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european space agency
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Packet telecommand standard

Prepared by:
The Standards Approval Board (STAB)
for Space Data Communications

Approved by:
The Inspector General, ESA

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SPACE DATA COMMUNICATIONS PROCEDURES, SPECIFICATIONS & STANDARDS

Space Data Communications is the subject of the PSS-04 branch of the ESA Procedures, Specifications & Standards (PSS) series. This branch is further divided into two subbranches:

- the **Space Link Standards and Protocols** subbranch (document reference nos.: ESA PSS-04-1XX)
- The **Spacecraft Data Interfaces and Protocols** subbranch (document reference nos.: ESA PSS-04-2XX)

The purpose of these Space Data Communications PSS documents is to ensure the compatibility of spacecraft TT & C subsystems with the relevant ESA infrastructure (i.e. the ESA (ESOC) tracking and data-communication network and the ESA (ESTEC) satellite check-out facilities).

DOCUMENT CHANGE RECORD

Issue number and date	Sections affected	Remarks
Issue 1 June 1990	New document	Directly derived from the **CCSDS Recommendation for Space Data System Standards: Telecommand (References [1], [2], [3], and [4]).**
Issue 2 April 1992	Section 4.3.2 (page 20), Section 6.3.3 (pages 69, 71, 73, 74 and 87), Table 6.2 (pages 103 to 110), Table 6.3 (pages 114 to 116), Section 7.3.3 (page 127), Section 10.2 (page 143)	The changes are indicated by change bars in the margin and are only of an editorial nature. Otherwise, this Issue 2 is identical to Issue 1.

REFERENCES

[1] **Telecommand: Summary of Concept and Service**, Report **CCSDS 200.0-G-6**, Issue 6, Green Book, Consultative Committee for Space Data Systems, January 1987.

[2] **Telecommand Part 1: Channel Service, Architectural Specification**, Recommendation **CCSDS 203.0-B-1**, Issue 1, Blue Book, Consultative Committee for Space Data Systems, January 1987.

[3] **Telecommand Part 2: Data Routing Service, Architectural Specification**, Recommendation **CCSDS 202.0-B-1**, Issue 1, Blue Book, Consultative Committee for Space Data Systems, January 1987, together with **Telecommand Part 2.1: Command Operation Procedures, Detailed Specifications and State Matrices,** Document **CCSDS 202.0-B-1**, Issue 1, (Blue Book yet to be issued), Consultative Committee for Space Data Systems.

[4] **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.

[5] **Radio Frequency and Modulation Standard (ESA PSS-04-105),** Issue 1, 1989, European Space Agency.

[6] **Packet Utilisation Standard (ESA PSS-07-101),** Issue 1, (to be issued in 1991/92) European Space Agency.

[7] **Packet Telemetry Standard (ESA PSS-04-106),** Issue 1, January 1988, European Space Agency.

[8] **Telecommand Decoder Specification (ESA PSS-04-151),** Issue 1 (to be issued in 1991/92), European Space Agency.

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1. PURPOSE AND SCOPE

1.1 PURPOSE

The purpose of this Standard is to establish uniform requirements for the implementation of spacecraft "Packet Telecommand" systems by ESA. To this end the Standard:

- establishes a common framework and provides a common basis for the data structures of ESA spacecraft telecommand streams;
- allows ESA spacecraft projects to proceed coherently with the implementation of spaceborne telecommand systems which are compatible with the ESA ground systems;
- potentially provides a high level of commonality between both ESA spaceborne and ground-based telecommand systems and the ground systems of other CCSDS Agencies (1);
- provides recommendations for the definition of a minimum acceptable level of end-to-end performance for telecommand systems conforming to this Standard.

1.2 SCOPE

This Standard belongs to the Space Link Standards and Protocols subbranch of the ESA PSS branch for Space Data Communications. This Standard supersedes the **PCM Telecommand Standard (TTC-A-01).**

The Packet Telecommand concept embraces multiple layers of data communication protocol which are specified in a set of three separate documents:

(a) The **Radio Frequency and Modulation Standard,** (Reference [5]), which specifies the characteristics of the **"physical"** data channel.

(b) The **Packet Telecommand Standard**, (this document, Reference PSS-04-107), which specifies essentially the **"data link"** protocols and ser-

NOTE (1): CCSDS: Consultative Committee for Space Data Systems. This Standard is directly derived from a technical recommendation on telecommand issued by the CCSDS (References [1] to [4]).

vices to be used on board ESA spacecraft and at the ground network facilities. Therefore, whenever the standard ESA ground network is to be used, spaceborne telecommand systems shall comply with this Standard, as well as with Reference [5].

(c) The **Packet Utilisation Standard**, (Reference [6]), which specify the high-level user data structures and protocols that are required to generate strings of Telecommand Packets so that:

- these packets are 'transported' in an orderly and efficient manner to the various application processes on board the spacecraft;
- the activities specified by the data contained in the packets are effectively executed by the application processes.

Reference [6] applies to spaceborne data systems whenever ESA spacecraft control and/or data processing facilities are used for the effective operation of the spacecraft systems.

Therefore, taking advantage of this layered architecture, individual space missions may decide to comply with the full set of Standards or with only part of it. For example, if only uplink data communication compatibility is required, as would be the case for inter-Agency cross-support, then only (a) and (b) would apply.

2. APPLICABILITY

2.1 GENERAL

This Standard applies to all spacecraft using the ESA ground network standard facilities and services.

The capabilities provided within the constraints of this Standard will accommodate the requirements of a great variety of applications for data handling subsystems, thus providing a universal basis for cost-effective and technically compatible development of supporting equipment in different projects.

2.2 EXCEPTIONS

In **exceptional cases,** owing to mission-specific requirements, some deviations from this Standard may be warranted. Waivers to any requirements set forth in this Standard may be obtained **only after:**

- the technical and/or operational advantages of such deviations have been **demonstrated**, and/or
- it has been shown that the intended change is **in line** with the **existing systems.**

Requests for waivers should be addressed by the Project Manager to the ESA Standards Approval Board (STAB) for Space Data Communications. Such requests should be submitted as early as possible, preferably during the study phase of the project.

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3. SYSTEM OVERVIEW

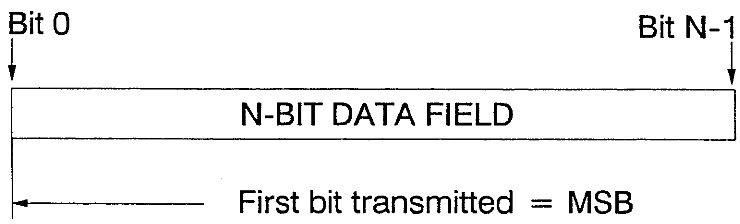
3.1 BIT NUMBERING CONVENTION AND NOMENCLATURE

The following **CAUTION** should be observed when interpreting the bit numbering convention which is used throughout this Standard.

CAUTION

In this document the following convention is used to identify each bit in a forward-justified N-bit field.

The first bit in the field to be transmitted (i.e. the most left-justified bit when drawing a figure) is defined to be "Bit 0"; the following bit is called "Bit 1" and so on, up to "Bit N-1". When the field is used to express a binary value (such as an integer), the Most Significant Bit (MSB) shall be the first transmitted bit of the field, (i.e., "Bit 0").



Spacecraft data fields are often grouped into 8-bit "words" which conform to the above convention. The following nomenclature is used throughout this Standard to describe this grouping:

OCTET = 8-bit word

In this document, the above-defined convention for identifying a bit is also used for identifying each octet in a forward-ordered N-octet field.

3.2 TELECOMMAND SYSTEM LAYERS AND SERVICES

Figure 3.1 is a functional diagram of the telecommand data flow, from the creation of a data set by an application process (source) operating on the ground, through to the delivery of the same data set to another application process (sink) operating within a spacecraft instrument or subsystem.

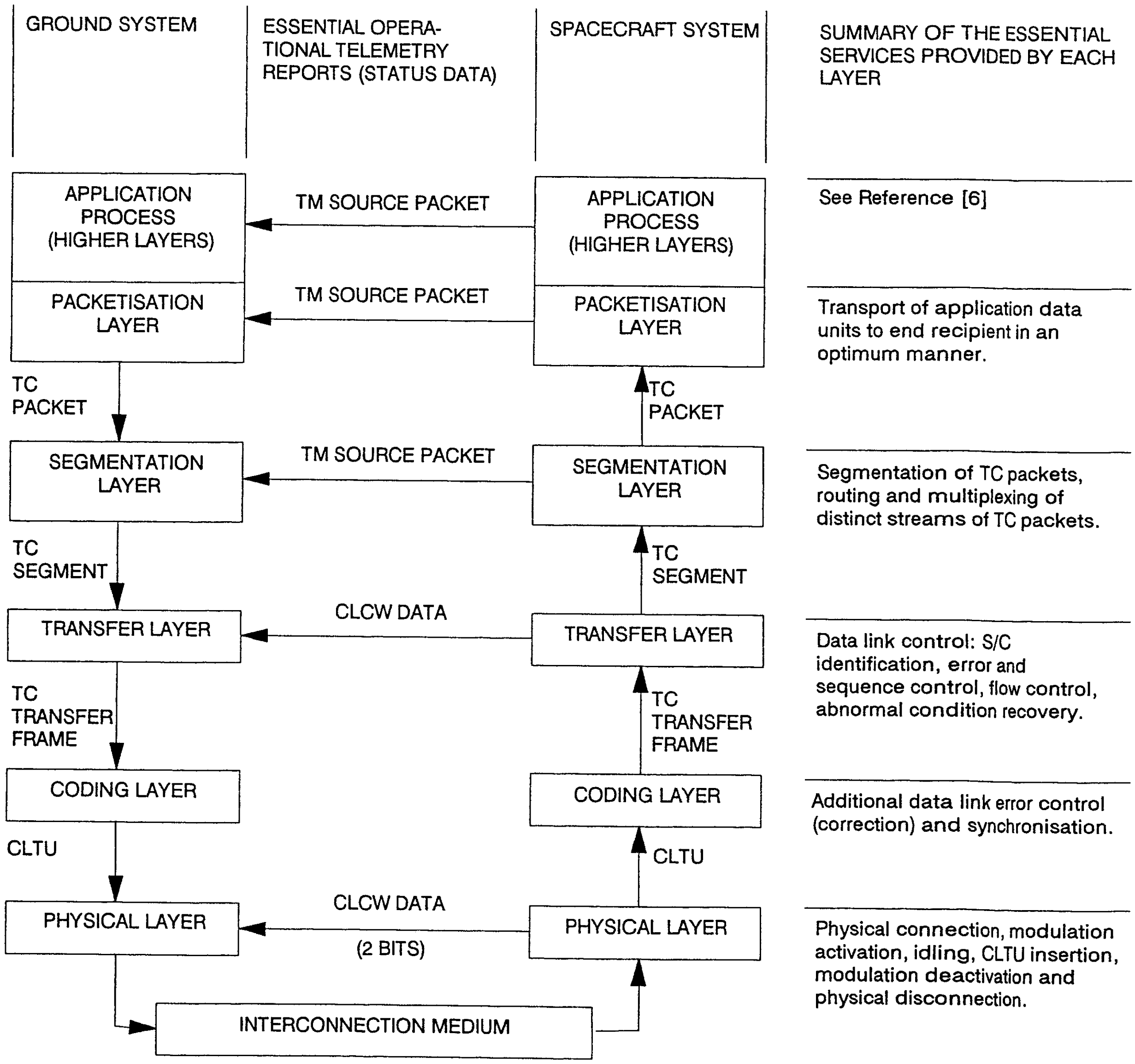


Figure 3.1 TELECOMMAND SYSTEM LAYERS AND SERVICES

The Packet Telecommand System is organised as a set of independent 'layers', each layer providing specific services to the layer above. These services are provided by functions and protocols that are defined for each layer (a protocol is a set of rules and formats which govern the communication between the peer processes in the same layer).

Since each layer is independent of the layers above, individual missions have some latitude [1], when defining their telecommand systems, to decide how "high" in the layered architecture they wish (or need) to be compatible.

The layers are:

(a) Packetisation Layer

One of the first capabilities offered by the system is to allow the user to optimise the size and structure of his application data set with a minimum of constraints imposed by the ground-to-spacecraft communication system. The user should thus be able to define his data organisation independently of other users, and to adapt this organisation to the various modes of his spaceborne instrument or subsystem.

The data structure which makes this independence possible is the **Telecommand (TC) Packet.** User data are encapsulated within a packet by prefixing them with a standard label (the Packet Header), and an attaching error control field at the end, so that the end-to-end transport services of the Packetisation Layer can be provided (i.e. application process identification, sequencing, error detection, delivery reporting etc.).

(b) Segmentation Layer

The possibility that a major spacecraft subsystem may fail makes it necessary to be able to select alternative "routes" for the various streams of protocol data units from the layer above (e.g. standard TC Packets, but other data structures are possible, so long as they are octet-based). Another requirement is that since most space communication systems are capacity-limited, multiple users must be guaranteed a minimum access to the uplink data channel.

NOTE (1): This latitude is also influenced by the particular implementation of the supporting infrastructure. See Section 3.3 on ground network interfaces.

It is therefore important to be able to manage the data flow in an orderly manner. To this end, two mechanisms are provided, which form the basic functions of the **Segmentation Layer.**

- **Segmentation - The Telecommand (TC) Segment** structure is used to encapsulate a single complete protocol data unit from the layer above (e.g. a TC Packet), or portions of that protocol data unit, if its length exceeds the maximum TC Segment length allowed for the data field of the lower-layer protocol data unit, the **Telecommand (TC) Transfer Frame** (see Paragraph (c) below);
- **Multiplexing** - The TC Segment structure allows distinct sources of TC Packets to be multiplexed on the data link. To achieve this, **the Segmentation Layer** provides a number of "service access points" which are multiplexed at segment level: the **Multiplexer Access Points (MAPs).**

These two mechanisms permit:

- any long TC Packets to be broken into shorter pieces so that they may be inserted into the length-limited TC Transfer Frames, as shown in Figure 3.2;

- subsystem data interfaces to be implemented on board a spacecraft in such a way as to meet various requirements:
  - redundant interface access, in case of reconfiguration after failure of major subsystems;
  - operational access to the link for each major user (e.g. bandwidth allocation);
  - operational access mechanisms for each major user within its allocated bandwith (e.g. 'priority' access versus 'normal' access).

At the receiving end, the various streams of TC Packets are demultiplexed by a MAP selection process, as shown in the top diagram of Figure 3.3 (see Paragraph (f) further). If segmentation of TC Packets is in use, a packet assembly process is required for each distinct stream of packets.

