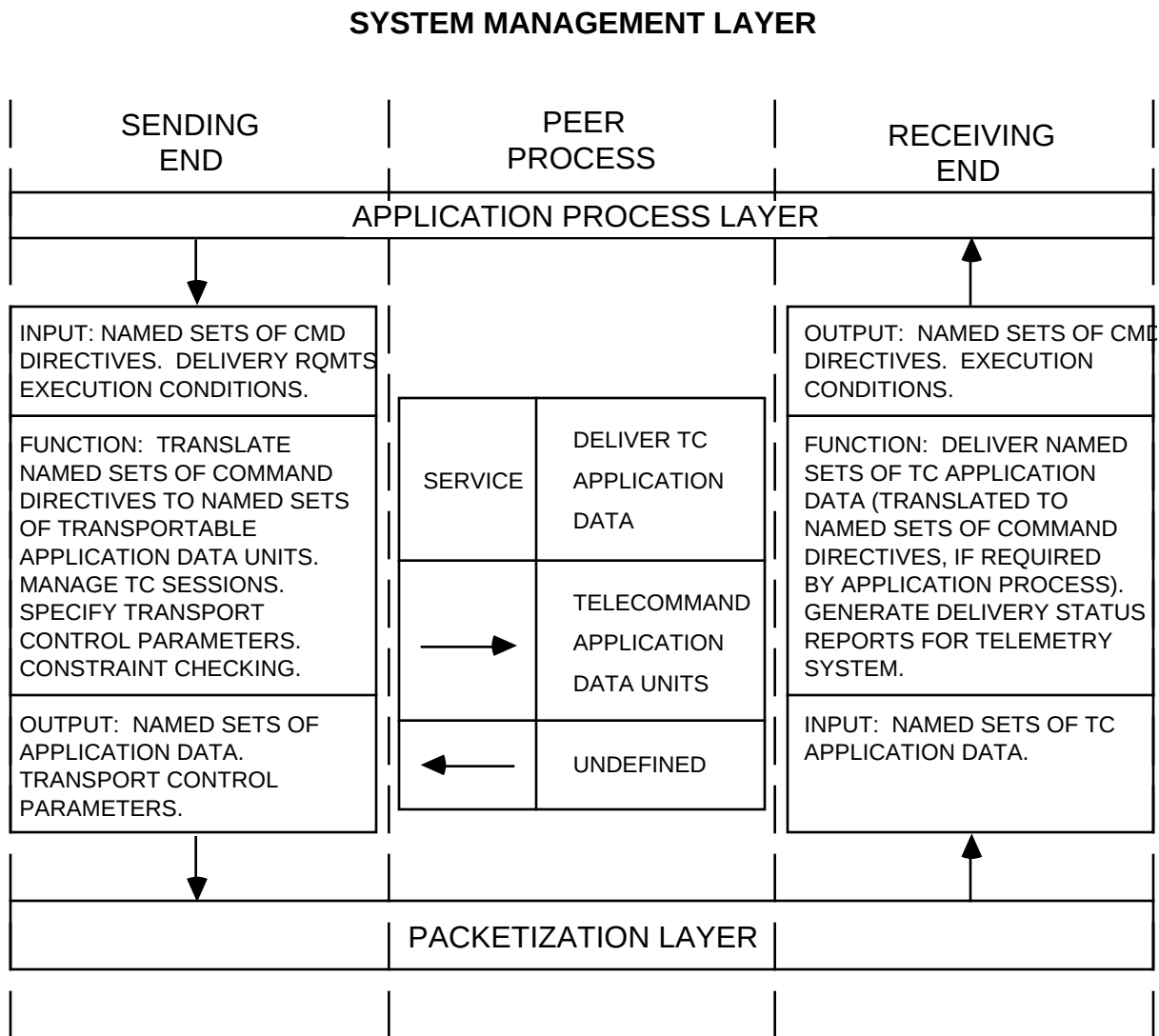


Figure 3-2: TC System Management Layer

Inputs at the sending end of the TC System Management layer are integrated, aggregated, and named sets of multi-user command directives, along with control instructions specifying their overall delivery requirements. The named command directives are parsed by the System Management layer and translated (if required) into correspondingly named sets of TC application data which are compatible with handling by the layer below.

The TC application data are partitioned into appropriate blocks for transmission during individual TC sessions, and (along with necessary control instructions) are passed to the layer below for transport. At the receiving end of the TC System Management layer, named sets of user application data may (if required by the application processes) be translated back into correspondingly named sets of command directives, or may be passed directly to the layer above. Status reports may be formulated and returned to the sending end of the layer (via Telemetry Packets) if information relating to the correctness, completeness, and sequentiality of the received data is required by particular mission processes: the CCSDS presently does not define these reports.

Session control instructions are created by the sending end of the System Management layer, which are addressed to the receiving end of the layer and are passed to the layer below for transport. These session control instructions to the receiving end of the layer define naming conventions and conditions for delivering either the application data or the retranslated command directives to the TC Application Process layer.

3.1.3 TC PACKETIZATION LAYER

The TC Packetization layer is currently the highest layer which CCSDS Recommendations cover in detail. The TC Packet is an autonomous command data unit which may be directly interpreted by the device that is being controlled. The format of the TC Packet is specified in Reference [2].

The basic service of the TC Packetization layer is to provide error-free transport of one set of application data to the System Management layer on the spacecraft. An enhanced service is to provide error-free transport of the application data content of named sets of interdependent TC Packets (i.e., TC Files) to the TC System Management layer on the spacecraft. Figure 3-3 depicts the activities and interfaces of the TC Packetization layer.

Inputs to the sending end of the Packetization layer are named sets of transportable TC application data, plus transport control instructions including naming conventions. The TC application data are placed within the data field of TC Packets, and encapsulated within Packet headers containing information such as the name of destination application, sequence control, and packet length. If required, TC Files are constructed according to the procedures defined in Reference [2].

The TC Packets, or files of TC Packets, are passed to the layer below along with control instructions that request lower layer services such as the segmentation or multiplexing of packets or files. TC Packets may also be created for routing to the receiving end of the

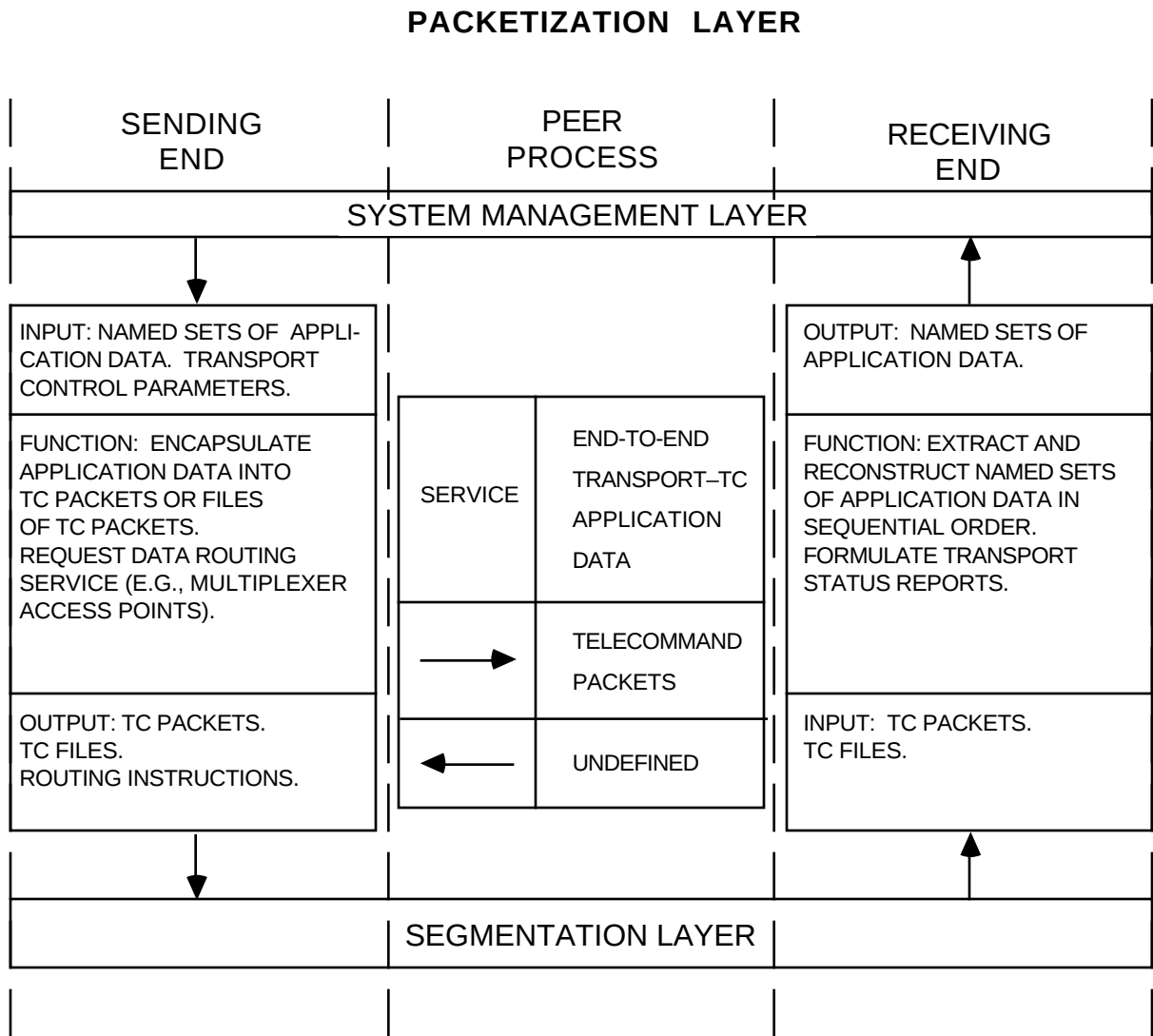


Figure 3-3: TC Packetization Layer

Packetization layer, containing control instructions which define the system conditions that must exist before the TC application data are passed back across the interface to the TC System Management layer.

At the receiving end of the TC Packetization layer, the named sets of TC application data are extracted from the data fields of the TC Packets in the sequential order in which they were given at the sending end, and passed to the layer above. Status reports may be formulated and returned to the sending end of the layer (via Telemetry Packets) if information relating to the correctness, completeness, and sequentiality of the received data is required by particular mission processes: the CCSDS presently does not define these reports.

It should be noted that many of the telecommanding functions within and above the

Packetization layer will probably be implemented within user application processes, such as the instrument and subsystems themselves, rather than as external supporting services.

3.2 TC DATA ROUTING SERVICE

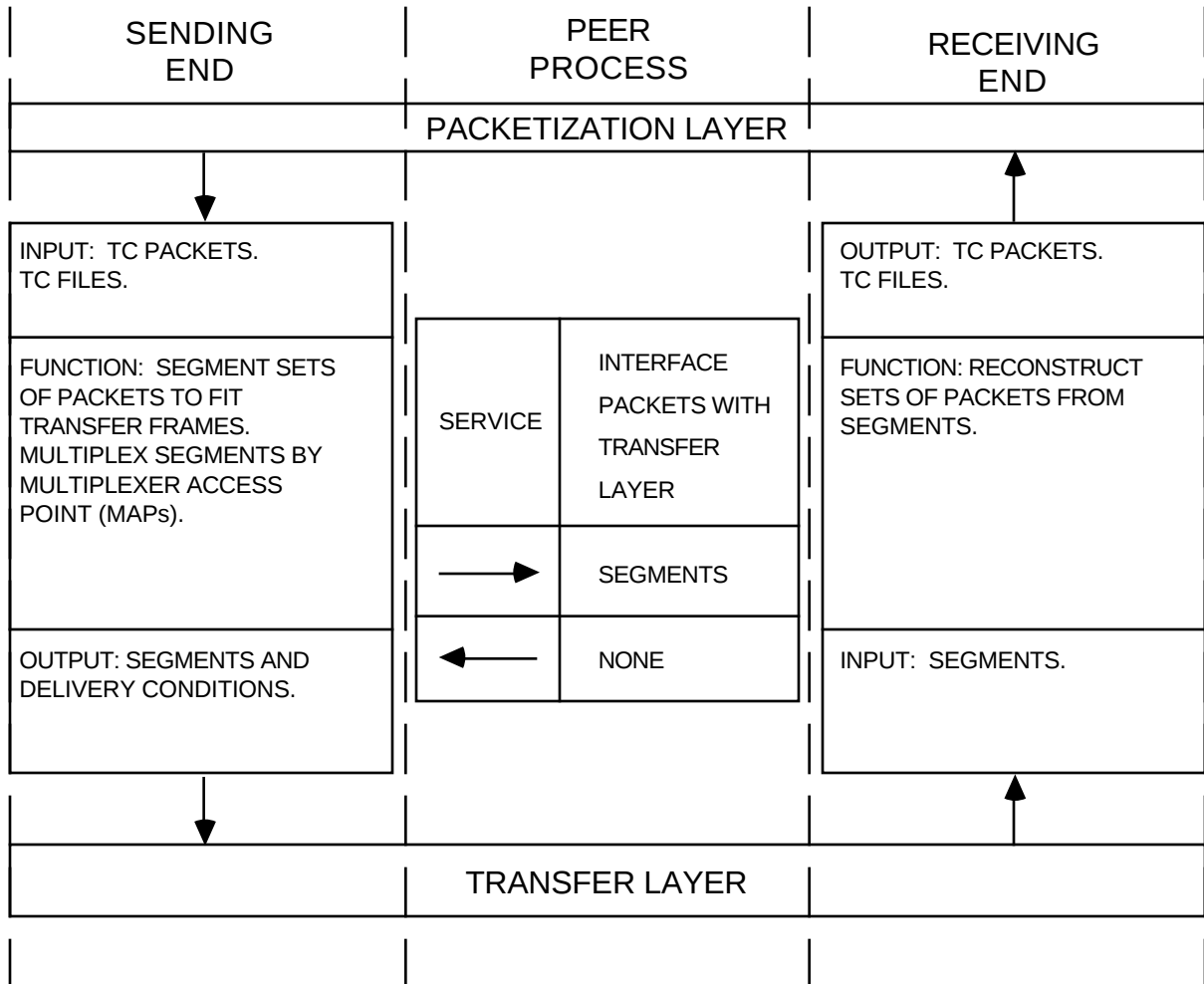
The TC Data Routing Service provides a pivotal function within the TC System by performing the error-controlled communication of higher layer TC data through the ground-to-space data link, relying on the lower layer TC Channel Service in order to perform its task. The combination of the Data Routing and Channel Services provides users with a powerful mechanism for the flow control and guaranteed transfer of TC data between the sending and receiving ends of the TC System. The CCSDS therefore has focussed its attention on fully specifying these services so that robust, mission-independent user support systems may be rapidly developed. The Data Routing Service contains two layers: the **TC Segmentation layer** and the **TC Transfer layer**. The detailed protocols and formats for the TC Data Routing Service are specified in References [3] and [5].

3.2.1 TC SEGMENTATION LAYER

The TC Segmentation layer is optional, i.e., it may be bypassed if its services are not required.

The basic service of the Segmentation layer is to prepare variable-length TC data units from the layer above (e.g., TC Packets, or other user-supplied data structures) for transfer through the space data link, using the lower TC Transfer layer service. Since the data unit of the TC Transfer layer (the TC Frame) has an upper length limit, the Segmentation layer must break the higher layer TC data units into suitable sized pieces for insertion into the data field of the frame. A second aspect of its service is the capability to multiplex together segments of data from different TC data units for the purpose of flow control: to accomplish this, the Segmentation layer provides "Multiplexer Access Points" (MAPs) to the layer above. Figure 3-4 depicts the activities and interfaces of the TC Segmentation layer.

TC Packets (or other higher layer user data structures) are input to the sending end of the layer, plus data routing control instructions (assignment of TC Packets or TC Files to particular MAPs). The input data are first broken into pieces (segments) which will fit into the data field of the lower layer TC Transfer Frames. Each segment must only contain a piece of ONE input data unit, i.e., a new segment must be started at each boundary between higher layer data units. Every segment is labelled with a Segment Header that conveys segment order. The segment is further labelled to identify with which multiplexing port it is associated, so that it may be properly routed and reconstructed at the receiving end: this is accomplished by assigning a MAP identifier to each segment, also conveyed in the Segment Header. The completed TC Segment is output to the layer below, the TC Transfer layer, for encapsulation within the data field of one TC Transfer Frame.

SEGMENTATION LAYER**Figure 3-4: TC Segmentation Layer**

At the receiving end of the TC Segmentation layer, TC Segments are received from the layer below, sorted by MAP, and the individual higher layer TC data units are reconstructed prior to passing them across the interface to the layer above. Since the Segmentation layer relies completely on the guaranteed delivery service of the layer below, it contains no layer-unique reporting procedures.

Appreciating the functional utility of the multiplexing feature of the Segmentation layer requires an understanding of the characteristics of the underlying Transfer layer. The Transfer layer, which utilizes TC Frames as its data units, interfaces with the single physical data channel in the layer below it. The TC Frames themselves feature an independent multiplexing capability, since each frame may be assigned with its own "Virtual Channel" (VC) identifier. Individual TC Frames may (by giving them different VC identifiers) each carry different higher layer TC

data units: this therefore provides a Transfer layer multiplexing capability which is functionally similar to the Segmentation layer MAPs.

However, since the Transfer layer contains the closed-loop retransmission procedures which control the delivery of TC Frames to the spacecraft, having a large number of VCs that are simultaneously "open" will increase the complexity of the reporting mechanism between the receiving and sending end of this layer. The MAP feature of the Segmentation layer allows the user data multiplexing to be performed ABOVE the Transfer layer, i.e., on one Virtual Channel, thus potentially simplifying the Transfer layer reporting and reducing its associated telemetered traffic. Conversely, it is important to recognize that this potential simplification of the Transfer layer is bought at the price of the increased complexity and communications overhead associated with the Segmentation layer.

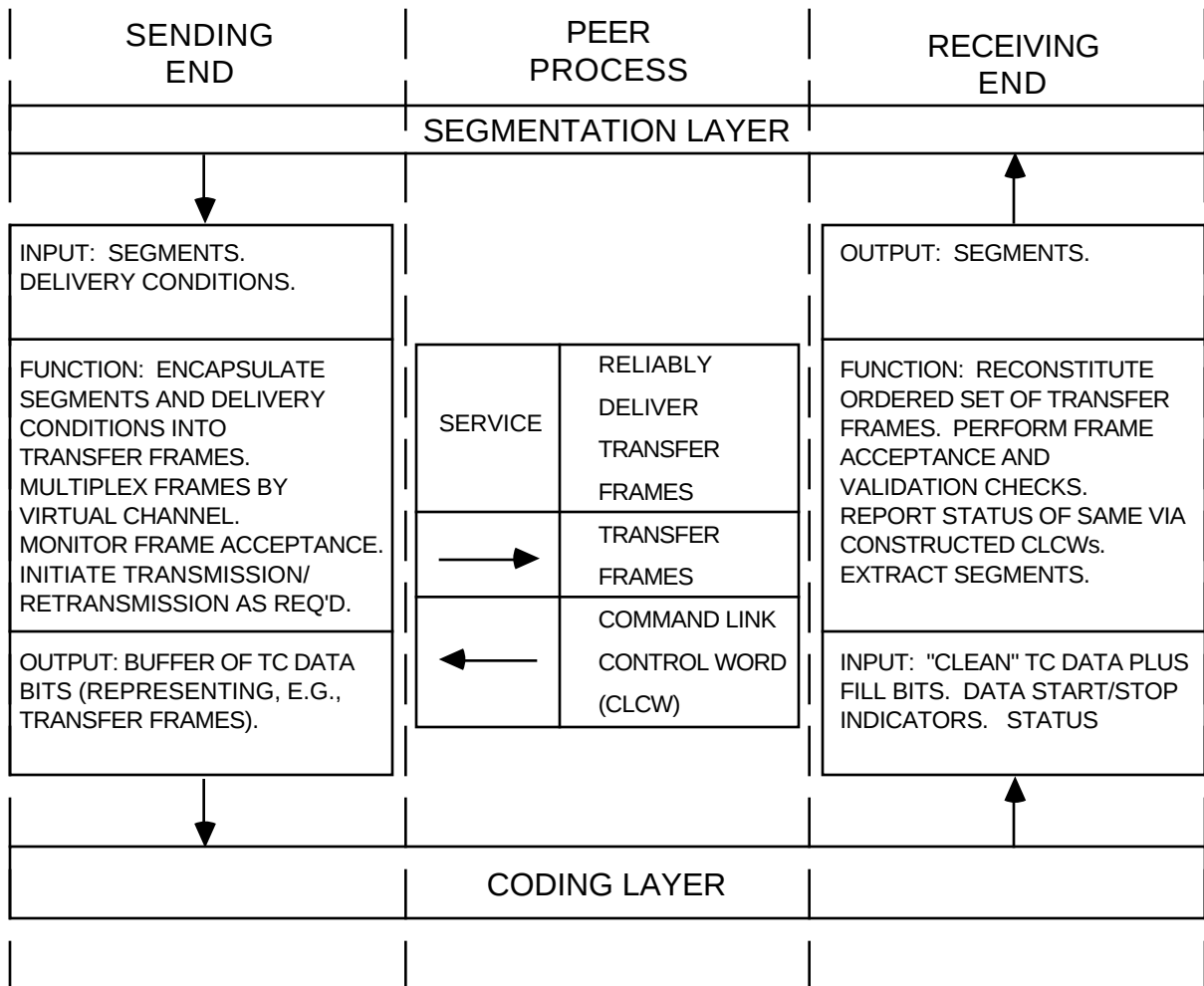
Missions are therefore free to decide whether or not to implement a Segmentation layer: if the higher layer TC data units (e.g., TC Packets) are all short enough to fit within a maximum-length TC Transfer Frame (and the reporting complexity is acceptable), the Virtual Channel feature of the TC Transfer Frame may be used for multiplexing, and the Segmentation layer may be completely omitted. It will be noted when reading Reference [3] that the CCSDS Recommendations theoretically allow up to 64 Virtual Channels in the Transfer layer, each with up to 64 MAPs attached to it within the Segmentation layer. This theoretically huge multiplexing capability is an artifact of the decision to provide alternative multiplexing mechanisms, and a real implementation will usually use a much more restricted repertoire of MAP and VC capabilities.

3.2.2 TC TRANSFER LAYER

The basic service of the TC Transfer layer is the GUARANTEED error-free communication of higher layer TC data units to the receiving end of the layer above, correct and without omission or duplication, and in the same sequential order in which they were received from the layer above at the sending end. THIS GUARANTEED SERVICE IS CENTRAL TO THE OPERATING PHILOSOPHY OF THE TC SYSTEM: the Transfer layer is therefore the "core" of the standard CCSDS telecommanding concept. In order to provide this service, the TC Transfer layer draws upon the supporting lower layer TC Channel Service. Figure 3-5 depicts the activities and interfaces of the TC Transfer layer.

The sending end of the TC Transfer layer encapsulates each higher layer TC data unit (e.g., TC Packet, TC Segment or a non-standard user data structure) within the data field of a TC Transfer Frame: one (and ONLY one) TC data unit is inserted into the data field of each frame. The header of the TC Frame contains key data link control information such as spacecraft and Virtual Channel identification, frame sequence number, and frame length.

The operating configuration of the TC Transfer layer is specified by control instructions received from higher layers. The sending end of the Transfer layer formulates special TC Transfer Frames called "Control Commands" which it transmits to a "Frame Acceptance and

TRANSFER LAYER**Figure 3-5: TC Transfer Layer**

Reporting Mechanism" (FARM) at the receiving end of the layer in order to set up the receiving parameters.

The sending end of the layer passes the assembled TC Frames to a "Frame Operation Procedure" (FOP), which provides the control of their transmission to the spacecraft. The FOP batches the TC Frames and delivers them to the layer below (the Coding layer) as buffers of serial information bits (corresponding to one or more back-to-back frames) for encoding and transmission to the spacecraft.

At the receiving end of the TC Transfer layer, the inputs from the layer below are "clean" decoded information bits and data stop/start indicators which mark the gross boundaries of the buffers of bits that were given to the Coding layer at the sending end: however, trailing fill bits

may have been inserted by the encoding process. The Transfer layer therefore uses the length information in each TC Frame to delimit each frame in the buffer, and to discard any trailing fill.

The reconstructed, delimited frames are input to the receiving-end FARM, which performs validation and acceptance checks based on sequence information and other criteria that are fully specified in Reference [3]. The status of frame acceptance by the FARM is telemetered back to the FOP at the sending end via the Command Link Control Word (CLCW) in the trailers of standard Telemetry Transfer Frames. The pair of peer-layer procedures executed by the FOP and FARM are together known as a "Command Operation Procedure" (COP). Based on CLCW reports from the FARM, the FOP makes appropriate retransmission decisions for frames which were rejected or otherwise missed by the FARM, according to the rules of the governing COP.

Under closed-loop retransmission control of the selected COP, and utilizing the error-protection services of lower layers, the TC Frames are assembled at the receiving end of the layer so that they are error-free, in sequence and with no omission or duplication. Once this service is guaranteed, their data contents are then stripped and passed to higher layers.

Three COPs, which are recursively related to each other, are presently defined. In order of increasing complexity they are:

(1) COP-0

COP-0 operates on the principle of sequential frame acceptance and retransmission, without frame sequence numbering. The FOP initiates the transmission of TC Frames whose sequence numbers are not used. The FARM only accepts frames if they are received without detected error. As soon as an error is encountered, the FARM enters a lockout condition and rejects all subsequent frames until reset by a Control Command from the FOP. The FOP monitors a CLCW counter, generated by the FARM, that indicates how many good frames were accepted. When it observes the FARM in lockout, it uses this counter to compute how far to back up, sends an unlock command, and begins retransmission.

(2) COP-1

COP-1 operates on the principle of sequential frame acceptance and retransmission, with frame sequence numbering. The FOP initiates the transmission of TC Frames whose sequence numbers are arranged in upcounting sequential order. The FARM only accepts frames if their sequence numbers match the expected upcounting order. As soon as a sequence error is encountered, the FARM rejects all subsequent frames whose sequence numbers do not match the expected order. The FOP monitors the CLCW to determine if frames are being rejected, and if so backs up and retransmits the series of frames, beginning with the frame whose sequence number matches the number which the FARM is expecting.

(3) COP-2

COP-2 operates on the principle of sequence-independent frame acceptance and selective retransmission, with frame sequence numbering. The FOP initiates the transmission of TC Frames whose sequence numbers are originally arranged in upcounting sequential order. Although nominally expecting the received frames to be in sequential order, the FARM will accept any frame whose sequence number falls within certain allowable windows. Any discontinuities in the received sequence are noted by the FARM, and the sequence numbers of detected "missing" frames are reported to the FOP via telemetered CLCWs. The FOP then schedules the retransmission of these missing frames at an opportune time.

Since the numbering of frames is a key feature of COP-1 and COP-2, it is important to understand the terminology which is used within the CCSDS Recommendations:

- (1) The FOP, which is the numbering authority, maintains a master counter which assigns the frame sequence number. The current value of this master counter, i.e., the number which will be assigned to the NEXT TC Frame, is called V(S).
- (2) The frame sequence number which is contained within any particular transmitted TC Frame is called N(S).
- (3) The FARM maintains a counter which contains the value of the next TC Frame sequence number which it expects to receive. The current value of this counter is called V(R).
- (4) The telemetered CLCW contains reports of the observed values of V(R). The observed value of V(R), received by the FOP in a particular CLCW, is called N(R).

This relationship is summarized in Figure 3-6.