(c) Data Link Sublayers

The most critical function of any spacecraft telecommand system is that which concerns the data link. Ideally, TC Segments must be transferred to the spacecraft without error, omission or duplication, and in their original sequence. To achieve this two data link sublayers have been defined:

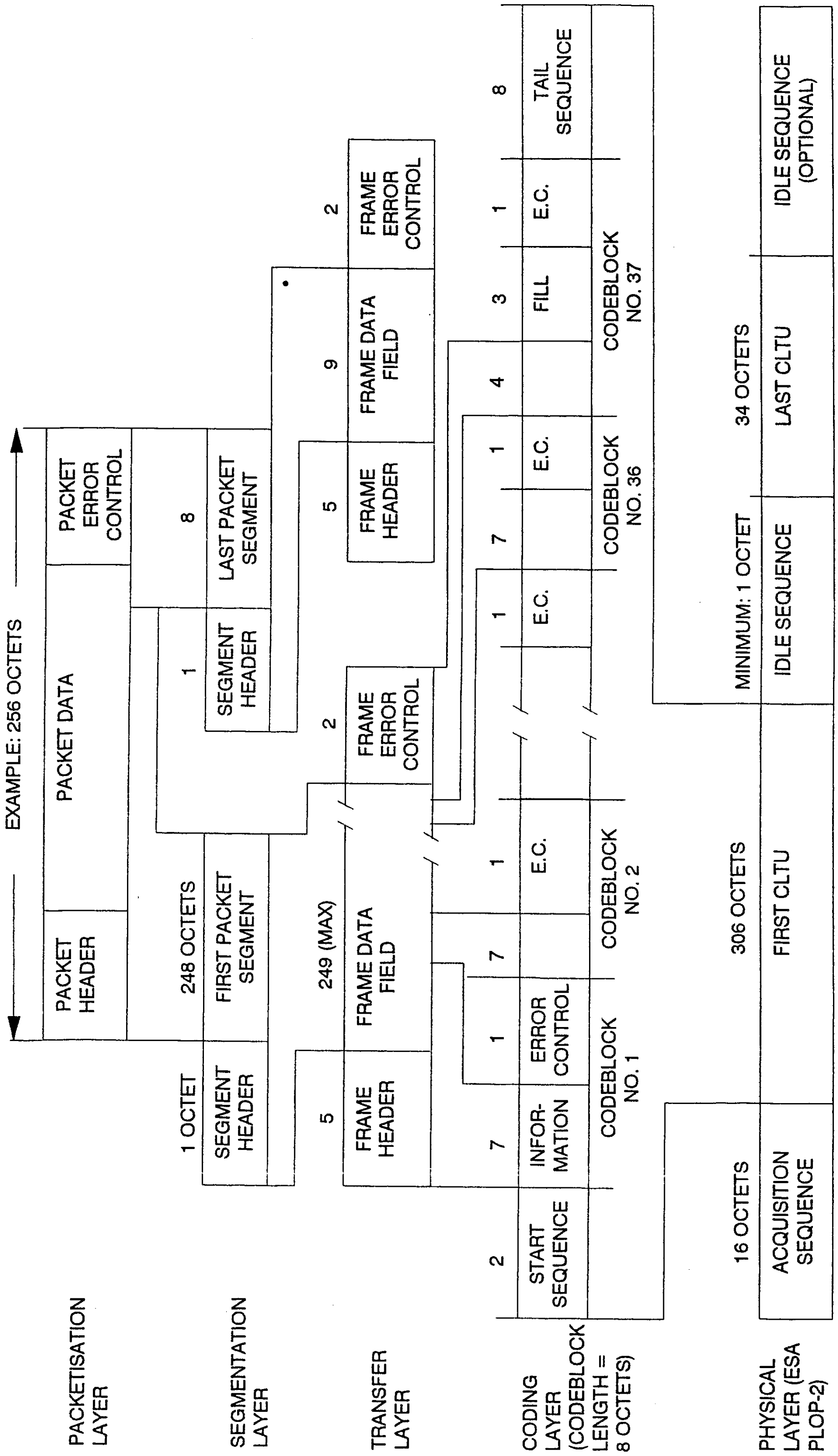


Figure 3.2 EXAMPLE OF THE SUCCESSIVE DATA STRUCTURES GENERATED BY THE LOWER LAYERS OF THE TELECOMMAND SYSTEM

- **The Transfer Layer** - This layer provides the mechanisms for the transmission of protocol data units called **Telecommand (TC) Transfer Frames.** The TC Transfer Frame is limited in size so that the error control mechanisms it contains may perform efficiently: error-detecting cyclic redundancy code (CRC) and "automatic request for retransmission" (ARQ). The ARQ selected for this standard is the CCSDS Command Operation Procedure "one" (COP-1);
- **The Coding Layer** - This layer provides the forward error correction (and detection) capability without which the data link services would be of poor quality because of the probability of channel-noise-induced errors. The basic protocol data unit is the **Command Link Transmission Unit (CLTU)** which is essentially made of one or more **Telecommand (TC) Codeblocks** containing the information bits making up one TC Transfer Frame. The layer also provides synchronisation services for all the layers above (as seen from the receiving end).

(d) Physical Layer

The lower layer of the Packet Telecommand concept is the Physical Layer. It is mainly concerned with providing a physical connection, via modulated radio signals, between the transmitting station and the receiving spacecraft. The major specification of this layer is therefore to be found in Reference (5). Nevertheless, a small part, specific to the Packet Telecommand concept, is specified in this Standard. It concerns the **Carrier Modulation Modes (CMMs)** and the **Physical Layer Operation Procedure (PLOP)** which combine to control the orderly activation and modulation of the radio frequency carrier.

(e) Telemetry Reporting

In the functional diagram shown in Figure 3.1, the receiving-end process of each layer provides, in principle, a report on its activities to its peer process at the sending end. In practice, these reports are transmitted to the ground transmission process by telemetry. In Figure 3.1, and throughout this document, the telemetry standards used are those of the **Packet Telemetry Standard** (Reference [7]) which has been provided with the features necessary to support Packet Telecommand Systems. One particular feature is the **Command Link Control Word (CLCW)**, which is essentially concerned with the operation of the telecommand data link protocol **(COP 1)**. The CLCW resides as protocol control information in the Trailer of each Telemetry (TM) Transfer Frame. This choice was made on grounds of equipment standardisation and consistency of equipment tasks: COP-1 data link services are provided by remote, self-contained ground stations which do not process the data contained in the TM Source Packets they acquire (see subsection 3.3 below).

All other reports on the spaceborne telecommand processes must be sent via specific TM Source Packets.

In this Standard, guidelines for data formats and acknowledgement procedures are provided where applicable, up to the delivery, in memory, of a TC Packet. Detailed reporting activities on the Packetisation Layer and all layers above are to be found in Reference [6].

(f) Optional Services of the Segmentation Layer

For ESA telecommand systems, the Segmentation Layer and its services must be provided as described in Paragraph (b).

For those missions that may require telecommand data protection transparent to the TC Packet users, an additional, optional function of the Segmentation Layer is available: the **Authentication Sublayer**. Figure 3.3 shows a schematic representation of this optional function within the Segmentation Layer.

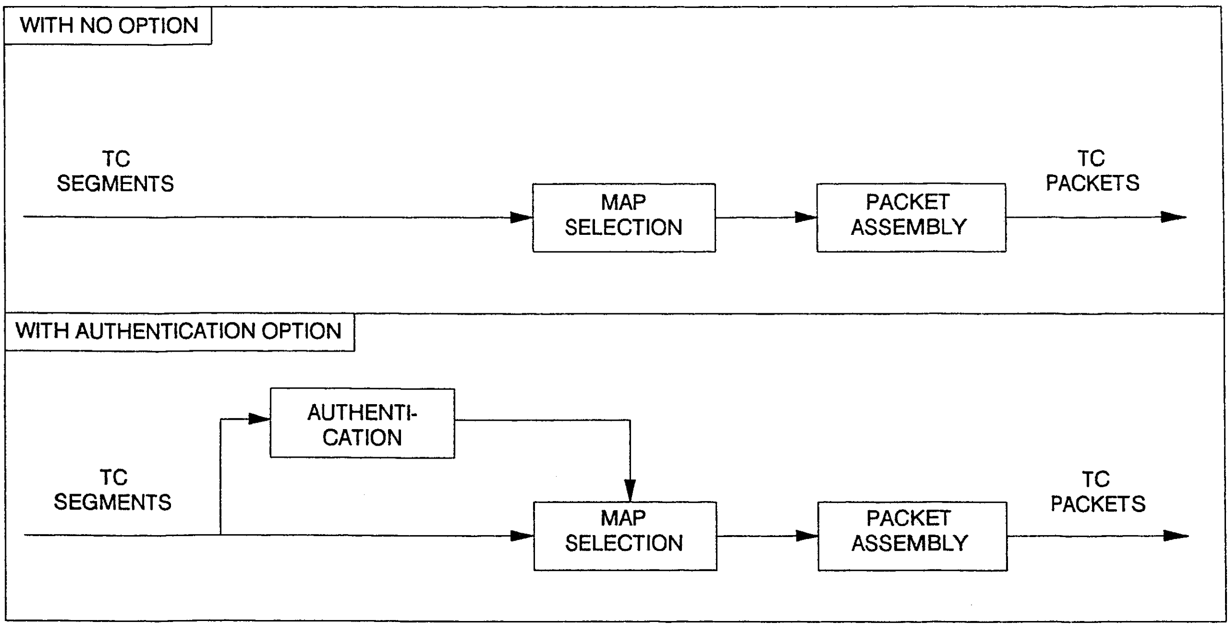


Figure 3.3 AUTHENTICATION OPTION OF THE SEGMENTATION LAYER (AT THE RECEIVING END)

The Authentication Sublayer provides data protection services at TC Segment Level by means of "encrypted authentication" techniques. These techniques ensure that only an authorised party (the spacecraft control centre in the ESA case) may uplink telecommand data to the spacecraft. In effect, a field, spanning the last octets of the TC Segment, contains a unique signature which is a complex function of a secret key and the rest of the TC Segment bits (which are left untouched).

The services of the sublayer are only operationally efficient if the layer below can provide services of the COP-1 type (i.e. guaranteeing delivery in sequence, without error, omission or duplication).

Reporting is done via a specific TM Source Packet.

3.3 NETWORK INTERFACE SERVICES

The ESA Packet Telemetry and Telecommand Systems were conceived to match the ESA ground data network architecture and operational philosophy, which is influenced by the distributed location of most of its elements over the Earth. Figure 3.4 shows a typical topological configuration of the ESA ground data network. As can be seen, the Control Centre is, in principle,

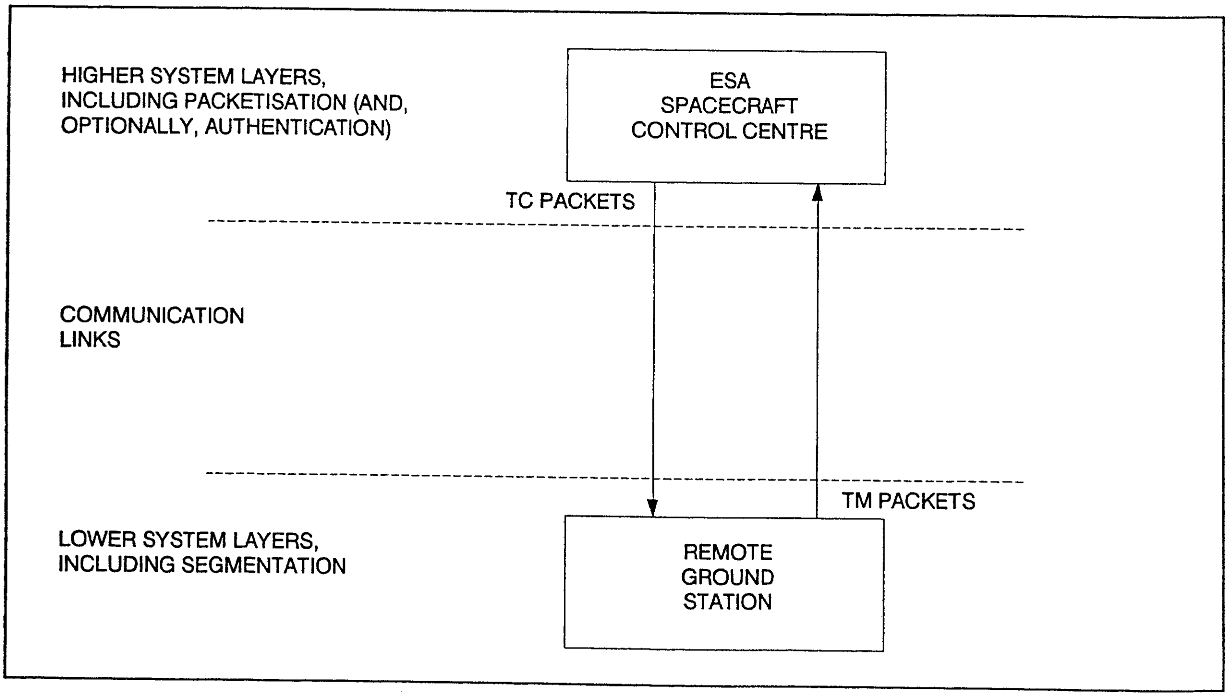


Figure 3.4 ESA GROUND DATA NETWORK CONFIGURATION

only concerned with data processes pertaining to the Packetisation Layer and above, for both telemetry and telecommand. The Remote Ground Stations, on the other hand, are concerned with the data processes pertaining to the layers below the Packetisation Layer.

The communication lines drawn between the Spacecraft Control Centre and the Remote Ground Station are, usually, hired data lines of modest capacity. They are also redundant, since unexpected disconnections may occur.

The advantages of a layered architecture are immediately visible. All time-critical functions are concentrated in the front-end Ground Stations. This is particularly true for the closed-loop operation of the COP-1 data link protocol. The services of the ground communication links are only required for the packet data proper.

Figure 3.5 shows a detail of the Ground Station interface with the Control Centre. Three interfaces are offered, each providing a different service.

Service 1: Sequence-Controlled Service for Packets (without Authentication of Segments)

This service applies to **standard TC Packets** as defined in Section 8. A TC Packet is transmitted to the spacecraft only when received "complete and correct" by the Ground Station. The Ground Station is responsible for creating the TC Segments. To achieve this, each TC Packet is provided with its MAP information. The MAP information includes multiplexing instructions as specified by the Control Centre. **Thus, multiplexing is performed at TC Segment level** (and, consequently, at TC Transfer Frame level).

The correct reception of each Transfer Frame by the spacecraft is monitored, and delivery in sequence of the TC Packets is ensured by proper retransmission of the rejected frames.

Service 2: Sequence-Controlled Service for Packets (with Authentication of Segments)

This service is a variation of Service 1 for missions using **standard TC Packets and the encrypted authentication of TC Segments.** For reasons of security (in particular: encryption key management) the authentication process normally resides in the Control Centre. Therefore, it is necessary to transfer the TC Packets in a slightly altered form, in which the Authentication Tail (signature) for each TC segment is inserted at the expected place in the Packet Data Field as shown in Figure 3.6 (this means that the Control Centre

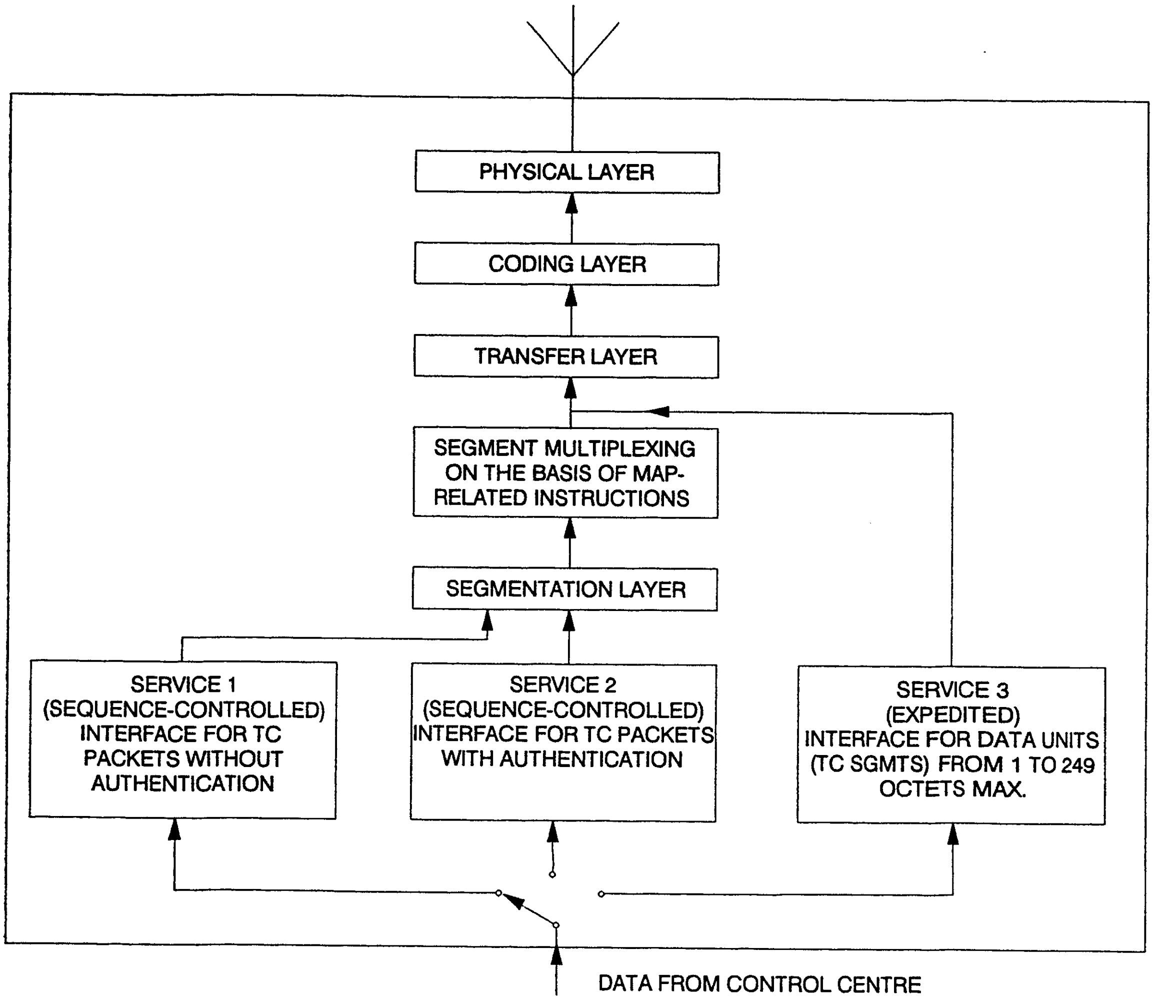


Figure 3.5 ESA GROUND STATION TELECOMMAND DATA INTERFACE

has to perform the segmentation process as well as the authentication process before delivering the "altered" packet). The Ground Stations will be able to handle TC Packets presented in such a format. TC Packets are transmitted to the spacecraft when they have been received "complete and correct" by the Ground Station. **Data multiplexing is performed at TC segment level, as for Service 1.**

The correct reception of each Transfer Frame by the spacecraft is monitored, and delivery in sequence of the TC Packets is ensured by proper retransmission of the rejected frames.