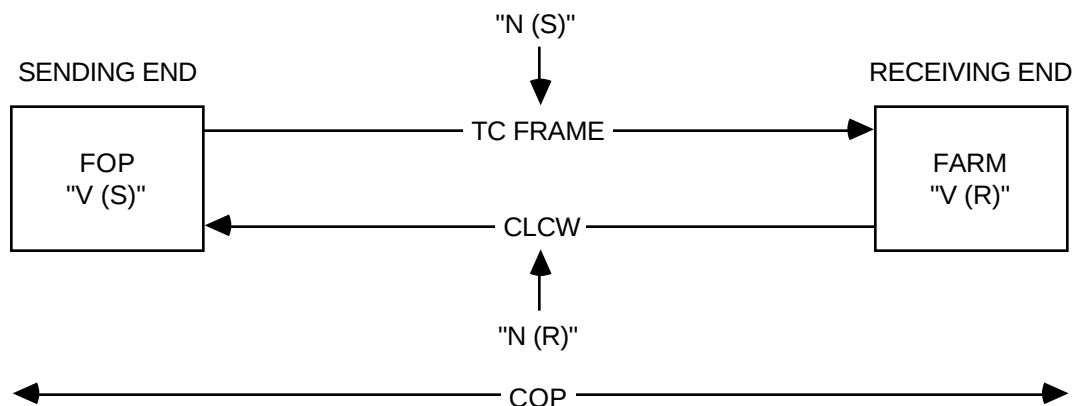


Figure 3-6: Transfer Layer Numbering Relationships

3.3 TC CHANNEL SERVICE

Operation of the TC Channel Service begins when at least one complete TC Transfer Frame is prepared for radiation through the telecommand channel to the spacecraft. The TC Channel Service provides error-controlled transmission of the TC Frame(s) through the channel. Error control is achieved via forward error detection/correction techniques. The TC Channel Service is composed of two layers, the **Coding layer** and the **Physical layer**. The operating data structures and protocols for the Channel Service are specified in Reference [4].

3.3.1 TC CODING LAYER

The basic service of the TC Coding layer is to provide for the reliable delivery of TC information bits across the physical medium to the spacecraft. Figure 3-7 depicts the activities and interfaces of the TC Coding layer.

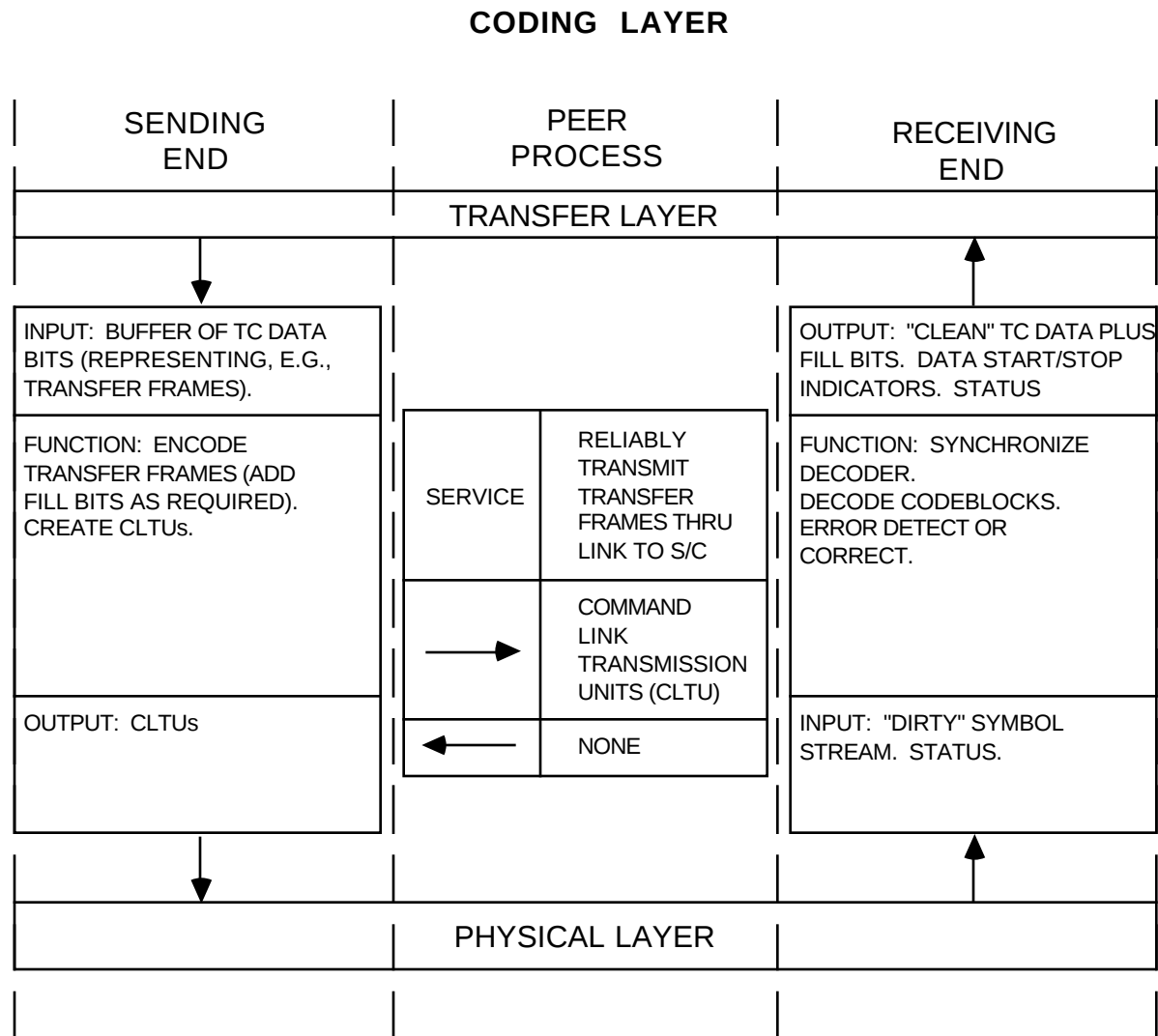


Figure 3-7: TC Coding Layer

Inputs to the sending end of the Coding layer are buffers of TC information bits from the layer above. Each buffer corresponds to one or more serial, back-to-back TC Transfer Frames. The information bits are encoded, piece by piece, into short fixed length TC Codeblocks, whose format and encoding technique is specified in Reference [4]. Each Codeblock contains parity bits that provide error detection or correction capabilities for the information bits. Fill bits may be added by the Coding layer to complete the last Codeblock.

The sequence of TC Codeblocks (i.e., the symbol representation of one or more TC Frames plus any appended fill) is then encapsulated into a Command Link Transmission Unit (CLTU). The boundaries of the CLTU are delimited for the receiving end of the Coding layer by the Start and Tail sequences. The delimited CLTUs are passed to the layer below, the TC Physical layer, for modulation onto the space data channel.

At the receiving end of the TC Coding layer, a "dirty" (potentially corrupted by channel noise) symbol stream plus control information (e.g., whether the physical channel is active or inactive) is received from the layer below. Searching for the Start sequence, the Coding layer finds the boundaries of the CLTU, synchronizes the decoder with the TC Codeblocks, and decodes them. The decoder may operate in an error-detecting-only mode, or may optionally perform error correction. If no errors are detected, or (optionally) if errors are detected and corrected, the Coding layer passes "clean" octets of decoded TC data to the layer above (including any appended fill): CLTU Start and Tail Sequences, which are not decodable codeblocks, are not transferred. Should an (optionally uncorrectable) error be estimated to have occurred within any TC Codeblock within a given sequence, the remainder of the sequence is discarded and no further data are passed to the layer above until the Coding layer is reset by the detection of another Start sequence. There are no reporting mechanisms between the receiving and sending ends of the Coding layer.

3.3.2 TC PHYSICAL LAYER

The service of the TC Physical layer is to provide a physical connection, via radio signals, between the transmitting station and the receiving spacecraft. Figure 3-8 depicts the activities and interfaces of the TC Physical layer.

Inputs to the sending end of the Physical layer are CLTUs, plus control information from the layer above defining the requested transmission services. The Physical layer controls the activation and deactivation of the physical channel by invoking various "Physical Layer Operations Procedures" (PLOPs).

A PLOP consists of sequential application of different "Carrier Modulation Modes" (CMMs). The CMMs include an unmodulated carrier, a carrier modulated with an Acquisition sequence, a carrier modulated with TC symbols corresponding to one CLTU, and a carrier modulated with an Idle sequence. Using an appropriate PLOP, the CLTUs are radiated to the spacecraft as physical waveforms.

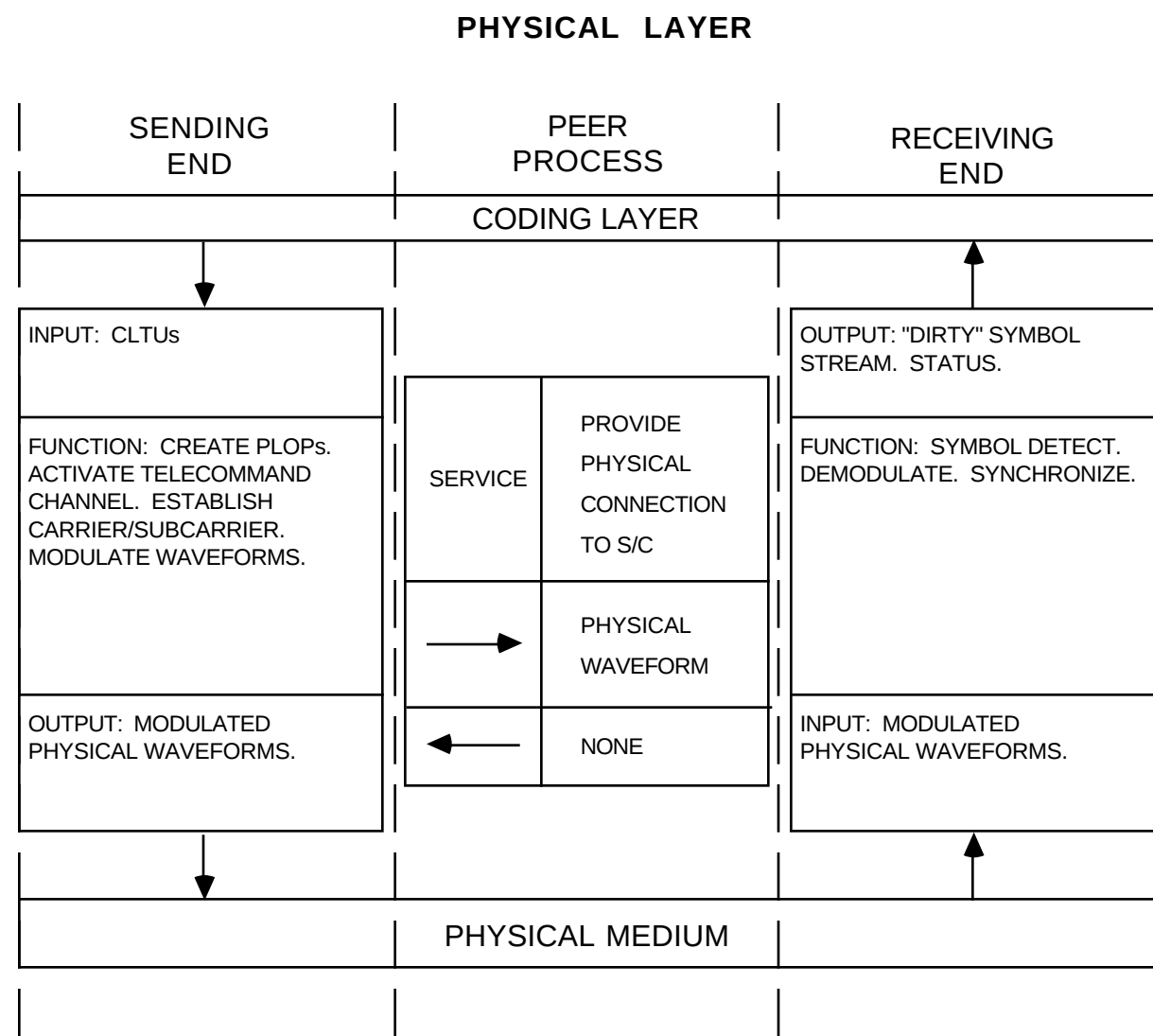


Figure 3-8: TC Physical Layer

At the receiving end of the TC Physical layer, the modulated radio frequency waveforms are received, detected, demodulated, and symbol-synchronized: the Acquisition sequence provides a preamble for synchronization purposes. The synchronized "dirty" symbol stream is delivered to the layer above, along with control information describing the status of the rf processes.

3.4 INTER-LAYER DATA EXCHANGE

The present set of CCSDS Recommendations for telecommand deals primarily with the specification of the layered architecture and the data structures and protocols which operate ACROSS each layer. The mechanisms for transferring TC data and their associated control

instructions BETWEEN the layers are currently left unspecified. However, the CCSDS is currently developing a concept for a general set of "standard data interchange structures" (Reference [9]) which could facilitate such inter-layer communication, particularly at the sending end of the TC System. Instances of standard data interchange structures known as "Standard Formatted Data Units" (SFDUs) will probably be developed to perform the interconnection of the sending-end layers: at present these are left as potential items of future work for the CCSDS.

It should also be noted that the layered hierarchy does not also imply that the time-ordered FLOW of operations through the layers is necessarily sequential. For instance, it is perfectly valid to pre-assemble and pre-number TC Frames, pre-encode them, batch them into CLTUs and then put the prefabricated CLTUs "on the shelf" for later radiation under control of the Transfer layer FOP and the Physical layer PLOP. The inter-layer control instructions must accommodate such non-time-sequential operations.

3.5 INTER-AGENCY CROSS-SUPPORT SERVICES

A major feature of the layered CCSDS TC System architecture is its potential for providing a significantly more comprehensive level of cross support between Agencies than is possible at present, thus enabling the development of simple and cost-effective interfaces for the wide range of international space missions which are anticipated in the future. However, the present CCSDS Recommendations have not addressed the physical implications of cross support.

The CCSDS has established a systems panel to study and recommend the various inter-Agency cross-support gateways and service access points. The current status of this work may be found in Reference [10].