STANDARD SERVICE 1 TC PACKET:

o SPECIFIED PACKET LENGTH = 294
o ACTUAL PACKET LENGTH = 300 OCTETS

300	
PACKET HEADER	PACKET DATA FIELD (including Packet Error Control)
6	294

STANDARD SERVICE 2 TC PACKETS (i.e. ALTERED SERVICE 1 TC PACKET) :

o SPECIFIED PACKET LENGTH = 294
o AUTHENTICATION TAIL LENGTH = 9 OCTETS
o ACTUAL PACKET LENGTH = 318 OCTETS

318				
PACKET HEADER	DATA	AUTH. TAIL	DATA	AUTH. TAIL
6	233	9	61	9

248 = max. packet segment length

Figure 3.6 EXAMPLE OF SERVICE 2 TC PACKET

Service 3: Expedited Service

This service is concerned with TC Transfer Frames containing standard TC Segments.

Each TC Segment is transmitted to the spacecraft as soon as received "complete and correct" by the Ground Station. No retransmission takes place, nor any verification of correct reception by the spacecraft (this must be carried out by the Control Centre).

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4. PHYSICAL LAYER

4.1 OVERVIEW OF THE LAYER

The TC Physical Layer, which is the lowest layer in the Packet Telecommand system, directly interfaces with the transmission medium (typically: a radio path through space). As such, it must activate and deactivate the physical connection between the transmitting ground station and the receiving spacecraft, and act as the logical interfacing mechanism between the transmission medium and the Coding Layer.

The characteristics of the physical connection are specified in Reference [5].

Inputs to the sending end of the TC Physical Layer are Command Link Transmission Units (CLTUs), which are the protocol data units provided by the Coding Layer. The Physical Layer controls the activation and deactivation of the physical connection by invoking a Physical Layer Operation Procedure (PLOP).

The PLOP consists of the sequential application of several Carrier Modulation Modes (CMMs). The CMMs are concerned essentially with:

- an unmodulated carrier;
- a carrier modulated with an Acquisition Sequence;
- a carrier modulated with one CLTU;
- a carrier modulated with an Idle Sequence.

At the receiving end of the TC Physical layer, the modulated radio frequency waveforms are detected and demodulated, and a "dirty" (i.e. potentially corrupted by channel noise) bit stream (NRZ-L) is delivered to the Coding Layer with control information on the physical connection (channel activation/deactivation).

4.2 STANDARD DATA STRUCTURES WITHIN THE LAYER

4.2.1 Acquisition Sequence

The Acquisition Sequence is a data structure forming a preamble which provides for initial symbol synchronisation within the incoming stream of detected symbols at the receiving end.

The standard length of the Acquisition Sequence is 128 bits. This length must be considered as a minimum length, since greater lengths may be obtained by idling, as described in Section 4.3.

The NRZ-L bit pattern of the Acquisition Sequence shall be alternating "zeros" and "ones", **ending with "one" when immediately followed by an Idle Sequence.**

4.2.2 CLTU

The CLTU is the protocol data unit provided, at the sending end, by the Coding Layer. The CLTU is defined in Section 5. The NRZ-L bit transition density characteristics of the CLTU are dominated by those of its main constituent part: the TC Codeblock, with at least two transitions per code-block.

4.2.3 Idle Sequence

The Idle Sequence is the data structure which provides for maintenance of bit synchronisation:

- between the Acquisition Sequence and the first CLTU to be transmitted, effectively extending the length of the Acquisition Sequence (optional);
- between successive CLTUs;
- when no CLTUs are available.

The **minimum** length of an Idle Sequence shall be **eight bits**. The maximum length is unconstrained, i.e. as required by the telecommanding operations.

The NRZ-L bit pattern is that of the Acquisition Sequence, i.e. alternating "zeros" and "ones", **always beginning with a "zero".**

4.3 STANDARD PROCEDURES WITHIN THE LAYER

4.3.1 Carrier Modulation Modes

The Carrier Modulation Modes (CMMs) specify the various states of data modulation which may exist upon the radio frequency (RF) carrier forming the physical connection. These states correspond to the absence or presence of the data structures defined in Section 4.2. The various CMMs are shown in Table 4.1 and specified in the next subsections.

MODE	STATE
CMM - 1	Unmodulated RF carrier only (*)
CMM - 2	RF Carrier modulated with Acquisition Sequence
CMM - 3	RF Carrier modulated with one protocol-data unit from layer above (e.g., one CLTU)
CMM - 4	RF Carrier modulated with Idle Sequence

Note (*): "Unmodulated" here means "as far as **telecommanding** is concerned"

Table 4.1 CARRIER MODULATION MODES

4.3.1.1 CMM-1

This mode is concerned with the establishment of the radio-frequency part of the physical connection, as specified in Reference [5] (Link Acquisition Procedures). The procedure requires that the lock status of the spacecraft transponders be transmitted in the telemetry data for operational use by the transmitting ground station. This shall be achieved by means of the "No RF Available" flag, which is transmitted as Bit 16 of the CLCW (the CLCW, in general, and Bit 16, in particular, are fully specified in Section 6).

4.3.1.2 CMM-2

This mode is concerned with the establishment of the modulation part of the physical connection. The procedure requires that an Acquisition Sequence of at least 128 bits be transmitted and that a performance quality indicator of the received bit stream be transmitted in the telemetry data for operational use by the transmitting ground station. This shall be achieved by means of the "No Bit Lock" flag, which is transmitted as Bit 17 of the CLCW (see Section 6). The flag provides the same service throughout CMM-3 and CMM-4.

4.3.1.3 CMM-3

This mode is concerned with the transmission of one protocol data unit (from the layer above) on the physical connection. In this standard, the layer above (as seen from the transmitting end) is the Coding Layer, and the protocol-data unit is the CLTU.

4.3.1.4 CMM-4

This mode is concerned with the maintenance of the modulation part of the physical connection. The procedure requires the transmission of an Idle Sequence of varying length as specified hereafter:

(a) Between the Acquisition Sequence and the first CLTU to be transmitted.

This provision is **optional** and can be used to effectively increase the length of the Acquisition Sequence.

(b) Between each successive CLTU.

This provision is **mandatory**: there shall always be at least 8 bits of Idle Sequence between CLTUs. The maximum length of the Idle Sequence is unconstrained, and is dictated by the timing of the telecommanding operations (e.g. when no CLTU is immediately available).

4.3.2 Physical Layer Operation Procedure (PLOP)

A PLOP consists of a sequential application of the various CMMs in order to activate and deactivate the physical connection. The PLOP defined in this Standard follows the PLOP-2 recommendation specified in Reference [2]. A complete sequence of CMMs, from the initial application of CMM-1 to the removal of CMM-1 forms a "Telecommand PLOP". Figure 4.1 shows a Telecommand PLOP based on the ESA PLOP-2.

4.3.3 Service Primitives of Interface between Physical Layer and Coding Layer

This section lists the service primitives of the interface between the Physical Layer and the Coding Layer. It does not include management information

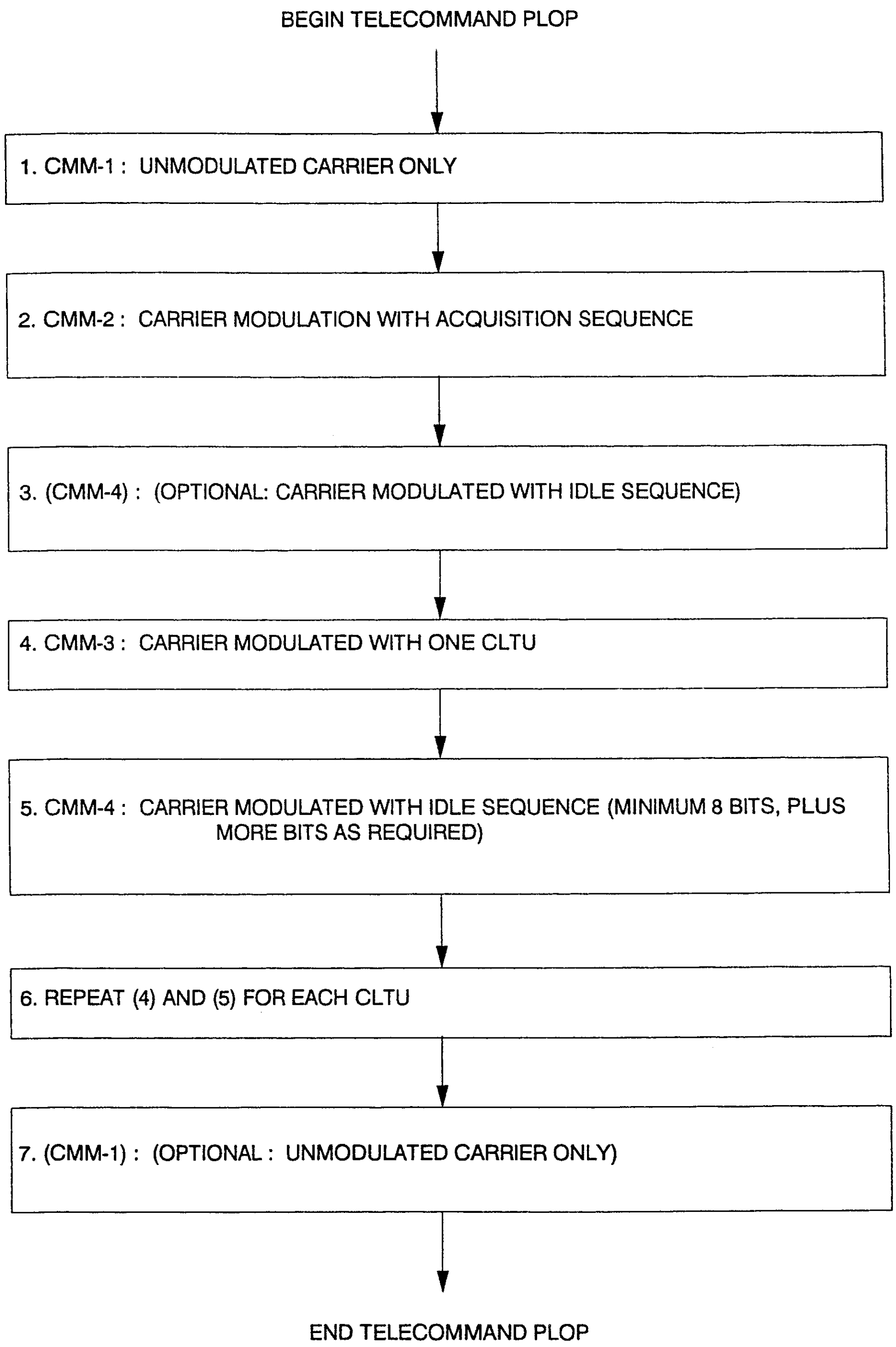

Figure 4.1 SEQUENCE OF CMMs COMPRISING THE ESA PLOP-2

(such as uplink bit rate) which must nevertheless be provided by the Higher Layers.

4.3.3.1 At the Sending End

There are two requests defined from the Coding Layer to the Physical Layer at the sending end of the link: the Transmit Request and the Abort Request. A Transmit Request is acknowledged by the Physical Layer, and an Abort Request is not.

(a) From the Coding Layer to the Physical Layer

- Transmit Request for CLTU
  Parameters:
  - request identifier
  - CLTU bits
- Abort Request
  Parameters: none

(b) From the Physical Layer to the Coding Layer

Each Transmit Request is acknowledged by the Physical Layer with one of two possible responses:

- Accept Response
  Parameters:
  - request identifier of Transmit Request
- Reject Response
  Parameters:
  - request identifier of Transmit Request

4.3.3.2 At the Receiving End

(a) From the Physical Layer to the Coding Layer

- Telecommand Symbol Arrived Indication
  Parameters:
  - input data bit (CLTU bit or Acquisition/Idle Sequence bit).
  - channel active indication

(b) From the Coding Layer to the Physical Layer

– No service primitives are specified.

4.3.4 Actions

4.3.4.1 At the Sending End

On receiving a Transmit Request for CLTU, the Physical Layer will respond to the Coding Layer in one of two ways:

- Accept Response to Transmit Request for CLTU: this means that the Physical Layer has stored the CLTU data which will be transmitted as soon as the preceding CLTU data has been transmitted
- Reject Response to Transmit Request for CLTU: this means that the Physical Layer cannot store the CLTU data because there is no more storage space for them.

Each response is identified by the interface-specific request identifier, which is one of the parameters of the Transmit Request.

At most, one Transmit Request may be outstanding: the corresponding Accept Response may be delayed by the Physical Layer until it is ready to receive the next Transmit Request. If a second Transmit Request is received while the preceding one is still outstanding, the Physical Layer generates a Reject Response to the second request. To avoid this, the Higher Layer will keep track of the outstanding requests by means of a variable. When the Transmit Request is generated, the variable (flag) is set to "Not Ready". When the matching Accept Response is received, the Higher Layer resets the variable to "Ready".

On receiving an Abort Request, the Physical Layer shall erase all CLTUs in queue in the layer: **it shall not erase any CLTU being currently transmitted (i.e. undergoing the CMM-3 procedure).**

The Abort Request is used typically:

- to erase all non-transferred data when terminating a data link service;
- to erase all non-transferred data when the automatic retransmission mechanism of COP-1/AD operates, so that these data are not transmitted unnecessarily.

4.3.4.2 At the Receiving End

When bit modulation is detected and bit lock achieved, the Physical Layer is in the Channel Active State and it delivers the data bit stream to the Coding Layer, bit by bit. When no bit lock is achieved or, alternatively, when no bit modulation is detected, the Physical Layer is in the Channel Inactive State.

5. CODING LAYER

5.1 OVERVIEW OF THE LAYER

The Coding layer provides essentially the forward error correction capability without which the data link services offered by the Transfer Layer alone would be of poor quality. The Coding Layer also provides synchronisation services used by the layer above, at the receiving end.

Inputs to the sending end of the Coding Layer are TC Transfer Frames, which are the protocol data units provided by the Transfer Layer. Each Transfer Frame is encoded/embedded in one CLTU (Command Link Transmission Unit), which is the protocol-data unit of the Coding Layer.

A CLTU is made up of three distinct protocol-data elements:

(a) one 16-bit Start Sequence, the purpose of which is to mark the beginning of a CLTU and, therefore, of a Transfer Frame (synchronisation service).
(b) one or more TC Codeblock(s) of fixed selected length, to encode the protocol data unit from the layer above (i.e. the Transfer Frame). The maximum Codeblock length is that recommended by this Standard: 64 bits, with 56 bits for the information. "Fill octets" may be added by the Coding Layer to complete the last Codeblock when the Transfer Frame length does not match exactly that of the Codeblock sequence.
(c) one Tail Sequence of length equal to that of the TC Codeblock. This is, in effect, a "pseudo-Codeblock" consisting of 64 bits of idle sequence (alternating "zeros" and "ones"), the purpose of which is to mark the end of a CLTU (synchronisation service).

At the receiving end of the Coding Layer, a "dirty" symbol stream (plus control information on whether the physical channel is active or inactive) is received from the layer below. Searching for the Start Sequence, the Coding Layer finds the beginning of a CLTU and decodes the TC Codeblocks. As long as no errors are detected, or errors are detected and corrected, the Coding Layer passes "clean" octets of data to the layer above. Should any Codeblock contain an uncorrectable error, this Codeblock is abandoned, no further data octets are passed to the layer above and the Coding Layer returns to a Start Sequence searching mode until it detects one.

It should be noted that the receiving-end process has no knowledge of "fill octets": their presence will be detected by the layer above which will discard them. Also, the Start Sequence is not transferred to the layer above which only receives an indication to begin processing incoming octets as candidate TC Transfer Frames.

Finally, there is only a statistically very small chance (in harmony with the performance characteristics of the system) to decode a Tail Sequence. When this happens, the next Codeblock will (very likely) be found uncorrectable and the system will go back to the Start Sequence searching mode. The layer above will eventually find that too many data octets have been transferred (see Section 6).

No standard reporting data are defined for the operational activities of the Coding Layer. However, this does not preclude the definition of monitoring data for supervisory (housekeeping) purposes, as discussed in **Appendix C: Data Link Management and Monitoring**.

5.2 STANDARD DATA STRUCTURES WITHIN THE LAYER

5.2.1 Command Link Transmission Unit (CLTU)

The CLTU is the protocol-data unit of the Coding Layer. The CLTU is made of three structural components, as shown in Figure 5.1.

Each of the three components is specified in the next sections.

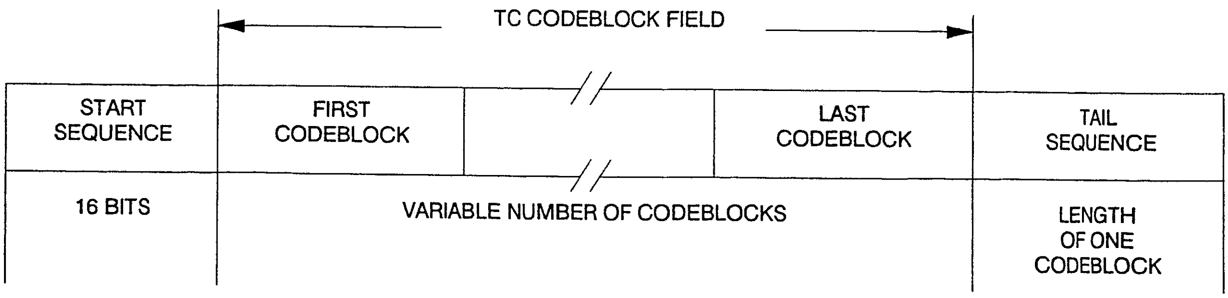

Figure 5.1 FORMAT OF THE CLTU

5.2.2 Start Sequence

The Start Sequence marks the beginning of the TC Codeblock Field within a CLTU. It consists of a 16-bit synchronisation pattern as follows:

1110	1011	1001	0000
First Transmitted Bit (Bit 0)			Last Transmitted Bit (Bit 15)

This pattern may be represented in hexadecimal notation as follows:

EB90

5.2.3 TC Codeblock Field

The TC Codeblock Field consists of one or more TC Codeblocks of fixed length. The general format of the TC Codeblock is shown in Figure 5.2.

MAXIMUM LENGTH : 8 OCTETS	
INFORMATION FIELD	ERROR CONTROL FIELD
SELECTABLE LENGTH 4, 5, 6 OR 7 OCTETS	1 OCTET

Figure 5.2 GENERAL TC CODEBLOCK FORMAT

The length of the TC Codeblock shall be **fixed** for any given mission. It shall be possible to select the following standard lengths:

- 8 octets (information field : 7 octets)
- 7 octets (information field : 6 octets)
- 6 octets (information field : 5 octets)
- 5 octets (information field : 4 octets)

Unless specifically required by the mission, the recommended Codeblock length is 8 octets.

The detailed specification of the encoding and decoding procedure is given in Section 5.3.

5.2.4 Tail Sequence

The Tail Sequence marks the end of the TC Codeblock Field within a CLTU. The length of the Tail Sequence shall be that of a TC Codeblock. Its pattern shall be alternating "zeros" and "ones", **ending with a "one"**. This pattern differs from the nearest codeblock of the same length by 2 bits (see also the TC Codeblock decoding procedure in Section 5.3).

5.3 STANDARD PROCEDURES WITHIN THE LAYER

5.3.1 TC Codeblock Encoding Procedure

A systematic block coding procedure is used which always processes 56 bits per Codeblock and which always generates 7 parity check bits per Codeblock. The parity check bits are then **COMPLEMENTED** and placed into the Codeblock as shown in Figure 5.3: P_0 through P_6, are located in the first seven bits of the last octet of the Codeblock. The complements are used to aid in maintaining bit synchronisation and detection of bit slippage (2 data transitions, at least, per Codeblock are guaranteed).

The last bit of the last octet, F_0,is a filler bit appended to complete the 8-bit Error Control Field. This Filler Bit shall always be a "zero".

INFORMATION FIELD	ERROR CONTROL FIELD	
$I_0, I_1, \ldots, I_{N-1}$	$\overline{P_0}, \overline{P_1}, \ldots, \overline{P_6}$	F_0
N = 32, 40, 48, 56 INFORMATION FIELD BITS	7 PARITY CHECK BITS	1 FILLER BIT

Figure 5.3 DETAILED TC CODEBLOCK FORMAT

The code is a (63,56) modified Bose-Chaudhuri-Hocquenghem (BCH) code which uses the following generator polynomial to produce the seven parity bits over 56 bits:

$$g(x) = x^7 + x^6 + x^2 + x^0$$

It may be desired to shorten the Codeblock. This is accomplished by reducing the number "N" of Information Field Bits contained within the Codeblock. To maintain octet boundaries and reasonable efficiency, 32, 40 and 48 bits are the only shortened Information Field sizes permitted.

The same encoding algorithm shown above for 56 bits also serves for the shortened cases **by forcing the coding algorithm to operate on 56-bit fields.** The difference between the shortened Information Field and the 56 bits is treated by the encoder as "virtual fill" (zeros) preceding the Information Field Bits. These leading zeros are not transmitted. In all cases the overall Codeblock length is always 8 bits longer than the Information Field.

The code generator implementation is shown in Figure 5.4. Note that the shift registers are initialised to zero. The ganged switch is in Position 1 while the N Information Field Bits are being transmitted, in Position 2 for the seven parity bits, and in Position 3 for the appended fill bit.

When the protocol-data unit from the layer above (i.e the Transfer Frame) is encoded, the first octets of this protocol-data unit will be placed in the Information Field of the first Codeblock in harmony with the "Bit and Octet

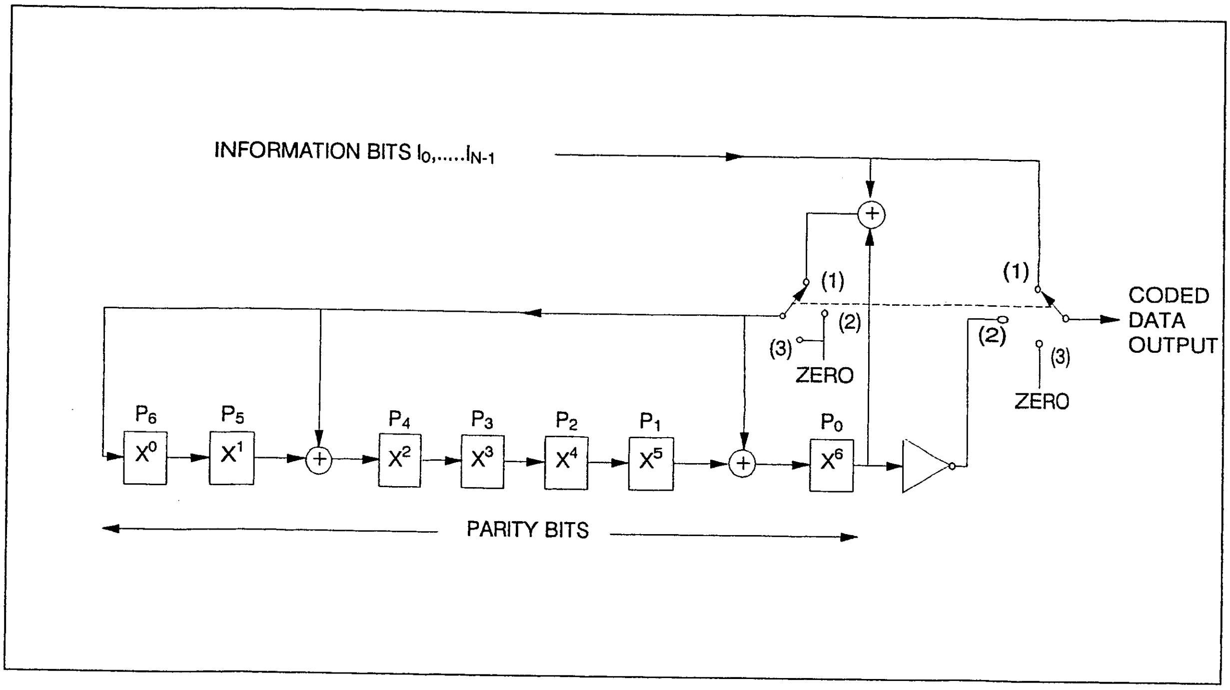

Figure 5.4 (63,56) MODIFIED BCH CODE GENERATOR

Convention" of Section 3: Bit "0" of Octet "0" of the data unit will be placed in Bit "0" of Octet "0" of the Codeblock Information Field, and so on. When the last octet of the Transfer Frame does not coincide with the last information octet of the last Codeblock in the CLTU Codeblock Field (see Figure 5.1), the last information octet(s) of this last Codeblock shall become "Fill Octet(s)". The pattern of a Fill Octet shall consist of a sequence of alternating "zeros" and "ones", ending with a "one".

At the sending end, the insertion of Fill Octets may be performed by the Coding Layer. At the receiving end, however, the removal of Fill Octets shall be the responsibility of the layer above (Transfer Layer).

5.3.2 CLTU Decoding Procedure

5.3.2.1 General Specification

The CLTU decoding procedure is presented in state diagram form in Figure 5.5. To support the state diagram, a list of "states" and "events" is given in Table 5.1.

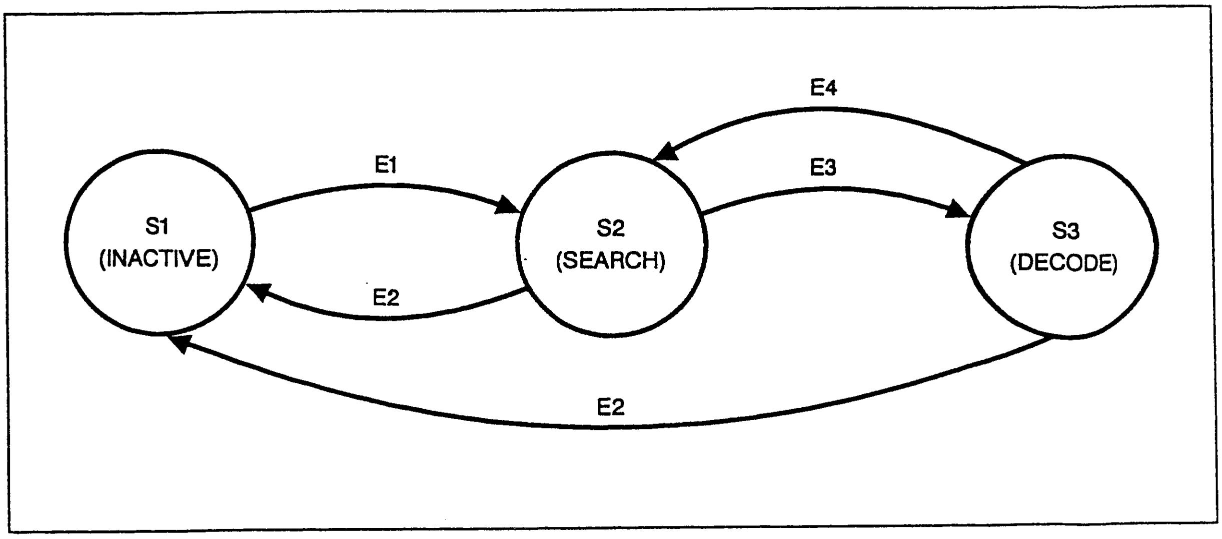

Figure 5.5 CLTU DECODER STATE DIAGRAM

(a) 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 synchronisation achieved), Event 1 (E1) occurs, CHANNEL ACTIVE. If the TC signal is lost or there is a loss of bit lock, Event 2 (E2), CHANNEL INACTIVE, occurs and the CLTU decoder returns to INACTIVE state (S1).

(b) Search State. When E1 occurs, the decoder goes into the SEARCH state (S2). The CLTU structural component unit that governs this event is the CLTU Start Sequence. The bit stream is searched, bit by bit, 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 in the TC Codeblock Field of the CLTU.

If at this point, the signal is lost or there is a loss of bit lock, E2 occurs and the CLTU decoder returns to S1.

(c) Decode State. Assuming E3 has occurred, the decoder enters the DECODE state, (S3). In the DECODE state, the decoder assumes that the incoming symbols are those of TC Codeblocks. Each candidate Codeblock is decoded in the Single Error Correction mode:

State Number	State Name	State Definition
S1	INACTIVE	The telecommand channel is inactive (i.e., "no bit lock is achieved") or, alternatively, no bit modulation is detected.
S2	SEARCH	The incoming bit stream is searched, bit by bit, for the Start Sequence pattern
S3	DECODE	Codeblocks, which are either free of error or which can be corrected, are received and decoded, and their information octets are transferred to the layer above.

Event Number	Event Name	Event Definition
E1	CHANNEL ACTIVATION	Bit modulation is detected and bit lock is achieved: telecommand bit stream is present.
E2	CHANNEL DEACTIVATION	Telecommand bit stream is not present (loss of bit lock or loss of telecommand signal).
E3	START SEQUENCE FOUND	The Start Sequence pattern has been detected, signalling the beginning of the first Codeblock of the CLTU.
E4	CODEBLOCK REJECTION	The decoder has indicated uncorrected errors in a Codeblock. No information octets from this Codeblock are transferred to the layer above.