ANNEX A
ACRONYMS AND TERMINOLOGY

ACRONYMS

CCSDS:	CONSULTATIVE COMMITTEE FOR SPACE DATA SYSTEMS
CLCW:	COMMAND LINK CONTROL WORD
CLTU:	COMMAND LINK TRANSMISSION UNIT
CMD:	COMMAND
CMM:	CARRIER MODULATION MODE
COP:	COMMAND OPERATION PROCEDURE
FARM:	FRAME ACCEPTANCE AND REPORTING MECHANISM
FOP:	FRAME OPERATION PROCEDURE
HDR:	HEADER
ID:	IDENTIFIER
MAP:	MULTIPLEXER ACCESS POINT
N(R):	THE VALUE OF V(R) WHICH IS OBSERVED BY THE FOP IN A PARTICULAR CLCW
N(S):	THE SEQUENCE NUMBER ASSIGNED BY THE FOP TO A PARTICULAR TRANSMITTED TC FRAME
PKT:	PACKET
PLOP:	PHYSICAL LINK OPERATIONS PROCEDURE
RF, rf:	RADIO FREQUENCY
S/C:	SPACECRAFT
SEG:	SEGMENT
ST SEQ:	START SEQUENCE
TC:	TELECOMMAND
TLM:	TELEMETRY
VC:	VIRTUAL CHANNEL
V(R):	THE NEXT EXPECTED TC FRAME SEQUENCE NUMBER; A COUNTER MAINTAINED BY THE FARM
V(S):	THE SEQUENCE NUMBER WHICH THE FOP WILL ASSIGN TO THE NEXT TRANSMITTED TC FRAME

TERMINOLOGY

ACCEPT:

Within the Transfer layer, recognition by the receiving end that a TC Frame has passed the validation and acceptance test criteria as programmed into the Frame Acceptance and Reporting Mechanism.

APPLICATION PROCESS LAYER:

The upper layer of the Telecommand Data Management Service.

CHANNEL SERVICE:

In the space data systems layered service architecture, the bottom service of the Telecommand System. Among its services it delivers the encoded bits of a buffer of transfer frames across the physical communications link under error-controlled conditions.

CLEAN:

Data which are declared to be error free within the error detection and (optional) error correction capabilities of the TC Coding layer.

CODEBLOCK:

The protocol data unit of the TC Coding layer. A TC Codeblock contains the encoded symbol representation of a small set of contiguous TC information bits.

CODING LAYER:

The upper layer of the TC Channel Service.

COMMAND:

An instruction sent from a user to a receiving application process in space in order to effect a change in that process.

COMMAND DIRECTIVE:

A machine-interpretable representation of a user-desired command action.

COMMAND LINK CONTROL WORD:

The TC Transfer layer protocol data unit for telecommand reporting, which is embedded in the trailer of a CCSDS Telemetry Transfer Frame. It conveys status information from the receiving end to the sending end of the TC Transfer layer.

COMMAND LINK TRANSMISSION UNIT:

Within the Coding layer, the protocol data unit which carries buffers of error-protected symbols (corresponding to one or more encoded Telecommand Transfer Frames) during transfer through the data channel to the spacecraft.

COMMAND OPERATION PROCEDURE (COP):

A sequence of procedural activities designed to assure the reliable, error-controlled delivery of Telecommand Transfer Frames. Each COP comprises a Frame Operation Procedure operating within the sending end and a Frame Acceptance and Reporting Mechanism operating within the receiving end.

CONTROL COMMAND:

A special, dedicated TC Transfer Frame containing control information to set up the receiving parameters of the spacecraft end of the TC Transfer layer.

CONTROL INSTRUCTION:

A data object which is passed between layers within the TC System in order to set up the parameters of data transfer.

DATA MANAGEMENT SERVICE:

In the space data systems layered telecommand architecture, the top service of the Telecommand System. It includes the primary facilities for interfacing the user with the systems used to communicate telecommands. Its bottom layer provides a protocol data unit known as a Telecommand Packet, which provides data formatting services so that command data may be transported between user application processes.

DATA ROUTING SERVICE:

In the space data systems layered telecommand architecture, the middle service of the Telecommand System. It provides a fundamental service within the TC System by guaranteeing the delivery of TC data from the sending to the receiving ends of the ground-to-space data link.

DELIVERY:

The process of passing transported telecommand data across the interface to the Application Process layer at the receiving end of the TC System.

DELIVERY CONDITIONS:

Control instructions, generated by the Application Process layer, which specify the parameters and conditions that are required to exist within lower layers in order to perform the delivery of telecommands from the sending to the receiving end of the TC System.

EXECUTION:

The act of effecting a commanded change within a spacecraft application process, in response to a telecommand which has been delivered to that process.

FILE:

An ordered aggregation of interrelated Telecommand Packets corresponding to a single, well defined spacecraft activity. A TC File has three distinguishing characteristics: 1) it has a File name; 2) it has a pre-defined length; and 3) it must be delivered intact and complete before being released for execution.

MULTIPLEXER ACCESS POINT (MAP):

An input port to the TC Segmentation layer which enables all user data units who are members of the sequence present at that port to be uniquely identified. Use of MAPs permits different streams of user data to be multiplexed together onto one Virtual Channel for flow control purposes.

OCTET:

An 8-bit word consisting of eight contiguous bits.

PACKET:

The protocol data unit of the TC Packetization layer which facilitates the end-to-end transport of command application data. The application data are encapsulated within a leading packet header.

PACKETIZATION LAYER:

The bottom layer in the Telecommand Data Management Service.

PHYSICAL LAYER:

The bottom layer of the TC Channel Service.

PHYSICAL LAYER OPERATION PROCEDURE (PLOP):

A sequence of procedural activities designed to activate and deactivate the physical telecommand channel by invoking radio frequency carrier and modulation techniques.

PROTOCOL:

A set of standard rules and procedures, plus their accompanying format conventions, that define the orderly exchange of information between peer entities within a given layer of the TC System.

RELIABLE:

Meeting the data quality, quantity, continuity, and completeness performance criteria which are specified for the Telecommand System.

SEGMENT:

The protocol data unit of the TC Segmentation layer which facilitates breaking long user data units into shorter, communications-oriented pieces and multiplexing them together for flow control purposes.

SEGMENTATION LAYER:

The upper layer of the TC Data Routing Service.

SESSION:

A period of time throughout which the sending and receiving ends of the TC System communicate for the purpose of transferring TC data.

SYMBOL:

A serial representation of bits, or binary digits, which have been encoded to protect them against transmission induced errors.

SYSTEM MANAGEMENT LAYER:

The middle layer of the Telecommand Data Management Service.

TELECOMMAND:

A generic term used to describe command data during the time that they are being telecommunicated to the spacecraft.

TELECOMMAND SYSTEM:

The end-to-end system of layered space mission telecommunication services which exist to enable a user to send commands, in a reliable and transparent error-controlled environment, to receiving elements in space.

TRANSFER FRAME:

The protocol data unit of the TC Transfer layer, which facilitates the transfer of TC data to a spacecraft through a space data link.

TRANSFER LAYER:

The lower layer of the TC Data Routing Service.

TRANSPARENT:

As viewed by the user, the invisible and seemingly direct (virtual) transfer of command data from the command originating point to the controlled process.

USER:

A human or machine-intelligent process which directs the progress of a space mission by sending commands to a space system.

VALIDATION:

A process performed at the receiving end of the Transfer layer to check the integrity of a TC Transfer Frame.

VIRTUAL CHANNEL:

Within the TC Data Routing Service, an identifier which permits all Transfer Frames who are members of a given sequence to be uniquely identified. It permits multiple user data types to be multiplexed together so that they may share the finite capacity of the single physical space data channel.

ANNEX B

TELECOMMAND TRANSFER FRAME

ERROR DETECTION

ENCODING/DECODING GUIDELINE

Purpose:

This Annex provides a description of the error detection encoding and decoding procedures which may be used in association with the optional Frame Error Control field of the Telecommand Transfer Frame.

B-1 CODING FOR ERROR DETECTION IN TRANSFER FRAMES

This Annex describes the error detection encoding/decoding procedure that is recommended for Transfer Frame coding.

The code specifies the same generator polynomial used by HDLC (ISO), ADCCP (ANSI), V.41 (CCITT), etc. It has the following capabilities when applied to an encoded block of less than 32,768 (2^{15}) bits:

- (1) All error sequences composed of an odd number of bit errors are detected.
- (2) All error sequences containing at most two bit errors anywhere in the encoded block will be detected.
- (3) If a random error sequence containing an even number of bit errors (greater than or equal to 4) occurs within the block, the probability that the error will be undetected is approximately 2^{-15} (or approximately 3×10^{-5}).
- (4) All single error bursts spanning 16 bits or less will be detected provided no other errors occur within the block.

B-1.1 ENCODING PROCEDURE

The encoding procedure accepts an (n-16)-bit data block and generates a systematic binary (n,n-16) block code by appending a 16-bit Frame Check Sequence (FCS) as the final 16 bits of the codeblock. This FCS is inserted into the Frame Error Control Word of the Transfer Frame Trailer. The equation for the FCS is:

$$\text{FCS} = [X^{16} \cdot M(X) \oplus X^{(n-16)} \cdot L(X)] \text{ modulo } G(X)$$

where

$M(X)$ is the (n-16)-bit message to be encoded expressed as a polynomial with binary coefficients

$L(X)$ is the presetting polynomial given by:

$$L(X) = \sum_{i=0}^{15} x_i \text{ (all "1" polynomial of order 15)}$$

$G(X)$ is the generating polynomial given by:

$$G(X) = X^{16} + X^{12} + X^5 + 1$$

n is the number of bits in the encoded message

$\oplus$ is the modulo 2 addition operator (Exclusive OR)

Note that the encoding procedure differs from that of a conventional cyclic block encoding operation in that:

The $X^{(n-16)} \cdot L(X)$ term has the effect of presetting the shift register to an all "1" state prior to encoding.

B-1.2 DECODING PROCEDURE

The error detection syndrome, $S(X)$, is given by

$$S(X) = [X^{16} \cdot C^*(X) \oplus X^n \cdot L(X)] \text{ modulo } G(X)$$

where $C^*(X)$ is the received block in polynomial form and $S(X)$ is the syndrome polynomial which will be zero if no error is detected and non-zero if an error is detected.

B-2 POSSIBLE IMPLEMENTATION

A possible implementation of the above-defined encoding/decoding procedure is described below.

B-2.1 ENCODING

Figure B-1 shows an arrangement for encoding using the shift register. To encode, the storage stages are set to "one", gates A and B are enabled (closed), gate C is inhibited (open), and $(n-16)$ message bits are clocked into the input. They will appear simultaneously at the output. After the bits have been entered, the output of gate A is clamped to "zero", gate B is inhibited, gate C is enabled, and the register is clocked a further 16 counts. During these counts the required check bits will appear in succession at the output.

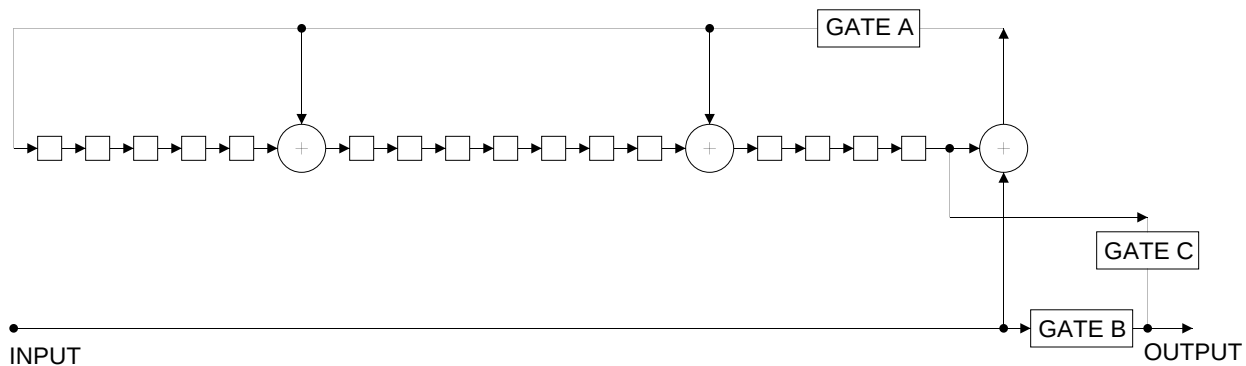


Figure B-1: Encoder

B-2.2 DECODING

Figure B-2 shows an arrangement for decoding using the shift register. To decode, the storage stages are set to "one" and gate B is enabled. The received n -bits [the $(n-16)$ message bits plus the 16 bits of the FCS] are then clocked into the input. After $n-16$ counts, gate B is inhibited, the 16 check bits are then clocked into the input, and the contents of the storage stages are then examined. For an error-free block, the contents will be zero. A non-zero content indicates an erroneous block.

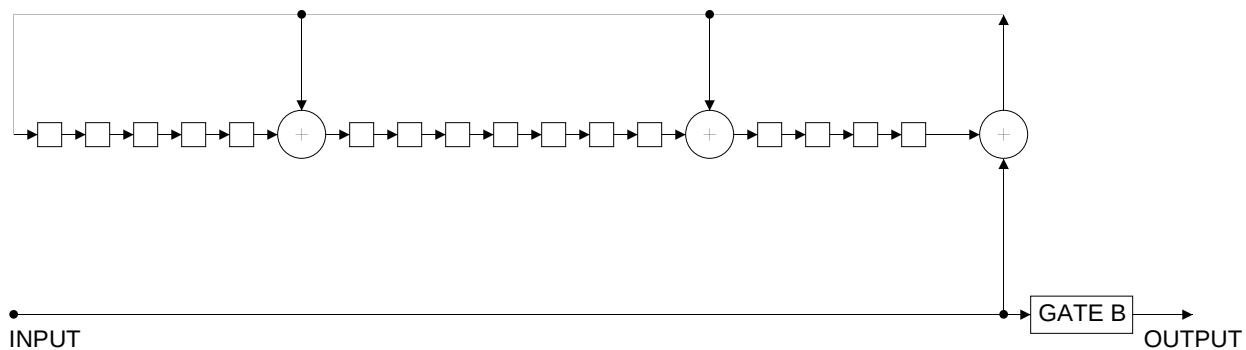


Figure B-2: Decoder

ANNEX C

DATA PROTECTION CONCEPT

Purpose:

This Annex defines a concept for the protection of Telecommand data sets so that security measures may be implemented if required by a particular mission.

Status:

This Annex is currently under development by the CCSDS.

For many missions, there is a firm requirement to prevent intentional or accidental commanding of the spacecraft by an unauthorized party. Some missions may also have user requirements to render the application data private so that they cannot be interpreted by unauthorized users. The methods which are implemented within the Telecommand System to satisfy these requirements are called Data Protection mechanisms.

Data Protection may be provided by physical or logical mechanisms. Physical mechanisms involve restricting personnel and terminal access to the networks through which command data flow. Logical mechanisms involve transformations of the command data in a manner which makes unauthorized manipulation or interpretation extremely difficult.

The necessarily open nature of most space data networks makes physical protection of the entire network impractical. In this environment, the Data Protection mechanisms must permit operation identical to "clear-text" communications flow through the mission's data networks insofar as provision of normal network telecommunications services are concerned. The CCSDS has therefore adopted two techniques which facilitate providing logical Data Protection within the Telecommand System: these are **ENCRYPTED AUTHENTICATION** and **DATA ENCRYPTION**.

These techniques provide means to ensure that either:

- (1) a command comes from an authorized source and that an unauthorized party cannot modify the information which is conveyed within its structure (Encrypted Authentication) and/or
- (2) that an unauthorized user cannot interpret its meaning (Data Encryption).

A given system may use Encrypted Authentication only, or both Encrypted Authentication and Data Encryption together.

(1) Encrypted Authentication

The CCSDS concept for providing Encrypted Authentication is that the sending end of the authentication process generates a unique authentication word by sending an encrypted block. This Encrypted Authentication word accompanies each clear-text block (user data unit) that is transmitted. The receiving equipment recognizes the Encrypted Authentication word by performing complementary decryption and checking functions, thus fully establishing the authenticity of the received user data unit. When Encrypted Authentication alone is used, the command application data themselves are not modified.

The Encrypted Authentication word is attached to the user data unit before transport to the spacecraft, and when received and recognized, an appropriate status message must be telemetered in clear-text back to the sending end for verification. This feature enables the system to recover from an interruption of the communications channel.

(2) Data Encryption

Data Encryption, which is a logical mechanism for providing Data Protection, implies that the command application data are transformed (rendered secret) to make them unintelligible to an unauthorized observer. A system using both Data Encryption and Encrypted Authentication thus differs from a system using only Encrypted Authentication since in the latter the application data are not transformed. In a Data Encryption system, the telecommand application data are transformed by applying special algorithms and can only be interpreted after processing by a complementary process at the receiving end.

The CCSDS makes no recommendation for the choice of an Encrypted Authentication or Data Encryption algorithm, or for the associated management procedures. The choice of algorithms is therefore left to the participating Agencies. However, the CCSDS does have some system-level requirements which are intended to ensure that the Encrypted Authentication or Data Encryption system characteristics are consistent with interoperability. These requirements are the following:

- (a) The command Encrypted Authentication and/or Data Encryption system shall operate normally within the Packetization, and/or Segmentation, and/or Transfer layers. For those missions which do not implement the TC Packet, Segment, or Transfer Frame data structures, the Encrypted Authentication or Data Encryption system should operate within the corresponding layers of the non-standard system. A standardized mechanism for implementing the system at the sending and receiving ends of the Packetization, Segmentation, and Transfer layers is recommended as being the most secure and manageable.
- (b) The Encrypted Authentication or Data Encryption mechanism shall not interfere with the standard telecommand verification techniques which operate within the CCSDS TC Transfer layer, and shall permit recovery from the effects of errors or interruptions in the communications process.
- (c) If implemented above the TC Packetization layer, the Encrypted Authentication word or transformed portion of the data shall be included completely within the Application Data field of the TC Packet.
- (d) If implemented above the TC Segmentation layer, the Encrypted Authentication word or transformed portion of the data shall be included completely within the Segment Data Field of the TC Segment.
- (e) If implemented above the TC Transfer layer, the Encrypted Authentication word or transformed portion of the data shall be included completely within the "Frame Data" field of the TC Transfer Frame (AD or BD frames only); if implemented within the TC Transfer layer, these shall be included completely

within the "Qualifying Data" field of a TC Transfer Frame (Type BC) which carries a Control Command.

- (f) The selected Encrypted Authentication or Data Encryption technique shall be transparent to the lowest layers of the TC System; i.e., the TC Coding and TC Physical layers. The Encrypted Authentication or Data Encryption technique shall not require the implementation of any physical security mechanisms within these lowest layers.

It should be noted that since bulk-encryption of Telecommand data at the Physical layer does not allow any interoperability except at the bit level, it is not a CCSDS-recommended technique.

ANNEX D
TELECOMMAND SYSTEM
PERFORMANCE NOTES

Purpose:

This Annex provides information on the performance that may be achieved for the various telecommand strategies and options given in the Recommendation for Telecommand.

Status:

This Annex is currently under development by the CCSDS.

D-1 INTRODUCTION

This Annex discusses the Telecommand (TC) Performance which may be obtained using the data units, techniques, and strategies described in the CCSDS Recommendation for Telecommand, Part 1: Channel Service (Reference [4]) and Recommendation for Telecommand, Part 2: Data Routing Service (Reference [3]). Performance data are presented to enable the system engineer to select values of relevant coding parameters and operational strategies so that system performance requirements may be satisfied. Telecommand operating strategies are described for different environments, as well as the procedures that are elements of the strategies.

D-2 PERFORMANCE CRITERIA AND NATURE OF THE PROBLEM

The objective of the Telecommand Service is to provide a highly reliable uplink service. "Reliable" service is considered to be achieved when the following two performance criteria are simultaneously met by the overall telecommand system:

(1) TC Frame Deletion Rate

A maximum of one telecommand frame is deleted (rejected) for every 1000 frames transmitted. This operating point is defined to be "Command Threshold".

(2) TC Frame Undetected Error Rate

A maximum of one telecommand frame for every 10^9 telecommand frames transmitted is erroneously accepted (that is, contains one or more undetected bit errors).

It should be noted that since performance is measured in terms of frames, considerations discussed herein extend through the physical and coding layers of the Channel Service and the transfer layer of the Data Routing Service.

D-2.1 Performance Components

The basic accounting unit of Telecommand is therefore the TC frame. To meet these performance objectives for the frame, the Channel Service and Data Routing Service specify standard techniques for constructing and handling the TC frame and its components:

- (1) To achieve bit acquisition (synchronization).**
- (2) To delimit the beginning of a continuum of bits (CLTU) comprising the telecommand bit stream.**

- (3) To encode the bit stream into a series of standard codeblocks which can provide error detection and/or correction.
- (4) To delimit the beginning and end of each telecommand frame.
- (5) To provide an optional error check over each telecommand frame to improve protection against undetected errors.
- (6) To delimit the end of a CLTU to prepare the spacecraft decoder to recognize the start of the next continuum (CLTU).

In addition, Reference [4] describes certain optional strategies (e.g., no errors vs. one error allowed in the CLTU start sequence). The performance of each of these is also discussed.

STRATEGIES

Reference [4], Section B-4, recommends two alternative strategies for combining telecommand options when a CLTU is sent. These are:

Strategy 1:

- | | | |
|------------|---|--|
| START | - | CLTU Start Sequence with no errors allowed |
| CODEBLOCKS | - | Decoded in Triple Error Detection mode |
| FINISH | - | Tail Sequence Codeblock Rejection or Stop modulation |

Strategy 2:

- | | | |
|------------|---|---|
| START | - | CLTU Start Sequence with 0 or 1 error allowed |
| CODEBLOCKS | - | Decoded in Single Error Correction, Double Error Detection mode |
| FINISH | - | Tail Sequence Codeblock Rejection or Stop modulation |

In general, Strategy 1 may be used when it is important to reduce the undetected error rate, while Strategy 2 may be used to reduce the operational complexities of retransmission.

Each of the data units and their performance will be reviewed in the following material. References [4] and [3] specify the details of constructing the above elements; this Annex describes how the on-board telecommand system handles each element and the performance that may be obtained. Throughout this note a binary symmetric telecommand channel with additive white gaussian noise is assumed.

D-2.2 On-Board Telecommand Logic

The Receiving End (i.e., spacecraft) telecommand decoder state diagram, upon which these discussions are based, is shown in Figure 3-4 of Reference [4] and is duplicated in this report as Figure D-1.

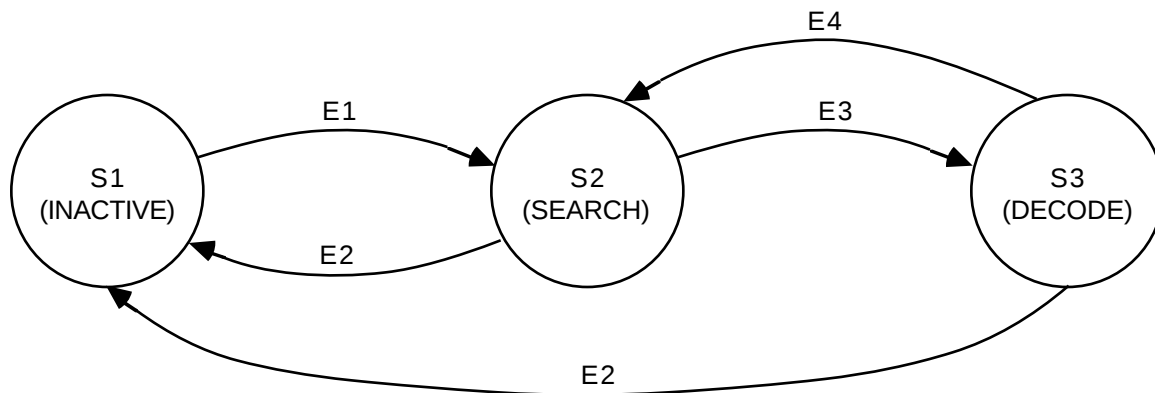


Figure D-1: TC Decoder State Diagram

Inactive State. The initial state for the TC channel is State 1 (S1), the INACTIVE state, where no bit modulation is detected. When a TC bit stream is detected (telecommand modulation applied and bit synchronization achieved), Event 1 (E1) occurs, CHANNEL ACTIVE. If the TC signal is lost or there is a loss of bit lock, Event 2, CHANNEL INACTIVE, occurs, and the spacecraft decoder returns to the INACTIVE state (S1).

Search State. When E1 occurs, the logic goes into the SEARCH state (S2). The unit that governs this event is the CLTU Start Sequence. The bit stream is searched for the CLTU Start Sequence; when the pattern has been detected, the decoder declares Event 3 (E3), START SEQUENCE FOUND, and assumes the next bit delimits the beginning of the first codeblock of a continuum of codeblocks of the CLTU. (Note: a codeblock is a codeword plus a filler bit.)

The probability of E3 occurring depends upon: 1) the decoder actually being in the SEARCH state when the start sequence arrives; 2) the bit error rate (BER) of the channel; and 3) the decoding strategy used. If, at this point, the TC signal is lost or there is a loss of bit lock, E2 occurs and the telecommand decoder returns to S1.

Decode State. Assuming E3 has occurred, the decoder enters the DECODE state, S3. The data unit that governs the DECODE state is the TC Codeblock. All TC Codeblocks are received and decoded in either the Triple Error Detection (TED) mode, or the Single Error Correction (SEC) mode. The use of mixed decoding modes may require additional coordination and more complex analysis. The data contents of decoded (valid) codeblocks are transferred to the layer above (i.e., the TC Frame Layer). The probability of the telecommand

decoder remaining in this state is a function of the decoding strategy, the BER, the length of the codeword (n), in bits, and the number of codewords in the CLTU.

Return from Decode State. If, during the decoding process, the decoder rejects a codeblock due to errors, no data from this codeblock are transferred to the layer above. This situation corresponds to Event 4 (E4), CODEBLOCK REJECTION, which returns the decoder to the SEARCH state (S2).

To end a CLTU, a Tail Sequence is included. The Tail Sequence is a codeblock (of the same length as all other codeblocks in the stream) having a unique pattern constructed in such a way to fail the decoder parity check and cause a CODEBLOCK REJECTION (E4), thereby interrupting the telecommand continuum. No further codeblocks are decoded, no further transfer of codeblock contents to the frame layer is possible, and the decoder logic returns to the SEARCH state (S2). Note that the ONLY function of the Tail Sequence is to force the decoder logic to the SEARCH STATE at the end of a CLTU: the Tail Sequence should not be used to delimit the end of a frame. This is because, in general, 1) there may be more than one frame in the CLTU, and 2) a frame that is not long enough to fill the last codeblock must be followed by fill bits (which are not part of the frame) to complete that codeblock.

If, during the decoding process, the physical layer signal is lost (carrier, modulation or bit sync), event E2, CHANNEL INACTIVE, occurs. Upon this event, the decoder returns to the INACTIVE state, S1.

Assembling the Frame. If all codeblocks comprising a complete transfer frame are successfully decoded, the frame layer recognizes that the frame it has been assembling from each codeblock is complete when the number of octets received equals one more than the count presented in the "Frame Length" field of the Transfer Frame Header. The frame can then be transferred to the addressee. Other frames in the CLTU are similarly transferred upon completion. If the continuum of codeblocks from the decoder is interrupted (i.e., CODEBLOCK REJECTION has been declared for whatever reason) and the frame length received does NOT yet equal one more than the count in the "Frame Length" field, that frame is rejected by the frame layer. Further action by the frame layer to recover the frame is dependent on the Command Operations Procedure (COP) in use. This process is more fully described in Reference [3]. Other checks on the frame, such as testing for previously undetected errors, may also be made at the frame layer before declaring acceptance or rejection, and before forwarding to the addressee.