Table 5.1 STATES AND EVENTS OF THE CLTU DECODER

- If the Codeblock is error free, or if it contained an error which has been corrected, its information octets are transferred to the layer above for further processing.
- If, during the decoding process, a codeblock is found uncorrectable, this Codeblock is abandoned and erased, i.e. its information octets are not 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 "pseudo-codeblock" (of the same length as all other Codeblocks in the stream) having a unique pattern constructed in such a way as to fail the decoder parity check and cause a CODEBLOCK REJECTION (E4), thereby returning 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 by means of a Codeblock rejection: the Tail Sequence pattern should not be detected otherwise.

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, and any on-going Codeblock process is abandoned.

5.3.2.2 Detailed Specification

(a) Start Sequence Detection

The Start Sequence provides two functions:

- to delimit the beginning of a CLTU;
- to resolve the ambiguity between a "one" and a "zero" (which is usually required because of the type of bit representation used on the link, e.g. NRZ-L).

In this Standard, these two functions are specified as mandatory. Detection of the Start Sequence pattern shall be achieved after a bit-by-bit search of the bit stream.

Furthermore, detection of the Start Sequence pattern shall be allowed with **one bit error** anywhere in the Start Sequence.

(b) TC Codeblock Decoding Procedure

Codeblocks shall be decoded in the Single Error Correction (SEC) mode. The following decoding algorithm shall be used:

(i) Process the received Codeblock, ignoring the Filler Bit.
(ii) If no errors are detected in the Codeblock, accept the Codeblock as correct and transfer the information octets to the layer above.
(iii) If one error is detected in the Codeblock, test the Filler Bit:

- If the Filler Bit = 0, correct the error and accept the Codeblock as in (ii).
- If the Filler Bit = 1, declare a Codeblock Rejection (Event E4).

(iv) If two errors are detected in the Codeblock, declare a Codeblock Rejection (Event E4). Ignore the Filler Bit.

The effect of this procedure is to keep the probability of rejecting a Tail Sequence high, taking advantage of the fact that the Filler Bit of a Codeblock is always "0", while the last bit of the "pseudo-codeblock" formed by the Tail Sequence is always "1". (See also Section 11 and Appendix D on performance).

5.3.3 Service Primitives of Interface between Coding Layer and Transfer Layer

This section lists the service primitives of the interface between the Coding Layer and the Frame Control Sublayer of the Transfer Layer. It does not include management information (such as TC codeblock length) which must nevertheless be provided by the Higher Layers.

5.3.3.1 At the Sending End

There are two requests defined from the Frame Error Control Sublayer of the Transfer Layer to the Coding Layer at the sending end of the link: the Transmit Request and the Abort Request. A Transmit Request is acknowledged by the Coding Layer, and an Abort Request is not.

(a) From the Transfer Layer to the Coding Layer

- Transmit Request for Frame
  Parameters:
  - request identifier
  - Transfer Frame octets
- Abort Request
  Parameters: none

(b) From the Coding Layer to the Transfer Layer

Each transmit request is acknowledged by the Coding Layer with one of two possible responses:

- Accept Response
  Parameters:
  - request identifier of Transmit Request
- Reject Response
  Parameters:
  - request identifier of Transmit Request.

5.3.3.2 At the Receiving End

(a) From the Coding Layer to the Transfer Layer

- Candidate Frame Arrived Indication
  Parameters:
  - candidate Transfer Frame octets including:
    - decoded frame octets
    - decoded fill octets

(b) From the Transfer Layer to the Coding Layer

- No service primitives are specified.

5.3.4 Service Primitives of Interface between Coding Layer and Physical Layer

These service primitives and their related actions are defined in Sections 4.3.3 and 4.3.4 respectively.

5.3.5 Actions

5.3.5.1 At the Sending End

On receiving a Transmit Request for Frame, the Coding Layer will respond to the Transfer Layer in one of two ways:

- Accept Response to Transmit Request for Frame: this means that the Coding Layer has stored the frame octets which will be processed as soon as the preceding frame octets have been transmitted
- Reject Response to Transmit Request for Frame: this means that the Coding Layer cannot store the frame octets because there is no more storage space for them.

Each response is identified by the interface-specific request identifier, which is one of the parameters of the Transmit Request.

At most, one Transmit Request may be outstanding: the corresponding Accept Response may be delayed by the Coding Layer until it is ready to receive the next Transmit Request. If a second Transmit Request is received while the preceding one is still outstanding, the Coding Layer generates a Reject Response to the second request. To avoid this, the Higher Layer will keep track of the outstanding requests by means of a variable. When the Transmit Request is generated, the variable (flag) is set to "Not Ready". When the matching Accept Response is received, the Higher Layer resets the variable to "Ready".

On receiving an Abort Request, the Coding Layer shall erase all data in the layer and shall signal the Physical Layer by sending an Abort Request. The Abort Request is not acknowledged by the Coding Layer.

The Abort Request is used typically:

- to erase all non-transferred data when terminating a data link service
- to erase all non-transferred data when the automatic retransmission mechanism of COP-1/AD operates, so that these data are not transmitted unnecessarily.

5.3.5.2 At the Receiving End

The Coding Layer receives the bit stream from the Physical Layer (e.g. RF transponder and demodulator), bit by bit. It also receives a Channel Active Indication signal which is used as specified in Section 5.3.2.

The Coding Layer delivers a synchronised block of octets to the Transfer Layer, which considers it as a candidate Transfer Frame, with the possible presence of appended fill octets.

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6. TRANSFER LAYER

6.1 OVERVIEW OF THE LAYER

6.1.1 Services and Protocols

The Transfer Layer provides the error-free data transfer capability of the space data link. The Transfer Layer draws upon the services of the lower Coding Layer to achieve this capability: forward error correction for high throughput of "clean" data and synchronisation. The main protocol data unit of the Transfer Layer is the TC Transfer Frame.

Inputs to the sending end of the Transfer Layer are TC Segments, which are the protocol data units from the Segmentation Layer. Each TC Segment is embedded into one TC Transfer Frame, which is, in turn, embedded in one single CLTU by the Coding Layer.

There are three types of TC Transfer Frames:

- two types for the "Sequence-Controlled Service"
- one type for the "Expedited Service"

(a) Sequence-Controlled Service

This service is that used for all normal spacecraft communications. It concerns essentially TC Transfer Frames carrying TC Segments: **the AD frames**. TC Segments, when transported within AD Transfer Frames, are delivered to the receiving end of the Transfer Layer with the following guarantee:

- The TC Segments will be delivered to the receiving end of the layer above in the same sequential order in which they were received from the layer above at the sending end, possibly with some variable delay (mission-specific) between Segments.
- No TC Segment will contain an error
- No TC Segment will be lost
- No TC Segment will be duplicated

The functions and protocols required to achieve this service are those defined by the CCSDS "Command Operation Procedure One" (COP-1). In COP-1, the AD service is based on an "automatic request for retransmission

(ARQ)" procedure of the "Go-back N" type with sequence-control mechanisms both on ground and on board the spacecraft, and the necessary presence of a standard return data report in the telemetry downlink: the Command Link Control Word (CLCW).

It is operationally necessary to configure the AD service protocol machine at the receiving end of the layer. This is done by means of protocol control instructions which are resident in the Transfer Layer. These control instructions are contained within special TC Transfer Frames **called BC frames** (they are also called "**control frames**", as opposed to "**data frames**"). The guarantee of the AD service is extended to the transfer of BC frames, but by much simpler means: the ARQ is a "Transmit-One, Stop-and-Wait" procedure with no sequence-control mechanism on board the spacecraft and the necessary presence of a data return path (CLCW).

(b) Expedited Service

This service is that used for exceptional spacecraft communications. Typically, this service is required for recovery in absence of telemetry downlink (i.e. no CLCW), or during unexpected situations (such as telecommand system lockout) requiring unimpaired access to the spacecraft data management system.

The Expedited Service is only concerned with TC Transfer Frames carrying TC Segments: **the BD frames**. TC Segments, when transported within BD Transfer Frames (also called "By-pass data frames"), are delivered at the receiving end of the Transfer Layer with the following guarantee:

- The TC Segments will be delivered to the receiving end of the layer above in the same sequential order in which they were received from the layer above at the sending end.
- No TC Segment will contain an error.
- Any number of TC Segments may be lost.

The BD service does not make use of an ARQ procedure: BD frames are simply transmitted once and forgotten by the sending end of the Transfer Layer. No use is made of the telemetry downlink data by the Transfer Layer. Any retransmission request must be made by the layers above.

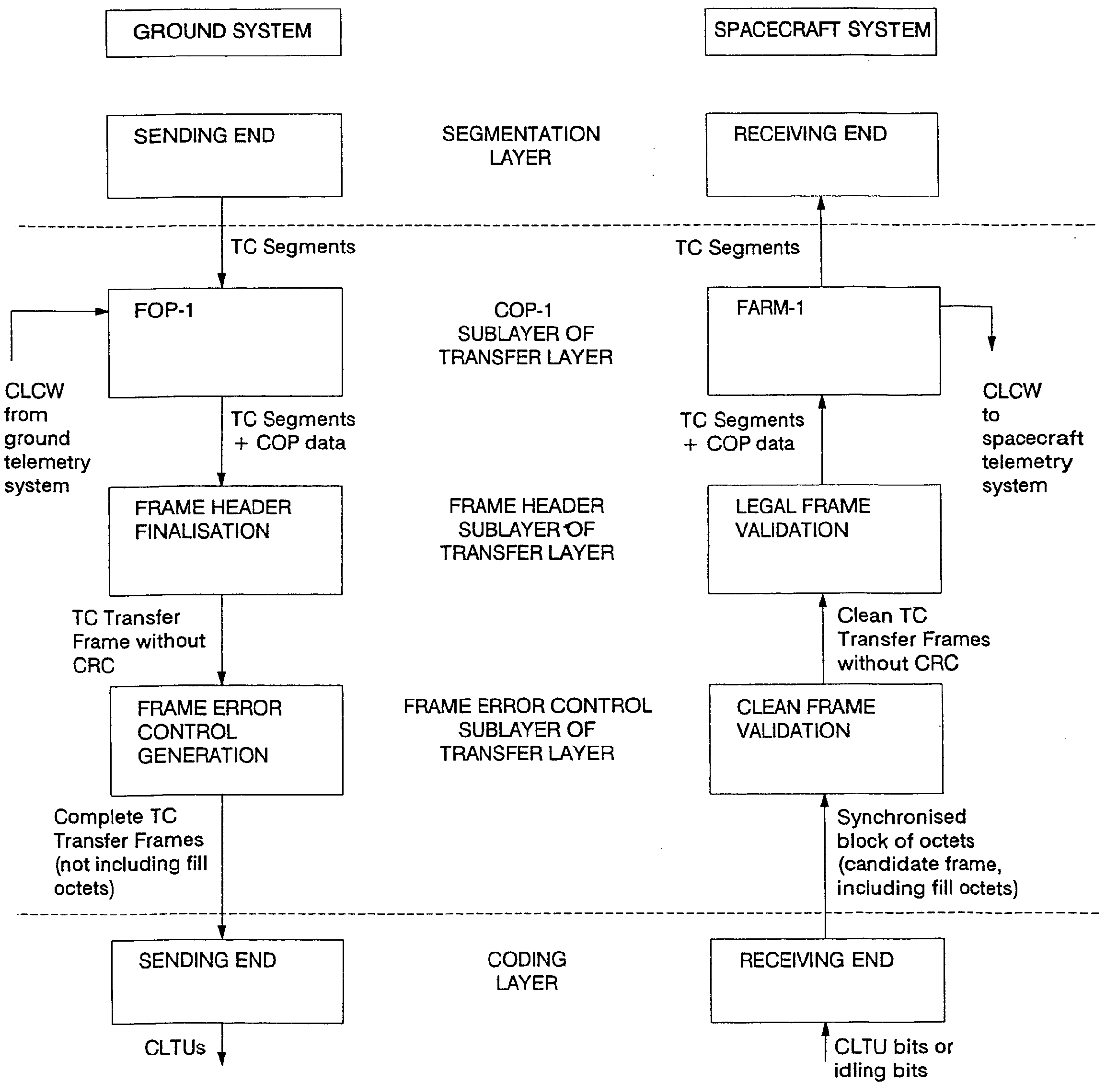

Figure 6.1 OVERVIEW OF THE ENVIRONMENT OF THE TRANSFER LAYER

6.1.2 Transfer Layer Sublayers

Figure 6.1 shows an overview of the environment in which the Transfer Frame operates and shows the data flow between elements.

The protocol and services of a layer are carried out by a set of functions performed within the layer. Individual functions of the Transfer Layer may be considered to belong to different sublayers within the layer. In this standard, three sublayers are distinguished:

- The COP-1 Sublayer
- The Frame Header Sublayer
- The Frame Error Control Sublayer

(a) COP-1 Sublayer

The COP-1 Sublayer is the highest layer within the Transfer Layer. The COP-1 Sublayer implements a communications protocol whose purpose is to detect and correct certain types of errors (e.g. AD Transfer Frames out of sequence) that may occur during transmission.

The COP-1 functions of the sending end of the COP-1 Sublayer are grouped into an entity called the "Frame Operation Procedure One" process, or FOP-1. The COP-1 functions at the receiving end of the COP Sublayer are grouped into an entity called the "Frame Acceptance and Reporting Mechanism One", or FARM-1.

The reporting function of the FARM-1 generates the CLCW which is telemetered back to the FOP-1 in the trailers of the Telemetry Transfer Frames, as specified in Reference [7]. Figure 6.1 shows the output and input parts of the telemetry system.

(b) Frame Header Sublayer

The Frame Header Sublayer lies below the COP-1 Sublayer and above the Frame Error Control Sublayer. The purpose of the Frame Header Sublayer at the sending end is to edit the complete header of each TC Transfer Frame to be generated.

Inputs to the Frame Header Finalisation process at the sending end of the Sublayer are essentially:

- TC Segments, for "data frames", or protocol control instructions for "control frames";
- COP-1-specific information (e.g. ARQ information);
- spacecraft-specific information (e.g. spacecraft identification information).

For each TC Segment (or protocol control instruction) the Frame Header Finalisation process provides a complete TC Transfer Frame, with the exception of the last two octets which form the Frame Error Control Field.

At the receiving end of the sublayer, "clean" frames are provided by the Frame Error Control Sublayer. These "clean" frames are essentially TC Transfer Frames without the Frame Error Control CRC. The Legal Frame Validation process verifies the conformity of the relevant frame header fields before passing the TC Segment (or protocol control instruction) with its COP-1 information to the FARM-1 for "acceptance".

(c) Frame Error Control Sublayer

The Frame Error Control Sublayer lies below the Frame Header Sublayer. The purpose of the Frame Error Control Sublayer is to ensure that the layer above does not receive frames that contain errors caused by the transmission process.

At the sending end, the Frame Error Control Generation process generates an error-detecting cyclic redundancy code (CRC) and places it in the last two octets (Frame Error Control field) of the TC Transfer Frame.

At the receiving end, a CRC error syndrome verification ensures that only "clean" frames are transferred to the sublayers above. This Clean Frame Validation process also ensures that any "fill octets" generated by the Coding Layer conform to the protocol rules and are removed.

6.2 STANDARD DATA STRUCTURES WITHIN THE LAYER

6.2.1 Transfer Layer Protocol Data Units

The communications protocol between the Transfer Layer elements on ground and the Transfer Layer elements on board the spacecraft is conducted using the two following protocol data units:

- The TC Transfer Frame, carried by the telecommand uplink.
- The Command Link Control Word (CLCW), carried by the telemetry downlink.

For various reasons, and in particular for reasons of efficient packing of data into octet-sized units, the layout of the various fields in these protocol data units does not closely reflect the layering of the telecommand system. The layout of the structures is described globally in this Section 6.2 rather than in the sections relating to each sublayer because it is not possible to separate the data elements belonging to each sublayer in a practical manner.