D-3 FACTORS AFFECTING FRAME REJECTION RATE

Each of the factors of performance of frame rejection rate are detailed below. In subsequent sections, the performance for several different CLTU organizations is given.

D-3.1 Bit Synchronization Factor

Initially, the on-board decoder is in the INACTIVE state. When a signal first appears (subsequent to achieving rf carrier lock), it will contain an acquisition pattern consisting of a series of alternating "ones" and "zeros". This pattern has the maximum transition density so as to provide the fastest lock-up time for the on-board bit synchronizer. The preferred length of 128 bits was chosen to provide 0.9999 probability of acquisition of bit sync based on experience with a number of hardware implementations operating at the command threshold level.¹ Clearly, this length may be modified as needed to suit different hardware characteristics or channel bit error rates (such as, for example, a noise-free channel used during ground testing). When bit synchronization has been achieved, the decoder leaves the INACTIVE state and enters the SEARCH state.

BECAUSE THE PROBABILITY OF ACHIEVING BIT SYNCHRONIZATION IS PRIMARILY HARDWARE-DEPENDENT, THIS ANALYSIS WILL ASSUME THAT BIT SYNCHRONIZATION HAS ALREADY BEEN ACHIEVED.

D-3.2 CLTU Start Sequence Factor

Once the on-board decoder is in the SEARCH state, it begins looking for the required CLTU Start Sequence. The Start Sequence provides two functions: 1) to resolve the ambiguity between a "one" and a "zero" if needed (e.g., when NRZ-L symbol representation is used), and 2) to delimit the beginning of the CLTU.

The Start Sequence is a fixed-pattern marker 16 bits long. It follows immediately after the acquisition sequence and before the first codeblock of the CLTU. As a consequence of recognizing the CLTU Start, the start of the first codeblock is then also delimited, since it immediately follows the start sequence. In decoding serially transmitted block codes, it is usually necessary to know the point at which the block starts and its length. The codeblock length which has been chosen for the mission must be known *a priori*, and must remain constant.

Two operating strategies for recognizing the start sequence are presented in Reference [4]: In the first strategy (denoted by subscript A), the decoder requires that the entire 16 bits be received without error. In the second (denoted by subscript B), the decoder allows one of the 16 bits to be in error and will still declare the start of a CLTU.

For the first strategy (that is, all 16 bits must be correct to declare a CLTU start) the probability of rejecting (missing) a CLTU start is found by simply taking the probability that one or more bit errors may fall on any of the 16 bits of the start sequence:

¹ For example, the probability of the TDRSS transponder achieving bit lock in response to this acquisition sequence is equal or greater than 0.9999.

$$\begin{aligned}
 \langle \text{Prob. of rejecting a START, no errors allowed} \rangle &= P_{sA} \\
 &= 1 - (1 - p)^{16} \quad \text{[EQ. A]}
 \end{aligned}$$

where p is the channel bit error rate.

For the second strategy (in which one bit error is allowed) it is necessary for TWO or more bit errors to appear in the start sequence before it will be rejected. In this case,

$$\begin{aligned}
 \langle \text{Prob. of rejecting a START, 1 error allowed} \rangle &= P_{sB} \\
 &= 1 - [(1 - p)^{16} + 16p(1-p)^{15}] \quad \text{[EQ. B]}
 \end{aligned}$$

These values are tabulated in Table D-1.

**Table D-1: Probability of Rejection of CLTU Start Sequence
(for case where no errors are allowed (P_{sA}) and
one error allowed (P_{sB}))**

Case	Channel Bit Error Rate		
	10^{-4}	10^{-5}	10^{-6}
P_{sA}	1.60×10^{-3}	1.60×10^{-4}	160×10^{-5}
P_{sB}	1.20×10^{-6}	1.20×10^{-8}	1.20×10^{-10}

P_{sA} or P_{sB} , above (depending on the strategy selected), constitutes the first factor of the overall frame rejection rate.

It should be noted that there is also the remote possibility that the proper start sequence may be missed because of a false (premature) start. The start pattern was chosen for its property that it would require at least 6 changed bits to declare such a premature start.

D-3.3 Codeblock Factor

Once CLTU Start has been recognized, the decoding process begins for the codeblocks that follow.

The code specified in Reference [4] is a (63,56) BCH code. The codeword² contains an information field of one of the lengths shown in Table D-2, followed by 7 parity bits. To complete the codeblock (which, to meet general formatting rules for ease of handling, must be an integral number of octets), a single final fill bit set to "zero" is always appended to the codeword. Normally, one TC codeblock length is selected for a mission, and all codeblocks are this length.

When decoding in the "Triple Error Detection" (TED) mode, the code has the property that it can detect one-, two- or three-bit errors. Alternatively, when decoding in the "Single-Bit Error Correction" (SEC) mode, it can correct one bit in error, and detect two bits in error within the codeblock.

Decoding is performed by the Channel Service on a continuum basis. That is, as long as each codeblock is valid (after correction, if error correction is employed) the information content of each codeblock as it is accepted continues to be passed from the Coding layer to the Transfer layer where each frame is assembled. If a codeblock failure occurs, the continuum is broken; the decoder notifies the Transfer layer and ceases transferring any further data to it.

While 64 bits is the preferred codeblock length (because it allows minimum coding overhead to achieve the given performance), it is possible to shorten the codeblock while still using the same coding algorithm. Permitted lengths for shortened codeblocks are 56, 48, and 40 bits, and are made possible by simply setting both encoder and decoder to assume the leading untransmitted octets of each codeblock are always "zero". This is called "virtual fill".

The permitted organizations of the codeblock, including the relationship between codeblock length, virtual fill, information bits, parity bits, and fill bits, are shown below:

Table D-2: Codeblock Organization

Codeblock length, bits	Virtual fill, bits	Codeword length, bits (n)	Information bits (k)	Parity bits	Fill bit
64	0	63	56	7	1
56	8	55	48	7	1
48	16	47	40	7	1
40	24	39	32	7	1

² "Codeword" refers to the code itself; for an (n,k) code, the codeword is always n bits long. "Codeblock" as used here refers to the physical implementation in the bit stream and includes the final fill bit. Codeblocks may be 40, 48, 56 or 64 bits in length.

The equation characterizing codeblock rejection using TED mode is:

$$\begin{aligned}
 &\text{<Prob. of 1 or more codeblocks} \\
 &\text{of the CLTU being detected as} \\
 &\text{in error (using TED mode)>} = P_{CA} \\
 &= 1 - [1 - p]^n]^N \qquad \qquad \qquad \text{[EQ. C]}
 \end{aligned}$$

where

- p = channel bit error rate
- n = number of bits in codeword (1 less than codeblock)
- N = number of codeblocks

For the SEC case, the equation for rejection of 1 or more codeblocks becomes:

$$\begin{aligned}
 &\text{<Prob. of 1 or more codeblock of} \\
 &\text{the CLTU being in error AND} \\
 &\text{UNCORRECTABLE (SEC mode)>} = P_{CB} \\
 &= 1 - [(1-p)^n + np(1-p)^{n-1}]^N \qquad \qquad \qquad \text{[EQ. D]}
 \end{aligned}$$

Table D-3 provides values for both P_{CA} and P_{CB} for different numbers of 64-bit codeblocks for the three different channel error rates, and these values are plotted in Figure D-2.

The codeblock factor is the second factor affecting frame rejection performance. Performance is discussed next.

**Table D-3: Probability of Codeblock Rejection
(for 64-bit codeblocks, n=63) as a Function of Number
of Codeblocks, N**

N	BER = 10^{-4}	BER = 10^{-5}	BER = 10^{-6}
P_{CA} (TED mode)			
1	6.28×10^{-3}	6.30×10^{-4}	6.30×10^{-5}
2	1.25×10^{-2}	1.26×10^{-3}	1.26×10^{-4}
4	2.49×10^{-2}	2.52×10^{-3}	2.52×10^{-4}
6	3.71×10^{-2}	3.77×10^{-3}	3.78×10^{-4}
9	5.51×10^{-2}	5.65×10^{-3}	5.67×10^{-4}
12	7.28×10^{-2}	7.53×10^{-3}	7.56×10^{-4}
16	9.59×10^{-2}	1.00×10^{-2}	1.01×10^{-3}
20	1.18×10^{-1}	1.25×10^{-2}	1.26×10^{-3}
24	1.40×10^{-1}	1.50×10^{-2}	1.51×10^{-3}
28	1.62×10^{-1}	1.74×10^{-2}	1.76×10^{-3}
32	1.83×10^{-1}	2.00×10^{-2}	2.01×10^{-3}
36	2.03×10^{-1}	2.24×10^{-2}	2.27×10^{-3}
37	2.08×10^{-1}	2.30×10^{-2}	2.33×10^{-3}
74	3.73×10^{-1}	4.56×10^{-2}	4.65×10^{-3}
110	5.00×10^{-1}	6.70×10^{-2}	6.91×10^{-3}
149	6.09×10^{-1}	8.96×10^{-2}	9.34×10^{-3}

P_{CB} (SEC mode)			
1	1.95×10^{-5}	1.95×10^{-7}	1.95×10^{-9}
2	3.90×10^{-5}	3.90×10^{-7}	3.91×10^{-9}
4	7.78×10^{-5}	7.81×10^{-7}	7.81×10^{-9}
6	1.17×10^{-4}	1.17×10^{-6}	1.17×10^{-8}
9	1.75×10^{-4}	1.76×10^{-6}	1.76×10^{-8}
12	2.33×10^{-4}	2.34×10^{-6}	2.34×10^{-8}
16	3.11×10^{-4}	3.12×10^{-6}	3.12×10^{-8}
20	3.89×10^{-4}	3.90×10^{-6}	3.91×10^{-8}
24	4.67×10^{-4}	4.69×10^{-6}	4.69×10^{-8}
28	5.44×10^{-4}	5.47×10^{-6}	5.47×10^{-8}
32	6.22×10^{-4}	6.25×10^{-6}	6.25×10^{-8}
36	7.00×10^{-4}	7.03×10^{-6}	7.03×10^{-8}
37	7.19×10^{-4}	7.22×10^{-6}	7.23×10^{-8}
74	1.44×10^{-3}	1.44×10^{-5}	1.45×10^{-7}
110	2.14×10^{-3}	2.15×10^{-5}	2.15×10^{-7}
149	2.89×10^{-3}	2.91×10^{-5}	2.91×10^{-7}

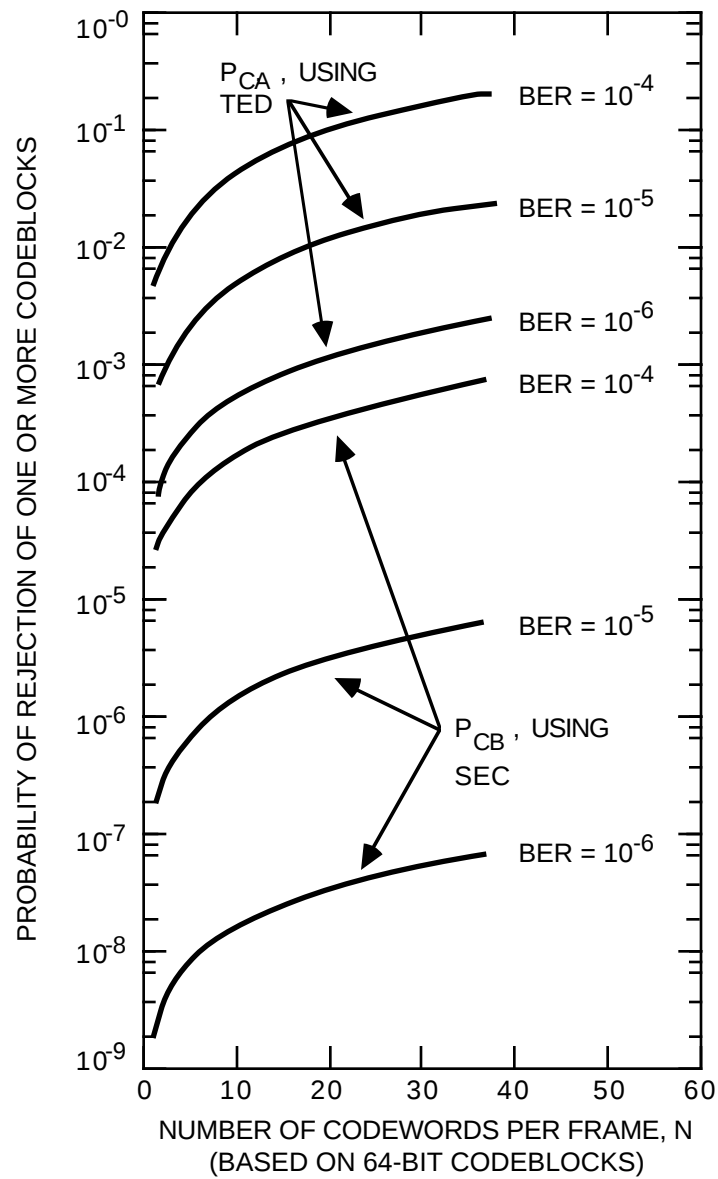


Figure D-2: Probability of Rejection of One or More Contiguous 64-Bit Codeblocks as a Function of Number of Codeblocks, N

D-4 FRAME REJECTION RATE: TYPICAL TC ORGANIZATIONS

The Telecommand Transfer Frame is the accounting entity for telecommand performance. A frame may be any integral number of octets in length, from a minimum consisting of only a primary header (5 octets or 40 bits) to the maximum number of octets that can be counted by the "Frame Length" field in the header (256 octets or 2048 bits).

The TC Frame is serially inserted into the "information" fields of as many Codeblocks as necessary. If the length of a frame is not exactly the same as the total data space of the Information fields in the required codeblocks, fill is added to the Information field of only the LAST codeblock. If more than one frame resides in a CLTU, frames are organized contiguously and any necessary fill is added only in the LAST codeblock of the CLTU.

The necessary TC building blocks are the TC Frame, CLTU, and the codeblocks. These may be organized in several different ways depending on the performance required, operational convenience, accounting convenience, etc. Three organizations are described below: One frame per CLTU; multiple frames per CLTU; and multiple CLTUs. Frame performance may be assessed by considering the performance of a sequence of codeblocks and the effect of their organization into CLTUs.