6.2.2 TC Transfer Frame Format

The TC Transfer Frame, which is shown in Figure 6.2, consists of the following major fields:

MAJOR FIELD	LENGTH (OCTETS)
Frame Header	5
Frame Data Field	Variable (1 to 249)
Frame Error Control Field (Mandatory)	2
Total =	Variable (8 to 256)

5 OCTETS	1 TO 249 OCTETS	2 OCTETS
FRAME HEADER	FRAME DATA FIELD	FRAME ERROR CONTROL FIELD (MANDATORY)

Figure 6.2 TRANSFER FRAME FORMAT

6.2.2.1 Frame Header

The Frame Header, which is shown in Figure 6.3, consists of 40 bits (5 octets) grouped into octets as follows:

FIELD	LENGTH (BITS)
First Two Octets:	
- Version Number	2
- Bypass Flag	1
- Control Command Flag	1
- Reserved Field A	2
- Spacecraft ID	10
Third Octet:	
- Virtual Channel ID	6
- Reserved Field B	2
Last Two Octets:	
- Frame Length	8
- Frame Sequence Number	8
Total =	40

2 OCTETS					1 OCTET		1 OCTET	1 OCTET
VERSION NUMBER	BYPASS FLAG	CONTROL COMMAND FLAG	RESERVED FIELD A	SPACE CRAFT ID	VIRTUAL CHANNEL ID	RESERVED FIELD B	FRAME LENGTH	FRAME SEQUENCE NUMBER
2	1	1	2	10	6	2	8	8

Figure 6.3 FRAME HEADER FORMAT

The first two octets of the Frame Header are subdivided as follows:

(a) Version Number (Bits 0,1)

The Version Number is a 2-bit field identifying the formal structure of the Transfer Frame. The Version Numbers are defined by the CCSDS. **IN THIS STANDARD, ONLY ONE VERSION NUMBER (VERSION 1) IS RECOG-**

NIZED, which specifies the TC Transfer Frame structure described herein. This number is:

Bits 0,1 = 00

(b) Bypass Flag (Bit 2)

The Bypass Flag is used by the COP-1 Sublayer in combination with the Control Command Flag to select the type of Transfer Frame and the required transfer service. The term "bypass" signifies that the sequence-control mechanism of FARM-1 is not used for the service.

- When the flag is set to "0", the Transfer Frame is said to be of the type "A": the FARM-1 sequence-control mechanism is used.
- When the flag is set to "1", the Transfer Frame is said to be of the type "B": the FARM-1 sequence-control mechanism is not used.

The next paragraph (c) on the Control Command Flag specifies how both flags are used in combination.

(c) Control Command Flag (Bit 3)

The Control Command Flag is used by the COP-1 Sublayer in combination with the Bypass Flag to select the type of Transfer Frame and the required transfer service. A "Control Command" is a protocol control instruction used by the COP sublayer to configure the protocol machine at the receiving end (FARM-1).

- When the flag is set to "0", the Transfer Frame does not carry Control Commands, but data units (e.g. TC Segments): the frame is said to be of the type "D" ("data frame").
- When the flag is set to "1", the Transfer Frame does not carry data, but Control Commands: the frame is said to be of the type "C" ("control frame").

Since, as mentioned in Section 6.1.1, control frames do not make use of the FARM-1 sequence-control mechanism, they must also be of the B type. Table 6.1 specifies how the combined states of the Bypass Flag and the Control Command Flag must be interpreted.

BYPASS FLAG	CONTROL COMMAND FLAG	INTERPRETATION
0	0	AD Frame: carries data in the Sequence-Controlled Service mode.
0	1	ILLEGAL COMBINATION
1	0	BD Frame: carries data in the Expedited Service mode.
1	1	BC Frame: carries control command information in the Sequence-Controlled Service mode.

Table 6.1 INTERPRETATION OF COMBINED STATES OF "BYPASS" AND "CONTROL COMMAND" FLAGS

(d) Reserved Field A (Bits 4,5)

This 2-bit field is reserved by the CCSDS for future applications. In this Standard, the two bits must be set as follows:

Bits 4,5 = 00

(e) Spacecraft Identifier (Bits 6 through 15)

This 10-bit field provides positive identification of the spacecraft being commanded.

ESA Projects shall obtain these identifiers from the ESA Directorate of Operations (D/OPS), ESOC, Darmstadt, FRG.

The third octet of the Frame Header is subdivided as follows:

(f) Virtual Channel Identifier (Bits 0 through 5)

In this Standard, the Virtual Channel Identifier is used as a spacecraft sub-identifier, in combination with the Spacecraft Identifier. Therefore, this

6-bit field provides positive identification of the spacecraft telecommand chain (typically: two chains for redundancy) selected for operating the spacecraft.

ESA Projects shall obtain these identifiers from the ESA Directorate of Operations (D/OPS), ESOC, Darmstadt, FRG.

(NOTE: See also Section 6.3, where it is specified that both Spacecraft Identifier and Virtual Channel Identifier values, as well as some others, must remain constant throughout a distinct Transfer Layer service, from the time when a Directive signals the beginning of the service until the time when another Directive signals its termination).

(g) Reserved Field B (Bits 6,7)

This 2-bit field is reserved by the CCSDS for future applications. In this Standard, the two bits must be set as follows:

Bits 6,7 = 00

The fourth octet of the Frame Header contains the following field:

(h) Frame Length (Bits 0 through 7)

The Frame Length is an 8-bit field which specifies the number of octets contained within the entire TC Transfer Frame. The number is a binary value "C" expressed as follows:

C = [(Total number of octets) - 1]

The maximum number of octets in a TC Transfer Frame is 256, and the minimum number is 8 octets (corresponding to 1 octet of Frame Data Field).

The fifth octet of the Frame Header contains the following field:

(i) Frame Sequence Number (Bits 0 through 7)

The "Frame Sequence Number", which is denoted as N(S) is set to different values depending on the type of Transfer Frame:

- For type-AD Transfer Frames, the 8-bit field is set to the value of the FOP-1 variable "Transmitter_Frame_Sequence_Number" (which is denoted as V(S)) at the time each AD frame is prepared for transfer. (Because of propagation delays in the sending end of the telecommand system and during uplink, it is necessary to make a clear distinction between the current value of V(S) in the FOP-1 and the value of N(S) in each of the transmitted AD frames. Section 6.2.3, Paragraph (n), and the related Figure 6.6 provide more information on COP-1 variables and Frame Sequence Number values.)
- For type-BC and -BD Transfer Frames, the 8-bit field must be set to "all zeros".

6.2.2.2 Frame Data Field

The Frame Data Field is of variable length. This length is measured in integral octets, from a minimum of 1 octet to a maximum of 249 octets.

When the frame is a "data frame" (type-AD or -BD), the Frame Data Field contains a protocol data unit from the layer above, i.e. a TC Segment. The Transfer Layer does not interpret TC Segments, since its primary function is to transfer these data safely to the receiving end of the layer above.

When the frame is a "control frame" (type-BC), the Frame Data Field contains protocol information belonging to the Transfer Layer, i.e. a Control Command. Control Commands are data structures which are generated and used only within the layer:

- They are generated as a result of control directives from the layer(s) above.
- They are used to specify the governing FARM-1 parameters for the Virtual Channel to which they are addressed.

In a "control frame", the Frame Data Field can, effectively, be considered as an extension of the Frame Header. In this Standard, two Control Commands are defined to configure FARM-1:

- UNLOCK
- SET V(R)

A control frame shall only contain one Control Command at a time. The format of these commands is as follows:

(a) UNLOCK Control Command

FARM-1 has a built-in safety mechanism which will go into a "Lockout" whenever it receives a type-AD frame containing a Frame Sequence Number N(S) outside the limits of the "FARM-1 Sliding Window" (See specification further in Section 6.3).

The UNLOCK Control Command is provided to reset this "Lockout" condition.

The Control Command is encoded as a single octet with the value:

```
Bit 0 |      | Bit 7
      00000000
```

(b) SET V(R) Control Command

FARM-1 verifies the Frame Sequence Number, N(S), of incoming AD frames and maintains a count V(R) of the next-expected number. The N(S) of each incoming AD frame is checked against the value of V(R).

The SET V(R) Control Command allows V(R) to be preset to any desired value, if so required by the ground network. The Control Command is encoded as three octets with the values:

```
        FIRST          SECOND         THIRD
        OCTET          OCTET          OCTET

Bit 0 |                                       | Bit 23
      10000010       00000000       XXXXXXXX
```

The value to be set into V(R) is contained in the third octet of the set V(R) Control Command.

6.2.2.3 Frame Error Control Field

The Frame Error Control Field is a **mandatory** 16-bit field which occupies the two trailing octets of the TC Transfer Frame.

The purpose of this field is to provide a capability for detecting errors which may have been introduced into the frame by the lower layers during the transmission process and may have remained undetected [(1)].

The standard error detection encoding/decoding procedure, which is described in detail in the next paragraphs, produces a 16-bit Frame Check Sequence (FCS) which is placed in the Frame Error Control Field. The characteristics of the FCS are those of a cyclic redundancy code, and are generally expressed as follows:

(a) The generator polynomial is:

$$g(x) = x^{16} + x^{12} + x^5 + 1$$

(b) Both encoder and decoder are initialised to the "all-ones" state for each TC Transfer Frame.

(c) FCS generation is performed over the data space "D" as shown in Figure 6.4 where "D" covers the entire TC Transfer Frame less the final 16-bit FCS.

(d) The code has the following capabilities when applied to an encoded block of less than 32 768 (2^{15}) bits:

- All error sequences composed of an odd number of bit errors will be detected.
- All error sequences containing two bit errors anywhere in the encoded block will be detected.
- 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 3×10^{-5}).
- All single error bursts spanning 16 bits or less will be detected, provided no other errors occur within the block.

NOTE (1): See Section 11 on services and performance, where the influence of the frame error detection mechanism on the overall Transfer Frame rejection and undetected error rates is described.

This code is intended only for error detection purposes and no attempt should be made to utilise it for correction.

TRANSFER FRAME	
"D" DATA SPACE	FCS
6 TO 254 OCTETS	2 OCTETS

Figure 6.4 STANDARD FRAME CHECK SEQUENCE GENERATION

(a) Encoding Procedure

The encoding procedure accepts an (n-16)-bit message 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 block. This FCS is inserted into the Frame Error Control Field. The equation for FCS is:

$$FCS = [X^{16} . M(X) + X^{(n-16)} . L(X)] \text{ MODULO } G(X)$$

where: M(X) is the (n-16)-bit message to be encoded expressed as a polynomial with binary coefficients, n being the number of bits in the encoded message **(i.e. the number of bits in the complete Transfer Frame).**

L(X) is the presetting polynomial given by:

$$L(x)=\sum_{i=0}^{15} x^i$$

(all "1" polynomial of order 15)

G(X) is the CCITT Recommendation V.41 generating polynomial given by:

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

+ 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 $X^{(n-16)}$. L(X) term has the effect of presetting the shift register to an all ones state (rather than a conventional all zeros state) prior to encoding [(1)].

(b) Decoding Procedure

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

$$S(X) = [X^{16} . C^*(X) + X^n . L(X)] \text{ MODULO } G(X)$$

where: C* (X) is the received block in polynomial form.

S(X) is the syndrome polynomial which will be zero if no error has been detected.

6.2.3 Command Link Control Word Format

The Command Link Control Word (CLCW), which is shown in Figure 6.5, is a standard reporting data structure of the Packet Telecommand System.

The CLCW is a four-octet word generated by the spacecraft end of the telecommand system and inserted in the Trailer of each Telemetry Transfer Frame, as specified in Reference [7]. There are, typically, two telecommand Virtual Channels per spacecraft and therefore two CLCWs. **Appendix C (Data Link Management and Monitoring)** discusses the recommended options for CLCW multiplexing on the telemetry downlink.

The main features of this reporting system are:

- The CLCW is essentially meant to be used in automated transmission/re-transmission processes. Therefore, CLCW data must be delivered "clean" to the sending end of the telecommand system.
- The protocol information contained in the CLCW is such that it is not required that the TM Transfer Frame rate match the TC Transfer Frame rate. However, some minimum CLCW sampling rate must be estab-

---

NOTE (1): See also **Appendix B: Possible Realisation of a Frame Check Sequence Encoder-Decoder**.

lished for the proper operation of COP-1 in each mission environment (see also Section 6.3.3.2, Paragraph (xi)).

Although most of the CLCW data concerns the COP Sublayer, some of its information elements form reports addressed to other layers. Also, some information fields, which are not used in this Standard, are set to fixed values.

2 OCTETS

CONTROL WORD TYPE	CLCW VERSION NUMBER	STATUS FIELD	COP IN EFFECT	VIRTUAL CHANNEL IDENTIFIER	RESERVED FIELD
1	2	3	2	6	2

Control Word Type: As defined in Reference [7]

2 OCTETS

NO RF AVAIL	NO BIT LOCK	LOCK OUT	WAIT	RETRANSMIT	FARM B COUNTER	REPORT TYPE	REPORT VALUE
1	1	1	1	1	2	1	8

Figure 6.5 COMMAND LINK CONTROL WORD FORMAT

The fields of the CLCW can be characterised as follows:

FIELD	LENGTH (BITS)	**LAYER IN USE ON GROUND**
Control Word Type	1	TM/TC System
CLCW Version Number	2	TC System
Status Field	3	TC System
COP in Effect	2	TC Transfer Layer
Virtual Channel ID	6	TC Transfer Layer
Reserved Field	2	TC System
No RF Available Flag	1	TC System
No Bit Lock Flag	1	TC System
Lockout Flag	1	TC Transfer Layer

FIELD	LENGTH (BITS)	**LAYER IN USE ON GROUND**
Wait Flag	1	TC Transfer Layer
Retransmit Flag	1	TC Transfer Layer
FARM B Counter	2	TC Data Management Layer(s)
Report Type	1	TC System
Report Value	8	TC Transfer Layer
Total =	32	

Each CLCW field is specified in the next paragraphs.

(a) Control Word Type (Bit 0)

From a strict system point of view, this one-bit information does not belong to the telecommand system, although it is clearly associated with it. The Control Word Type flag is specified in Reference [7] as Bit 0 of the Operational Control Field of the Telemetry Transfer Frame Trailer. The flag is used by the receiving end of the telemetry system to route the information contained in the Operational Control Field to the relevant system or process.

Reference [7] specifies that when the data structure contained in the Operational Control Field is a CLCW, Bit 0 shall be set to 'zero'.

Therefore, when Bit 0 = 0, the receiving end of the telemetry system shall route the information contained in the Operational Control Field to the sending end of the telecommand system.

(b) CLCW Version Number (Bits 1,2)

The CLCW Version Number is a 2-bit field reserved by the CCSDS for potential evolution of the CLCW structure. **IN THIS STANDARD, ONLY ONE VERSION NUMBER (VERSION 1) IS RECOGNIZED**, which specifies the CLCW structure described herein. This number is:

Bits 1,2 = 00

(c) Status Field (Bits 3,4,5)

This 3-bit field is reserved by the CCSDS for future application. In this Standard, it is required that the field be set to the value "000".

(d) COP in Effect (Bits 6,7)

This 2-bit field is used to indicate which of the CCSDS-defined COPs is in use. **IN THIS STANDARD, ONLY COP-1 IS SPECIFIED,** which corresponds to the following value:

Bits 6,7 = 01

(e) Virtual Channel Identifier (Bits 8 through 13)

This 6-bit field contains the Virtual Channel Identifier of the TC Virtual Channel to which **all other Transfer Layer protocol information contained in the CLCW refers.**

(f) Reserved Field (Bits 14, 15)

This 2-bit field is reserved by the CCSDS for future application. In this Standard, it is required that the field be set to the value "0 0".

(g) "No RF Available" Flag (Bit 16)

The "No RF Available" Flag is dedicated to the Physical Layer, as specified in Section 4 (Carrier Modulation Mode CMM-1). Since RF transponders are typically redundant, the flag shall represent the logical product of all "Not Available" status on the spacecraft RF subsystem.

- When Bit 16 = "1", the RF physical connection is not available through any of the spacecraft transponders
- When Bit 16 = "0", the RF physical connection is available through at least one of the spacecraft transponders.

It should be noted that the presence of this flag in the CLCW fulfils an operational requirement. This does not preclude the transmission of more complete status information via a telemetry Source Packet for monitoring purposes.

(h) "No Bit Lock" Flag (Bit 17)

The "No Bit Lock" Flag is dedicated to the Physical Layer, as specified in Section 4 (Carrier Modulation Mode CMM-2). Since the spacecraft demodulation subsystem is typically redundant, the flag shall represent the logical product of all "No Bit Lock" status in the complete subsystem:

- When Bit 17 = "1", none of the spacecraft demodulation units has achieved bit lock.
- When Bit 17 = "0", at least one of the spacecraft demodulation units has achieved bit lock.

It should be noted that the presence of this flag in the CLCW fulfils an operational requirement. This does not preclude the transmission of more complete status information via a telemetry Source Packet for monitoring purposes.

(i) "Lockout" Flag (Bit 18)

The "Lockout" Flag is dedicated to the COP-1 Sublayer. The "Lockout" function of COP-1 is fully described in Section 6.3. The states of the flag are specified as follows:

- When Bit 18 = "1", this indicates that FARM-1 is in a "Lockout" state.
- When Bit 18 = "0", this indicates that FARM-1 is not in a "Lockout" state.

(j) "Wait" Flag (Bit 19)

The "Wait" Flag is dedicated to the COP-1 Sublayer. The "Wait" function of COP-1 is fully described in Section 6.3. The states of the flag are specified as follows:

- When Bit 19 = "1", this indicates that FARM-1 is in a "Wait" state.
- When Bit 19 = "0", this indicates that FARM-1 is not in a "Wait" state.

(k) "Retransmit" Flag (Bit 20)

The "Retransmit" Flag is dedicated to the COP-1 Sublayer. The "Retransmit" function is fully described in Section 6.3. The states of the flag are specified as follows:

- When Bit 20 = "1", this indicates that FARM-1 requests retransmission of all type - AD Transfer Frames starting with the frame of number N(R) as indicated in the "Report Value" field of the CLCW.
- When Bit 20 = "0", this indicates that FARM-1 does not request retransmission of type - AD Transfer Frames.

(l) FARM - B Counter (Bits 21, 22)

This 2 - bit field contains a sequential up-count (modulo 4) of each TC Transfer Frame of type B (BC or BD) declared valid by the Legal Frame Validation process and, therefore, "acceptable" by the FARM-1, as specified in Section 6.3.

The purpose of the FARM-B Counter is to support the verification process of type-B Transfer Frames by the layers above the Transfer Layer. The FARM-B Counter is not used by the FOP-1.

It should be noted that, to verify the correct reception of the two standard control frames (BC) defined in this standard (i.e. "Unlock" and "Set V(R)"), the FOP-1 process makes use of the following CLCW information:

- "Lockout" flag, for the "Unlock" Control Command
- "Report Value" field, for the "Set V(R)" Control Command.

For BD Frames, no check is performed by the FOP-1 to verify their reception on board the spacecraft.

(m) Report Type (Bit 23)

This field is not applicable to COP-1 and is thus ignored by the Transfer Layer processes on ground when the "COP in Effect" field (Bits 6,7) contains the value "01". In this standard, it is required that Bit 23 be set to the value "0".

(n) Report Value (Bits 24 through 31)

This 8-bit field is set to the value maintained by the FARM-1 and which specifies the next expected frame sequence number, V(R), at the time the CLCW contents have been sampled and acquired by the telemetry system on board the spacecraft.

Because of propagation delays in the telemetry system and downlink, the value of this field (as many others in the CLCW) can only reflect the state of the FARM-1 internal registers at the time when the CLCW is sampled by the telemetry system. Therefore, to make a clear distinction between the current value of the next expected frame sequence number, V(R), in FARM-1 and the value contained in the Report Value Field, this last value is referred to as the "Next Expected Frame Sequence Number", N(R), while V(R) is referred to as the "Receiver Frame Sequence Number". In the same fashion, V(S) is referred to as the "Transmitter Frame Sequence Number", and N(S) as the "Frame Sequence Number". Figure 6.6 provides an illustration of these values.

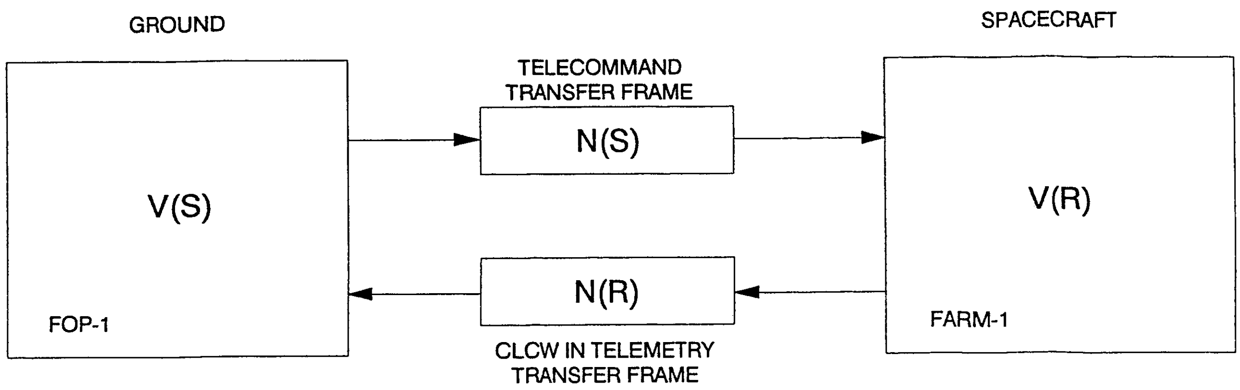

Figure 6.6 COP-1 VARIABLES, FRAME AND REPORT VALUES

6.3 STANDARD PROCEDURES WITHIN THE LAYER

6.3.1 Frame Error Control Sublayer

6.3.1.1 Service and Protocol

The service provided by the Frame Error Control Sublayer to the layer above (Frame Header Sublayer) consists in detecting any error introduced by the transmission process through the lower layers and the physical medium.

From a peer protocol standpoint, this service involves the following activities:

- **At the Sending End:**
  - the Frame Error Control Generation process generates the Frame Check Sequence (FCS, as defined in Section 6.2) for each Version 1 Transfer Frame.

- **At the Receiving End:**
  - the Clean Frame Validation process reads the Frame Length field (the fact that Version 1 Transfer Frames are used is implied).
  - the block of data and fill octets provided by the Coding Layer is verified against the protocol rules, assuming the TC codeblock length is known (fixed, mission-specific) by the process.
  - all candidate frames passing the test have any fill octets removed and go through an FCS error syndrome detection: only error-free frames are passed to the Sublayer above (Frame Header Sublayer) for further processing.

As already mentioned in Section 5.3, the insertion, at the sending end, of fill octets is best performed by the Coding Layer implementation. This is because, unlike the receiving end, the sending end must be able to support several TC Codeblock lengths. In the Coding Layer, a single and simple "octet-stuffing" mechanism will prove sufficient for any TC Codeblock length. This is not the case when the insertion is performed by the Transfer Layer.

The Sublayer contains no externally visible variable. All processing at both ends of the link is on a frame-by-frame basis with no values retained between activations of the Sublayer process.

6.3.1.2 Service Primitives of Interface between Frame Error Control Sublayer and Frame Header Sublayer

This section lists the service primitives of the interface between the Frame Error Control Sublayer of the Transfer Layer and the Frame Header Sublayer of the Transfer Layer.

(a) At the Sending End

There are two requests defined from the Frame Header Sublayer of the Transfer Layer to the Frame Error Control Sublayer of the Transfer Layer at the sending end of the link : the Transmit Request and the Abort Request. A Transmit Request is acknowledged by the Frame Error Control Sublayer, and an Abort Request is not.

- **From the Frame Header Sublayer to the Frame Error Control Sublayer**

– Transmit Request for Frame
  Parameters:
  – request identifier
  – Transfer Frame (without FCS)
– Abort Request
  Parameters: none

- **From the Frame Error Control Sublayer to the Frame Header Sublayer**

Each transmit request is acknowledged by the Frame Error Control Sublayer with one of two possible responses:

– Accept Response
  Parameters:
  – request identifier of Transmit Request.
– Reject Response
  Parameters:
  – request identifier of Transmit Request.

(b) At the Receiving End

- **From the Frame Error Control Sublayer to the Frame Header Sublayer**

– Clean Frame Arrived Indication
  Parameters:
  – Transfer Frame (without FCS)

- **From the Frame Header Sublayer to the Frame Error Control Sublayer**

– No service primitives are specified.

6.3.1.3 Service Primitives of Interface between Frame Error Control Sublayer (of the Transfer Layer) and Coding Layer

These service primitives and their related actions are defined in Sections 5.3.3 and 5.3.5 respectively.

6.3.1.4 Actions

(a) At the Sending End

On receiving a Transmit Request for Frame, the Frame Error Control Sublayer will respond to the Frame Header Sublayer in one of two ways:

- Accept Response to Transmit Request for Frame: this means that the Frame Error Control (F.E.C.) Sublayer has stored the frame data which will be processed as soon as the preceding frame data have been transmitted
- Reject Response to Transmit Request for Frame: this means that the F.E.C. Sublayer cannot store the frame data because there is no more storage space for them.

Each response is identified by the interface-specific request identifier, which is one of the parameters of the Transmit Request.

At most, one Transmit Request may be outstanding: the corresponding Accept Response may be delayed by the F.E.C. Sublayer until it is ready to receive the next Transmit Request. If a second Transmit Request is received while the preceding one is still outstanding, the F.E.C. Sublayer generates a Reject Response to the second request. To avoid this, the Higher Layer will keep track of the outstanding requests by means of a variable. When the Transmit Request is generated, the variable (flag) is set to "Not Ready". When the matching Accept Response is received, the Higher Layer resets the variable to "Ready".

On receiving an Abort Request, the F.E.C. Sublayer shall erase all data in the layer and shall signal the Coding Layer by sending an Abort Request. The Abort Request is not acknowledged by the F.E.C. Sublayer.

The Abort Request is used typically:

- to erase all non-transferred data when terminating a data link service;

- to erase all non-transferred data when the automatic retransmission mechanism of COP-1/AD operates, so that these data are not transmitted unnecessarily.

(b) At the Receiving End:

On receiving a Frame Arrived Indication, the Clean Frame Validation process will perform the following tasks, in the order given below:

- The number of octets in the block making up a Candidate Transfer Frame shall be checked to be greater than 7 octets.
- The Transfer Frame being assumed to be a Version 1 frame, and the TC Codeblock length being assumed fixed and known, the Frame Length field shall be read and the number of fill octets verified to be as specified in Section 5.
- Fill octets shall be removed from good frame candidates and the FCS decoding procedure carried out (CRC error syndrome verification).
- All candidate frames passing successfully all of the preceding validation checks are declared "clean" and transferred immediately to the layer above by means of a Clean Frame Arrived Indication; frames failing any of the preceding tests are declared "dirty" and are erased.

6.3.2 Frame Header Sublayer

6.3.2.1 Service and Protocol

The service provided by the Frame Header Sublayer to the layer above (COP-1 Sublayer) consists in providing recognizable protocol data units in the form of TC Transfer Frames.

From a peer protocol standpoint, this service involves the following activities:

(a) At the Sending End

- Frame Header Finalisation

The Frame Header is formatted into its final form. In the case of Control Frames (BC), one or other of the two standard Control Commands is inserted in the Frame Data Field.

(b) At the Receiving End

- Legal Frame Validation

For each "clean" frame, the Legal Frame Validation process verifies the format of the Frame Header and checks the Spacecraft and Virtual Channel Identifiers. In addition to this, the format of the BC frames (Control Frames) **actually implemented** within the Sublayer is also checked.

Frames declared "legal" are passed to the COP-1 Sublayer. Frames failing to pass the validation checks are erased.

The Sublayer contains no externally visible variable. All processing at both ends of the link is on a frame-by-frame basis with no values retained between activations of the Sublayer process.

6.3.2.2 Service Primitives of Interface between Frame Header Sublayer and COP-1 Sublayer

This section lists the service primitives of the interface between the Frame Header Sublayer of the Transfer Layer and the COP-1 Sublayer of the Transfer Layer.

The COP-1 Sublayer is represented by the FOP-1 at the sending end and the FARM-1 at the receiving end.

(a) At the Sending End

There are two requests defined from the COP-1 Sublayer of the Transfer Layer to the Frame Header Sublayer of the Transfer Layer at the sending end: the Transmit Request and the Abort Request. A Transmit Request is acknowledged by the Frame Header Sublayer, and an Abort Request is not.

- **From the COP-1 Sublayer (FOP-1) to the Frame Header Sublayer**

- Transmit Request for Frame
  Parameters:
    - request identifier
    - frame information, including:
        - version/format identifier
        - type identifier (AD, BD or BC)
        - spacecraft identifier
        - Virtual Channel identifier
        - N(S) for AD frames

    - data (TC Segment or Control Command)
- Abort Request
  Parameters:
    - Virtual Channel identifier

- **From the Frame Header Sublayer to the COP-1 Sublayer (FOP-1)**

Each Transmit Request is acknowledged by the Frame Header Sublayer with one of two possible responses:

- Accept Response
  Parameters:
    - request identifier of Transmit Request
    - Virtual Channel identifier
- Reject Response
  Parameters:
    - request identifier of Transmit Request.
    - Virtual Channel identifier

(b) At the Receiving End

- **From the Frame Header Sublayer to the COP-1 Sublayer (FARM-1)**

- Legal Frame Arrived Indication
  Parameters:
    - frame information, including:
      - type identifier (AD, BD or BC)
      - Virtual Channel identifier
      - N(S) for AD frames
      - data, i.e:
        - TC Segment for AD and BD frames
        - command activation for "Unlock" BC frame
        - V(R) command information for "Set V(R)" BC frame

The frame type identifier is used for demultiplexing the frame data of different services (AD, BD, BC). The Virtual Channel identifier is used to select that instance of the FARM-1 which is responsible for the Virtual Channel.

- **From the COP-1 Sublayer (FARM-1) to the Frame Header Sublayer**

– No service primitives are specified.

6.3.2.3 Service Primitives of Interface between Frame Header Sublayer and Frame Error Control Sublayer

These service primitives and their related actions are defined in Sections 6.3.1.2 and 6.3.1.4 respectively.

6.3.2.4 Actions

(a) At the Sending End

On receiving a Transmit Request for Frame, the Frame Header Sublayer will respond to the COP-1 Sublayer in one of two ways:

- Accept Response to Transmit Request for Frame: this means that the Frame Header (F.H.) Sublayer has stored the frame data which will be processed as soon as the preceding frame data have been transmitted
- Reject Response to Transmit Request for Frame: this means that the F.H. Sublayer cannot store the frame data because there is no more storage space for them.

Each response is identified by the interface-specific request identifier, which is one of the parameters of the Transmit Request.

At most, one Transmit Request may be outstanding: the corresponding Accept Response may be delayed by the F.H. Sublayer until it is ready to receive the next Transmit Request. If a second Transmit Request is received while the preceding one is still outstanding, the F.H. Sublayer generates a Reject Response to the second request. To avoid this, the Higher Layer will keep track of the outstanding requests by means of a variable. When the Transmit Request is generated, the variable (flag) is set to "Not Ready". When the matching Accept Response is received, the Higher Layer resets the variable to "Ready".

On receiving an Abort Request, the F.H. Sublayer shall erase all data in the layer and shall signal the Frame Error Control Sublayer by sending an Abort Request. The Abort Request is not acknowledged by the F.H. Sublayer.

The Abort Request is used typically:

- to erase all non-transferred data when initiating or terminating a data link service.
- to erase all non-transferred data when the automatic retransmission mechanism of COP-1/AD operates, so that these data are not transmitted unnecessarily.