D-4.1 One Frame, One CLTU

This section deals with the organization where each frame is contained in its own CLTU, as shown in Figure D-3. A codeblock rejection anywhere in the frame will cause rejection of that frame.

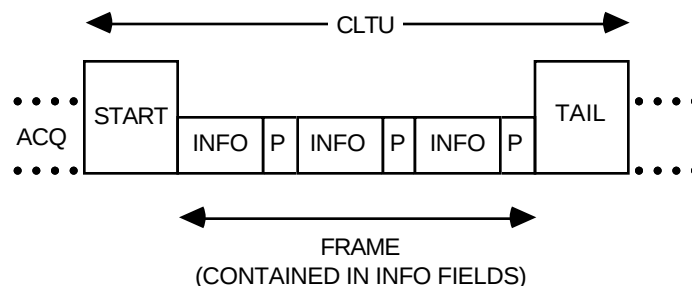


Figure D-3: Single Frame, Single CLTU Organization

The probability of frame rejection is determined from a) the probability of missing a CLTU start, OR b) the probability of finding a CLTU start AND the probability of rejecting one or more codeblocks.

For Strategy 1 (using TED mode, denoted by subscript A),

$$\begin{aligned} \text{<Prob. of frame rejection in a} \\ \text{standalone CLTU, TED mode>} &= P_{FA} \\ &= P_{SA} + (1 - P_{SA}) P_{CA} \end{aligned} \quad [\text{EQ. E}]$$

and for Strategy 2 (using SEC mode, denoted by subscript B),

$$P_{FB} = P_{SB} + (1 - P_{SB}) P_{CB} \quad [\text{EQ. F}]$$

Examples. To illustrate the range of performance obtained with this organization (one frame per CLTU), let us consider the shortest and longest permitted frame lengths. The shortest frame permitted is just a header: 5 octets or 40 bits. This frame could be organized into a single 48-, 56- or 64-bit codeblock, or two 40-bit codeblocks. The probability of rejection for such a frame is shown in Table D-4.

Table D-4: Probability of Rejection of a MINIMUM Length Frame as a Function of Codeblock Length Chosen

Code-block length, bits	Information field, bits	No. of code-blocks needed	Decoding mode	MINIMUM LENGTH FRAME		
				Probability of frame rejection for channel BER of		
				10 ⁻⁴	10 ⁻⁵	10 ⁻⁶
64	56	1	TED	7.87x10 ⁻³	7.90x10 ⁻⁴	7.90x10 ⁻⁵
			SEC	2.06x10 ⁻⁵	2.07x10 ⁻⁷	2.07x10 ⁻⁹
56	48	1	TED	7.08x10 ⁻³	7.10x10 ⁻⁴	7.10x10 ⁻⁵
			SEC	1.60x10 ⁻⁵	1.60x10 ⁻⁷	1.60x10 ⁻⁹
48	40	1	TED	6.28x10 ⁻³	6.30x10 ⁻⁴	6.30x10 ⁻⁵
			SEC	1.20x10 ⁻⁵	1.20x10 ⁻⁷	1.20x10 ⁻⁹
40	32	2	TED	9.36x10 ⁻³	9.40x10 ⁻⁴	9.40x10 ⁻⁵
			SEC	1.60x10 ⁻⁵	1.60x10 ⁻⁷	1.60x10 ⁻⁹

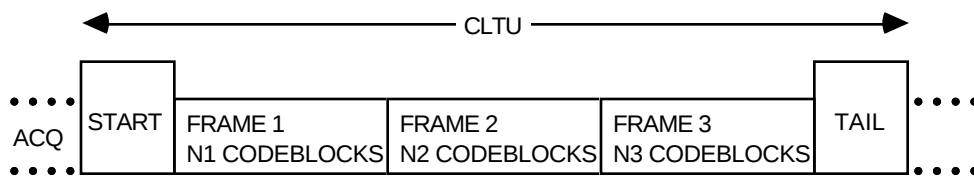
At the other extreme, the maximum frame length permitted is 256 octets or 2048 bits. Such a frame could be organized into either 40-, 48-, 56- or 64-bit codeblocks as shown in Table D-5. Tables D-4 and D-5 show how frame rejection performance varies with different parameters. It can be seen that the rejection performance is affected little by length of codeblocks, moderately by number of codeblocks, and greatly by the decoding mode.

Table D-5: Probability of Rejection of a MAXIMUM Length Frame as a Function of Codeblock Length Chosen

Code-block length, bits	Information field, bits	No. of code-blocks needed	De-coding mode	MAXIMUM LENGTH FRAME Probability of frame rejection for channel BER of		
				10 ⁻⁴	10 ⁻⁵	10 ⁻⁶
64	56	37	TED	2.09x10 ⁻¹	2.32x10 ⁻²	2.34x10 ⁻³
			SEC	7.21x10 ⁻⁴	7.24x10 ⁻⁶	7.24x10 ⁻⁸
56	48	43	TED	2.12x10 ⁻¹	2.35x10 ⁻²	2.36x10 ⁻³
			SEC	6.37x10 ⁻⁴	6.40x10 ⁻⁶	6.40x10 ⁻⁸
48	40	52	TED	2.18x10 ⁻¹	2.43x10 ⁻²	2.46x10 ⁻³
			SEC	5.61x10 ⁻⁴	5.63x10 ⁻⁶	5.63x10 ⁻⁸
40	32	64	TED	2.22x10 ⁻¹	2.48x10 ⁻²	2.51x10 ⁻³
			SEC	4.74x10 ⁻⁴	4.75x10 ⁻⁶	4.75x10 ⁻⁸

D-4.2 Multiple Frames, One CLTU

Since the CCSDS Recommendation (Reference [4]) does not limit the size of a CLTU, it is possible to have more than one frame in a single CLTU. An example of such an organization is shown in Figure D-4.

**Figure D-4: Multiple Frame, Single CLTU Organization**

The performance of multiple frames contained in a single CLTU is complicated by the fact that acceptance of each frame in the CLTU requires acceptance of the frame before it. If at any time a particular frame is rejected, frames preceding it will have been accepted, and the rejected frame and all those following are rejected. Thus it would appear prudent to base performance comparisons on the probability of rejection of the LAST frame in the CLTU, since the last frame is dependent on the performance of each of the preceding frames.

A simplification can be made if one realizes that the rejection of the LAST frame is simply dependent on the performance of the codeblock continuum through the last frame. Thus the same equations (Eqs. E and F) can be used as for a single frame if we consider the contiguous string of frames to be equivalent to one very long frame: the meaning of N then becomes the total number of codeblocks contained in the last frame plus all the preceding frames of the CLTU in question.

As an example, Table D-6 shows the probability of rejection of the LAST frame for a single CLTU containing 1, 2, 3, and 4 maximum length frames. Figures are derived only for the 64-bit codeblock ($n=63$).

Table D-6: Probability of Last Frame Rejection in a Multiple Frame CLTU Using Maximum Length Frames and 64-Bit Codeblocks

No. of maximum-length frames	Total number of bits	Total No. of codeblocks (N)	De-coding mode	Probability of rejection of last frame, with channel BER of		
				10^{-4}	10^{-5}	10^{-6}
1	2048	37	TED	2.09×10^{-1}	2.32×10^{-2}	2.34×10^{-3}
			SEC	7.21×10^{-4}	7.24×10^{-6}	7.24×10^{-8}
2	4096	74	TED	3.74×10^{-1}	4.57×10^{-2}	4.67×10^{-3}
			SEC	1.44×10^{-3}	1.45×10^{-5}	1.45×10^{-7}
3	6144	110	TED	5.04×10^{-1}	6.77×10^{-2}	6.98×10^{-3}
			SEC	2.16×10^{-3}	2.17×10^{-5}	2.17×10^{-7}
4	8192	147	TED	6.07×10^{-1}	8.92×10^{-2}	9.30×10^{-3}
			SEC	2.88×10^{-3}	2.89×10^{-5}	2.89×10^{-7}

D-4.3 Multiple CLTUs

While in theory any number of frames may be sent in one CLTU, very long CLTUs tend to be counter-productive: that is, the probability of frame rejection increases as the CLTU is made excessively long. In such cases it may be preferable to divide a large command load into a number of CLTUs sent sequentially. These CLTUs may either be: 1) sent as independent entities (modulation is dropped between CLTUs and the entire resynchronization process begins anew as in the single CLTU case), or 2) strung together in sequence while maintaining bit sync on the channel.

If CLTUs are separated by dropping modulation, each CLTU will perform as an independent entity and may be analyzed as shown in Sections D-4.1 or D-4.2. However, if the CLTUs are strung together tail-to-start with an uninterrupted bit stream as shown in Figure D-5, some further considerations are necessary.

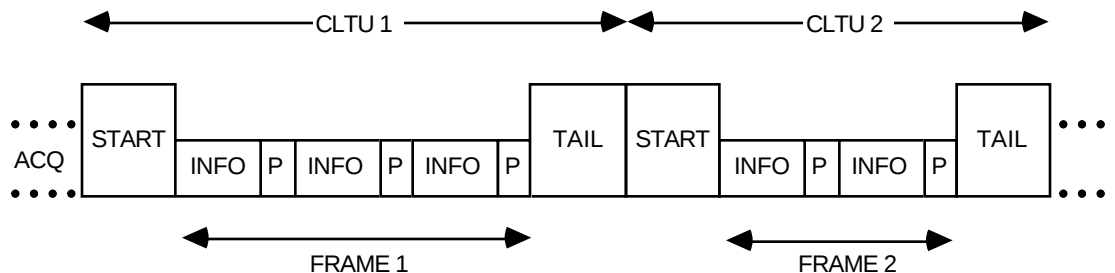


Figure D-5: Multiple Frame CLTU Organization (Contiguous CLTUs)

With this organization, the CLTU Tail Sequence becomes important, since the Tail Sequence must be relied upon to declare a CODEBLOCK REJECTION and force the decoder into SEARCH STATE at the end of each CLTU. ONLY IF THE DECODER IS IN SEARCH STATE WILL IT BE ABLE TO RECOGNIZE THE START SEQUENCE OF THE NEXT CLTU.

The decoder enters SEARCH state when a CODEBLOCK REJECTION is encountered (in this case caused by the tail sequence.) However, it is possible for the decoder to "miss" a tail sequence (i.e., the intended function, CODEBLOCK REJECTION, does not occur). Such a condition could happen if bit errors on the channel suitably change the tail sequence to make it an apparently valid codeblock, or (in SEC mode) make it appear (wrongly) to be correctable. This requires the received tail sequence to have at least 2 introduced bit changes in the TED mode, or 1 introduced bit change in the SEC mode.

Upon missing a tail sequence, the decoder remains in DECODE state after the first CLTU's tail and cannot recognize the next CLTU's START sequence which follows immediately. Although the Start Sequence of the next CLTU is NOT part of a codeblock and so has a high probability of causing CODEBLOCK REJECTION, this attribute is of no help at this point, since the start sequence has already passed. As a result, the entire CLTU which follows is missed.

The probability of missing a tail sequence when using the TED decoding mode is the probability that 2 or more changes are introduced into the tail sequence during transmission:

$$P_{TA} = 1 - [(1 - p)^n + np(1 - p)^{n-1}] \quad [\text{EQ. G}]$$

where n = length of tail sequence in bits.

The probability of missing a tail sequence when using the SEC decoding mode is the probability that one or more changes are introduced into the tail sequence during transmission:

$$P_{TB} = 1 - (1 - p)^n \quad [\text{EQ. H}]$$

It should be noted that Equations G and H are conservative approximations, since changes in certain locations may not result in a missed tail. Values are tabulated in Table D-7.

Table D-7: Probability of Missing Tail Sequence, P_{TA} (TED) and P_{TB} (SEC)

Tail Sequence length, bits	Decoding mode	Probability of missing a tail, for a Channel BER of		
		10^{-4}	10^{-5}	10^{-6}
64	TED (P_{TA})	1.95×10^{-5}	1.95×10^{-7}	1.95×10^{-9}
	SEC (P_{TB})	6.28×10^{-3}	6.30×10^{-4}	6.30×10^{-5}
56	TED (P_{TA})	1.48×10^{-5}	1.48×10^{-7}	1.48×10^{-9}
	SEC (P_{TB})	5.49×10^{-3}	5.50×10^{-4}	5.50×10^{-5}
48	TED (P_{TA})	1.08×10^{-5}	1.08×10^{-7}	1.08×10^{-9}
	SEC (P_{TB})	4.69×10^{-3}	4.70×10^{-4}	4.70×10^{-5}
40	TED (P_{TA})	7.39×10^{-6}	7.41×10^{-8}	7.41×10^{-10}
	SEC (P_{TB})	3.89×10^{-3}	3.90×10^{-4}	3.90×10^{-5}

The probability of rejection of the last frame in a CLTU which follows another CLTU (without reacquisition) may be evaluated as the probability of missing the tail of the preceding CLTU (P_{TA} or P_{TB}) OR the probability of rejecting the last frame of the subject CLTU.

That is,

$$\begin{aligned}
 &\langle \text{Prob. of frame rejection in} \\
 &\text{subsequent CLTU, TED decoding} \rangle = P_{F2A} \\
 &= P_{TA} + (1 - P_{TA})P_{FA} \\
 &= P_{TA} + (1 - P_{TA})[(P_{SA} + (1 - P_{SA})P_{CA}] \quad [\text{EQ. I}]
 \end{aligned}$$

where P_{FA} refers to the frame performance as previously calculated in Equation E (independent of a previous CLTU); and

$$\begin{aligned}
 \langle \text{Prob. of frame rejection in} \\
 \text{subsequent CLTU, SEC decoding} \rangle &= P_{F2B} \\
 &= P_{TB} + (1-P_{TB})P_{FB} \\
 &= P_{TB} + (1-P_{TB})[(P_{SB} + (1-P_{SB})P_{CB}] \quad [\text{EQ. J}]
 \end{aligned}$$

where P_{FB} refers to the frame performance as previously calculated in Equation F (independent of a previous CLTU).

Given equal length CLTUs, one can see that each subsequent CLTU will have a higher probability of rejection than the previous CLTU.

Example. Two maximum length frames could be packaged into two separate but contiguous CLTUs in an organization as shown in Figure D-5. The probability of rejection of the first (P_{F1}) and second (P_{F2}) frames in this organization may be compared (assuming 64-bit codeblocks, and BER of 10^{-5}) as shown in Table D-8.

Table D-8: Example of Performance of Frames in First and Second Contiguous CLTUs

Mode	P_{F1}	P_{F2}
TED	2.32×10^{-2}	2.32×10^{-2}
SEC	7.24×10^{-6}	6.37×10^{-4}

D-4.3.1 Performance Augmentation Using Double Tail Sequences. The performance of subsequent CLTUs can be improved by doubling all tail sequences. That is, the normal tail sequence of the CLTU is followed by an added second tail of the same length (or, equivalently, with an idle sequence having the same bit alignment as the tail sequence, which produces the same effect). It is less likely the combination of TWO tails will be missed, thus improving the reliability of the decoder reaching SEARCH state. Such an organization is shown in Figure D-6.

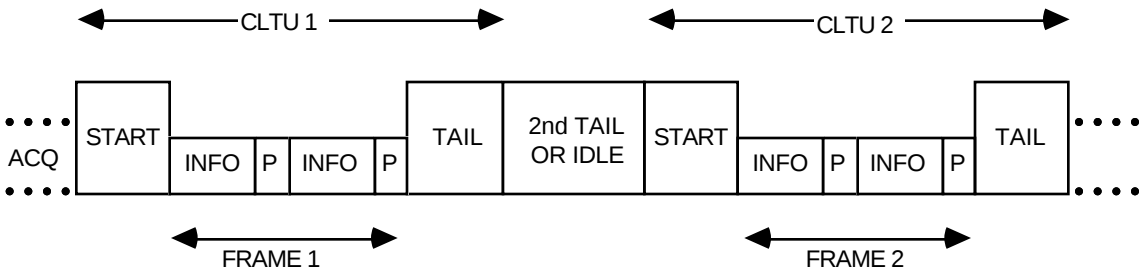


Figure D-6: Multiple CLTU Organization (With Added Tail/Idle)

With this organization, the probability of missing both tails is the probability of missing the first one AND the probability of missing the second; that is,

$$\begin{aligned} \text{<Prob. of missing a double tail} \\ \text{sequence, using TED decoding>} &= P_{\text{TAD}} \\ &= (P_{\text{TA}})^2 \end{aligned} \quad [\text{EQ. K}]$$

and

$$\begin{aligned} \text{<Prob. of missing a double tail} \\ \text{sequence, using SEC decoding>} &= P_{\text{TBD}} \\ &= (P_{\text{TB}})^2 \end{aligned} \quad [\text{EQ. L}]$$

With double tails, the probabilities of missing a tail shown in Table D-7 take on the new values shown in Table D-9.

**Table D-9: Probability of Missing DOUBLE Tail Sequence,
 P_{TAD} (TED) and P_{TBD} (SEC)**

Tail Sequence length, bits	Decoding Mode	Probability of missing a double tail, for a Channel BER of		
		10^{-4}	10^{-5}	10^{-6}
64	TED (P_{TAD})	3.78×10^{-10}	3.81×10^{-14}	3.81×10^{-18}
	SEC (P_{TBD})	3.94×10^{-5}	3.97×10^{-7}	3.97×10^{-9}
56	TED (P_{TAD})	2.19×10^{-10}	2.20×10^{-14}	2.21×10^{-18}
	SEC (P_{TBD})	3.01×10^{-5}	3.02×10^{-7}	3.02×10^{-9}
48	TED (P_{TAD})	1.16×10^{-10}	1.17×10^{-14}	1.17×10^{-18}
	SEC (P_{TBD})	2.20×10^{-5}	2.21×10^{-7}	2.21×10^{-9}
40	TED (P_{TAD})	5.46×10^{-11}	5.49×10^{-15}	5.49×10^{-19}
	SEC (P_{TBD})	1.52×10^{-5}	1.52×10^{-7}	1.52×10^{-9}

Example. If we take the example above of two maximum-length frames in separate but contiguous CLTUs (Table D-8) and use double tail sequences between the CLTUs (assuming 64-bit codeblocks and channel BER of 10^{-5}), the probability of rejection of the first and second frames is shown in Table D-10.

Table D-10: Example of Performance of Frames in First and Second Contiguous CLTUs Using DOUBLE Tail Sequences Between CLTUs

Mode	P_{F1}	P_{F2}
TED	2.32×10^{-2}	2.32×10^{-2}
SEC	7.24×10^{-6}	7.63×10^{-6}

D-4.3.2 Performance Augmentation Using Fill Bit. When using the SEC decoding mode (single bit error correction/double bit error detection), a single bit error in reception of a normal codeword will be corrected, making the codeblock acceptable. The following discussion only applies when using the SEC decoding mode where such corrections are possible. The tail sequence is not a codeword but is instead a specially constructed sequence designed to appear to the decoder as an "uncorrectable pattern". This means that when the tail sequence is received without change, the decoder will declare that the received sequence is an uncorrectable pattern, which forces it to leave the DECODE state and enter the SEARCH state.

However, if a single bit of this tail sequence becomes altered in the channel, the received sequence may no longer be recognized as "uncorrectable", and an improper correction may take place. Because the expected CODEBLOCK REJECTION did not occur, we say the tail sequence was "missed" (not recognized). The probability of this happening is given by Equation H.

Missing a tail sequence has far-reaching effects, since it is possible that the decoder will not be in SEARCH state for the next CLTU and therefore the entire subsequent CLTU may be missed.

This problem may be significantly reduced and the reliability of identifying a tail sequence improved by using the fill bit to *selectively inhibit* the SEC mode. As described in Reference [4], each valid codeblock terminates on a fill bit which is always set to "0". A tail sequence (which consists of an alternating pattern of ones and zeros starting with a zero) will always contain a "1" in the position normally occupied by the fill bit in a regular codeblock. This information can be exploited at the receiving end to inhibit the SEC mode whenever the fill bit is a "one". This process substantially improves the ability to identify a tail sequence with a negligible effect on the codeword acceptance process.

The recommended algorithm at the receiving end is as follows:

- (1) Test the received pattern alone (ignoring the fill bit) for errors.
- (2) If NO errors are detected in the received pattern, ACCEPT the codeword and IGNORE the fill bit.
- (3) If ONE error is detected in the received pattern, TEST the fill bit.
 - (a) If the fill bit = 0, correct the error in the pattern and ACCEPT it.
 - (b) If the fill bit = 1, declare a CODEBLOCK REJECTION.
- (4) If TWO errors are detected in the received pattern, declare a CODEBLOCK REJECTION. IGNORE the fill bit.

By selectively testing the fill bit, the probability of missing a tail sequence can be found from the probability of a single bit being changed in any portion of the tail sequence except the fill bit, AND that the received fill bit has also been changed. That is, TWO changes have to occur in the same codeblock, one of which must be the fill bit position.

$$\begin{aligned}
 &\text{<Prob. of missing a tail} \\
 &\text{sequence using fill bit test>} \qquad \qquad \qquad = P_{\text{TBF}} \\
 &\qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad \qquad = [1 - (1 - p)^n]p \qquad \qquad \qquad [\text{EQ. M}]
 \end{aligned}$$

Comparing this with Equation H, one can see that the probability of missing a tail sequence has now been reduced by several orders of magnitude (i.e., by the bit error rate, p .) Values are given in Table D-11.

Table D-11. Probability of Missing a Tail Sequence, P_{TBF} , Using the Fill Bit Algorithm (SEC Decoding Mode Only)

Codeblock length, bits	n, bits	Probability of missing tail sequence for channel BER of		
		10^{-4}	10^{-5}	10^{-6}
64	63	6.26×10^{-7}	6.30×10^{-9}	6.30×10^{-11}
56	55	5.47×10^{-7}	5.50×10^{-9}	5.50×10^{-11}
48	47	4.68×10^{-7}	4.70×10^{-9}	4.70×10^{-11}
40	39	3.89×10^{-7}	3.90×10^{-9}	3.90×10^{-11}

It should be noted that while this technique substantially reduces the likelihood of missing a tail sequence, there is a penalty in the form of a slight increase in frame rejection rate. That is, a codeblock containing one error which would normally be corrected and accepted may (but rarely) also have an error in its fill bit. If this algorithm were not used, the erroneous fill bit would not be tested and the codeblock would be accepted. Under this algorithm, such a codeblock would be rejected even though the information was correctable. The equation for codeblock rejection (P_{CB} , Equation D) must be modified to account for testing the fill bit (as shown for P_{CBF} , Equation N) but the effect on codeblock rejection is very slight:

$$\begin{aligned} &\text{<Prob. of codeblock rejection,} \\ &\text{SEC mode and using fill bit test>} = P_{CBF} \text{ (fill bit test)} \\ &= 1 - [(1-p)^n + (1-p)np(1-p)^{n-1}]^N \end{aligned} \quad [\text{EQ. N}]$$

Frame rejection performance for the frame in the second CLTU is then:

$$\begin{aligned} &\text{<Prob. of last frame rejection} \\ &\text{in subsequent CLTU,} \\ &\text{using SEC decoding} \\ &\text{and the fill bit algorithm>} = P_{F2BF} \\ &= P_{TBF} + (1-P_{TBF})P_{FBB} \end{aligned} \quad [\text{EQ. O}]$$

where

P_{TBF} = prob. of missing tail when using fill bit test (Equation M)

$P_{FBB} = P_{SB} + (1 - P_{SB})P_{CBF}$

and

P_{CBF} = prob. of codeblock rejection when using fill bit test (Equation N)

Example. The probability of frame rejection for the example of two maximum-length frames organized into separate CLTUs (as shown in Figure D-5) using SEC decoding mode, 64-bit codeblocks, channel BER of 10^{-5} and the fill bit algorithm is shown in Table D-12.

Table D-12: Example of Performance of Frames in First and Second Contiguous CLTUs Using Fill Bit Algorithm

Mode	P_{F1}	P_{F2}
SEC	7.47×10^{-6}	7.47×10^{-6}

D-5 UNDETECTED ERROR PERFORMANCE

The second performance requirement deals with undetected error, and requires that the probability of accepting a frame with an undetected error is greater than 10^{-9} . Again, the unit of accountability is the frame.

Often the methods used to improve frame rejection rate (such as SEC) cause reduced performance on undetected errors, and vice versa. Therefore an acceptable balance must be found between these two objectives. Reference [8] shows that the required undetected error performance will be met by the prescribed system using either TED or SEC decoding in a channel operating at a BER of 10^{-5} without extra precautions. However, if a greater margin of safety against undetected errors is desired, the cyclic redundancy code specified in Reference [8] may be added to each frame. For an overhead of 16 bits per frame and the same channel BER of 10^{-5} , this will provide an undetected frame error rate of 10^{-19} when using SEC decoding; with TED decoding, the performance is better. Figure D-7 shows curves comparing undetected error performance (with and without the added CRC) as a function of number of codeblocks in a frame for channel BER of 10^{-5} . These curves are from Reference [8].

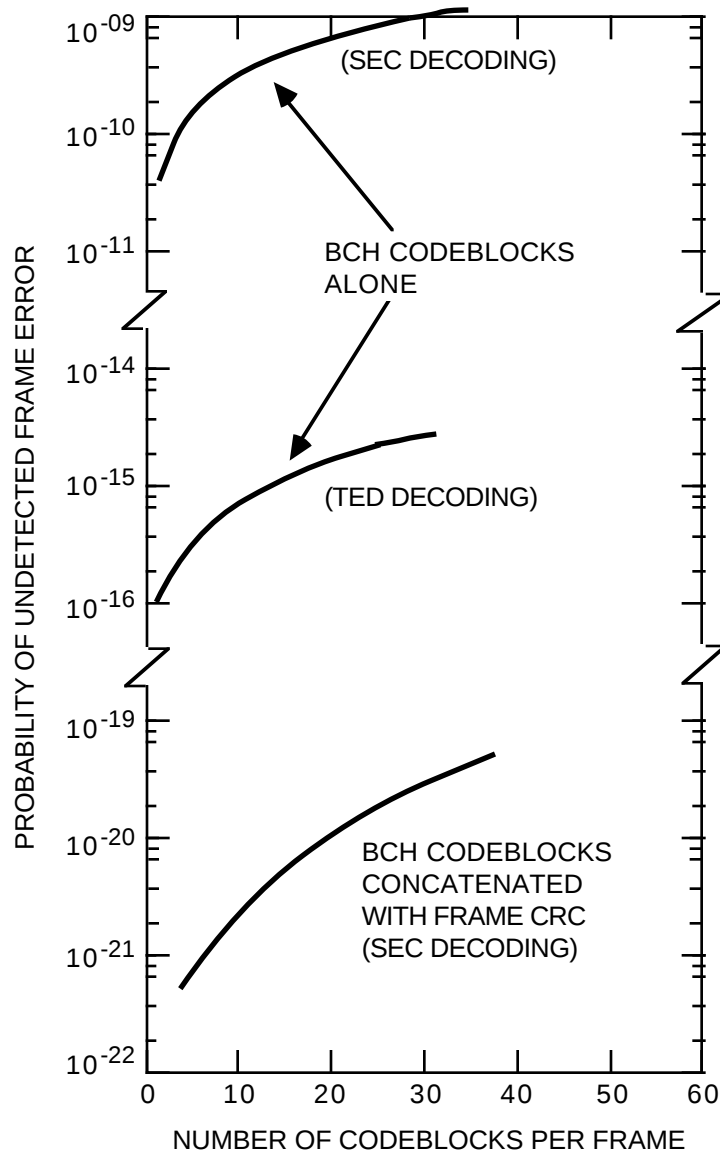


Figure D-7: Undetected Error Performance, With and Without Cyclic Redundancy Code

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