(b) At the Receiving End

On receiving a Clean Frame Arrived Indication, the Legal Frame Validation process will perform the following validation checks:

- The Version Number field and both Reserved Fields (A and B) must contain the value '00'.
- The value of the Spacecraft ID must be correct, as well as that of the Virtual Channel ID.
- The Bypass and Control Command flags must combine legally (AC combination is illegal).
- BC frames must contain a valid Control Command, i.e. one of the two possible formats defined in Section 6.2: "Unlock" and "Set V(R)".
- For all type-B frames (BC or BD), the Frame Sequence Number field must be set to "all zeros".

Every candidate frame passing successfully all of the preceding validation tests is declared "legal" and transferred immediately to the layer above (COP-1 Sublayer) by means of the Legal Frame Arrived Indication; all frames failing the tests are declared "illegal" and erased.

6.3.3 COP-1 Sublayer

NOTE: In this section, although it may be mentioned that the COP-1 Sublayer handles "frames", these are actually partial frames made up of a TC Segment plus COP-1 information.

6.3.3.1 Services and Protocols

(a) Services

For a particular Virtual Channel, the COP-1 Sublayer provides two distinct services to the layer above (Segmentation Layer). These services are:

(i) Sequence-Controlled Service

This service has been introduced in Section 6.1.1., Paragraph (a). It concerns two types of frames:

- AD for frames carrying data from the layer above (TC Segments)
- BC for the two frames carrying protocol control information for configuring the COP-1 Sublayer ("Unlock" and "Set V(R)").

The Sequence-Controlled Service is initiated by means of four distinct "Initiate AD Service Directives" as shown in Table 6.2 (FOP-1 State Table). Two of these directives consist in transmitting either of the two control frames (BC) prior to the actual transfer of TC Segments by means of data frames (AD). Each of the two control frames causes a well-defined action in the FARM-1, which is then reflected in the CLCW. A timer is used to cause retransmission of the control frame if the expected response is not received, with a limit on the number of automatic retransmissions allowed before the Higher Layer is notified that there is a problem in initiating the AD Service. The other two directives allow the AD Service to be started without prior transmission of a control frame, but with or without prior verification of the CLCW contents.

Once the COP-1 Sublayer has been configured by a directive from the Higher Layer for transmission of AD frames (in short: for an AD service), TC Segments are inserted frames in these and transmitted in the order in which they are presented, to the COP-1 Sublayer. The retransmission mechanism ensures that:

- No TC Segment is lost;
- No TC Segment is duplicated;
- No TC Segment is delivered out of sequence.

For the AD Frames, the automatic retransmission procedure makes use of several variables, the most notable being V(R), V(S), N(R) and N(S). (See Figure 6.6, in Section 6.2, and Section 6.3.3.2).

The AD Service also offers, if required, a flow control mechanism ("Wait" system) which permits the higher layers on board the spacecraft to signal that they are not able to cope with the incoming rate of uplink telecommand data.

For the BC Frames, the automatic retransmission procedure makes use of a very small number of variables, the most notable being the "Lockout" flag in the CLCW for the "Unlock" control frame, and the value "N(R)" in the CLCW for the "Set V(R)" control frame.

(ii) Expedited Service

This service has been introduced in Section 6.1.1, Paragraph (b). It concerns the BD type of frames. BD frames are only to be used in exceptional operational circumstances, typically during spacecraft recovery operations.

The service operates with one single request from the Higher Layer for each TC Segment ("Request to Transfer Segment: BD Service" in the FOP-1 State Table). There is only one transmission for each BD frame (i.e. no retransmission).

At the sending end, BD frames are given immediate access, as specified by the FOP-1 State Table.

At the receiving end, TC Segments carried by a BD frame will be passed to the Higher Layer immediately, independent of the value of the Lockout or Wait Flags.

ESA's baseline implementation of FARM-1 uses the same output buffer for TC Segments carried by either AD or BD frames in order to provide increased reliability through reduced complexity. In this case, when a BD frame is received, any TC Segment in the process of being transferred or "waiting" to be transferred will be erased, without any indication to the ground in the CLCW. **An operational consequence is that, for this implementation, the sending-end Higher Layer shall mandatorily and automatically terminate any ongoing AD Service before starting a BD Service on the same virtual channel, by sending a "Terminate AD Service Directive".**

(b) Protocols

From a peer protocol standpoint, the services described above involve the following activities:

(i) At the Sending End: FOP-1

The Frame Operation Procedure (FOP-1) of the COP-1 Sublayer protocol is described in this document by a finite-state automaton represented by the FOP-1 State Table (See Table 6.2).

The basic operation principle of the FOP-1 is that it remains in a state until an event occurs. When an event occurs, it is analysed until it is fully identified and then the operations specified for the combination of that event and that state are executed. Finally the state variable is updated with the new state value specified for the combination.

In the case of the arrival of a CLCW, various common operations are performed before the specific operations specified for the state/event combination are executed.

In particular, not included in the FOP-1 State Table are operations such as checking:

- the "COP in Effect"
- the "Virtual Channel Identifier"

Included in the FOP-1 State Table are the following operations:

- checking the value of the "Lockout" Flag
- checking the value of N(R)
- checking the value of the "Retransmit" Flag
- checking the value of the "Wait" Flag

A detailed description of the FOP-1 process is given in Section 6.3.3.6: Actions.

(ii) At the Receiving End: FARM-1

The Frame Acceptance and Reporting Mechanism (FARM-1) of the COP-1 Sublayer protocol is described in this document by a finite-state automaton represented by the FARM-1 State Table (See Table 6.3).

The overall pattern of the operation of the FARM-1 is that it remains in a state until an event occurs. When an event occurs, it is analysed until it is fully identified and then the operations specified for the combination of that event and that state are executed. Finally, the state variable is updated with the new state value specified for the combination.

The FARM-1 constantly generates a standard report, the CLCW, which is made available to the spacecraft telemetry system at regular intervals (Event E11 in FARM-1 State Table).

Not included in the FARM-1 State Table are operations concerning the validation of the frame (Clean Frame Validation and Legal Frame Validation). When a "valid frame arrives", this means that the Legal Frame Validation process has placed a "Legal" frame in the front end buffer of the FARM-1 protocol machine. This validation includes that of the two control frames ("Unlock" and "Set V(R)").

Included in the FARM-1 State Table are the following operations:

- checking the value of the Bypass Flag
- checking the value of the Control Flag
- checking the value of N(S) in AD frames

A detailed description of the FARM-1 process is given in Section 6.3.3.6: Actions.

6.3.3.2 Internal Variables

This section describes the variables used by the COP-1 protocol machines at each end of the Transfer Layer link. (The complete meaning of these variables can only be fully understood in conjunction with a careful reading of the COP-1 State Tables. It is those tables which, ultimately, contain the master definition of the COP-1 protocol.)

These variables are those which are defined as part of the protocol. Any implementation of the protocol machines is likely to have in addition many private, implementation-dependent variables.

(a) FOP-1 Variables

For each virtual channel the sending-end protocol machine maintains the following variables:

- State
- Lockout_Flag
- Wait_Flag
- Retransmit_Flag
- Transmitter_Frame_Sequence_Number (usually referred to as V(S)).
- Wait_Queue
- Sent_Queue
- To_Be_Retransmitted_Flag
- AD_Out_Flag

- BD_Out_Flag
- BC_Out_Flag
- Expected_Acknowledgement_Frame_Sequence_Number (usually referred to as NN(R))
- Timer_Initial_Value (also known as T1_Initial)
- Timeout_Type (also known as TT)
- Transmission_Limit
- Transmission_Count
- Suspend_State (also known as SS)
- FOP_Sliding_Window_Width (also known as K).

These are described in detail in the following sections.

(i) State

The state of the virtual channel may be one of the following:

- Active (S1)
- Retransmit without Wait (S2)
- Retransmit with Wait (S3)
- Initialising without BC Frame (S4)
- Initialising with BC Frame (S5)
- Initial (S6)

Each of the above represents a state of the FOP-1 finite-state automaton which implements the protocol at the sending end of the virtual channel.

"Active" state (S1) is the normal state of the protocol machine when there are no recent errors on the link and no incidents have occurred leading to flow-control problems.

The protocol machine is in the "Retransmit without Wait" state (S2) while the Retransmit Flag is "on" in the CLCW of the virtual channel but no other exceptional circumstances prevail.

The protocol machine is in the "Retransmit with Wait" state (S3) while the Wait Flag is "on" in the CLCW of the virtual channel and the machine has seen a condition which requires that it retransmits some frames when the Wait Flag is reset.

The protocol machine is in the "Initialising without BC Frame" state (S4) after receiving a particular directive called "Initiate AD Service (with CLCW check) Directive" (a successful check brings the protocol machine into S1).

The protocol machine is in the "Initialising with BC Frame" state (S5) after receiving an "Initiate AD Service (with Unlock) Directive" or "Initiate AD Service (with Set V(R)) Directive" while in the "Initial" state with BC_Out = Ready. A transmission of the BC frame and a subsequent "clean" CLCW status will bring the protocol machine into S1.

The protocol machine is in the "Initial" state (S6) whenever it is necessary to terminate an on-going service (this happens when a "Terminate AD Service Directive" is received or when an "Exception", i.e. an event which causes an Alert, occurs). In principle, the "Initial" state is the first state entered by the protocol machine for a particular virtual channel. Under COP-1 the number of virtual channels is decided at spacecraft design time (typically: two VCs, for redundancy). Although, in principle, all these virtual channels remain open during the life of the spacecraft, provision has to be made for interruptions of the physical link between the ground and the spacecraft and, particularly for low-orbit spacecraft, the operation of the one physical link from different ground stations. These considerations mean that it must be possible to start up a protocol machine on the ground more than once during the life of the spacecraft.

In the Initial State, data frames may only be transmitted if they are BD frames. To start the Sequence-Controlled Service, it is necessary to send one of four possible "Initiate AD Service Directives". If the directive is accepted and successfully executed, the protocol machine will eventually be set to the "Active" state (S1). If the directive is not successfully executed (as would be the case if the transmission of an Unlock BC frame is not confirmed in the CLCW reports from the spacecraft after the maximum allowed number of timer-initiated retransmissions), the FOP-1 generates an Alert Indication and re-enters the "Initial" state.

(ii) Lockout_Flag

When processing a CLCW for a particular virtual channel, the Lockout_Flag contains the value of the "Lockout" Flag from that CLCW.

(iii) Wait_Flag

When processing a CLCW for a particular virtual channel, the Wait_Flag contains the value of the "Wait" Flag from that CLCW.

(iv) Retransmit_Flag

When processing a CLCW for a particular virtual channel, the Retransmit_Flag contains the value of the "Retransmit" Flag from that CLCW.

(v) Transmitter_Frame_Sequence_Number (V(S))

The Transmitter_Frame_Sequence_Number, V(S), contains the value of the Frame Sequence Number, N(S), to be assigned to the next type AD frame to be transmitted.

(vi) Wait_Queue

The Wait_Queue is a virtual channel data structure of the Sequence-Controlled Service for data (AD service). TC Segments are received from the Segmentation Layer and held in the Wait_Queue until they can be accepted by the Transfer Layer. When it accepts a segment, the Transfer Layer encodes the segment data in a transfer frame and passes it to the Lower Layers for transfer to the spacecraft. (A copy is kept on the Sent_Queue, see Paragraph (vii) below.)

The Wait_Queue has a maximum capacity of one TC Segment.

The Wait_Queue and "Accept Response to Request to Transfer Segment" form the primary mechanism by which flow control as seen by the Segmentation Layer is governed. When a segment is on the Wait_Queue, this means that the Segmentation Layer has not yet received an Accept Response for the corresponding Request to Transfer Segment.

(vii) To_Be_Retransmitted_Flag

If retransmissions of the Sent_Queue are to be made because one or more frames were not acknowledged within the time allowed or were negatively acknowledged by a CLCW with the Retransmit Flag set, it is not reasonable to shut out all other FOP activity until the last frame on the Sent_Queue has been accepted by the Lower Layer (especially since the Lower Layer uses the Accept Response as its flow control mechanism). During that possibly extended time other events may occur, such as the arrival of a CLCW, which must be processed. To handle this situation, each frame on the Sent_Queue carries a To_Be_Retransmitted_Flag to distinguish a frame that has been transmitted (or retransmitted) and is awaiting acknowledgement (Flag reset) from one that must be retransmitted (Flag set). Upon receipt of an Accept

Response from the Lower Layer, these flags will be used to determine which frame on the Sent_Queue, if any, to retransmit next.

(viii) AD_Out_, BC_Out_ and BD_Out_Flags

The FOP-1 records whether or not a Transmit Request for Frame is outstanding for each of the three types of frames: AD, BC and BD. There are therefore three variables:

- AD_Out_Flag (for AD frames)
- BC_Out_Flag (for BC frames)
- BD_Out_Flag (for BD frames).

These may take one of two values:

- Ready
- Not_Ready

When the FOP-1 issues a Transmit Request for Frame, it sets the appropriate "Out" variable to Not_Ready. When the Transmit Request is accepted by the Lower Layer, the FOP-1 sets the variable to Ready.

(ix) Sent_Queue

The Sent_Queue is a virtual channel data structure in which the master copy of all type AD and BC frames on a virtual channel is held between the time a copy of the frame is first passed to the Lower Layers for transmission and the time the Transfer Layer has finished processing the frame.

The Transfer layer has finished processing a type AD or BC frame when:

- it receives (via the CLCW) a positive acknowledgement of receipt for the frame (perhaps after retransmission)
- an event causes the Transfer Layer to purge the Sent_Queue (i.e. an "Exception" or a "Terminate AD Service Directive").

Once the processing is finished, the master copy of the frame is removed from the queue and discarded and the (successful or unsuccessful) transfer of the segment data is reported to the Segmentation Layer by means of a Confirm Response (Positive or Negative).

(x) Expected_Acknowledgement_Frame_Sequence_Number (NN(R))

The Expected_Acknowledgement_Frame_Sequence_Number, NN(R), contains the value of N(R) from the previous CLCW on that virtual channel.

NN(R)-1 is the value of the sequence number of the latest type AD frame which the FOP-1 can guarantee has arrived safely. Because of the loop delay in the communications link, this value may lag behind the value of the FARM-1 Receiver_Frame_Sequence_Number, V(R).

(xi) Timer_Initial_Value (T1_Initial)

Whenever a frame of type AD or BC is transmitted, the Timer is started or restarted.

If a frame is lost on the physical link, no positive acknowledgement for that frame will be seen in the CLCW. If no later type AD or BC frame were transmitted on that virtual channel, there would be no way for the FOP-1 to discover that the frame had not arrived.

Therefore each virtual channel has a Timer which is started whenever a frame is transmitted or retransmitted. If an acknowledgement is seen for the frame, and no subsequent frame has been transmitted, then the Timer is cancelled. If the Timer expires and the FOP Transmission_Count has not reached the FOP Transmission_Limit (see following variables), it causes an event which initiates a recovery action in the FOP-1 protocol machine.

The Timer is not used when a type BD frame is transmitted.

The initial value to which the Timer is set (when it is started or restarted) is referred to as T1_Initial and may be changed by means of the Set T1_Initial Directive.

The smallest value of T1_Initial shall be the sum of the following delays for a given virtual channel:

- ground processing time of the layers below the FOP-1;
- time required to transmit a maximum-length frame (including the bits needed for CLTU and coding) as a serial bit stream;
- uplink propagation time (i.e. one way light time);
- on board processing time of the layers below the FARM-1;
- worst-case time required to sample and encode FARM-1 status data as a CLCW in the telemetry Transfer Frame;

- time required to transmit (as a serial bit stream) a telemetry Transfer Frame;
- downlink propagation time (i.e. one-way light time);
- ground processing time to extract the CLCW from the telemetry Transfer Frame and to deliver it to the FOP-1.

NOTE: A smaller value of T1_Initial may be used to force retransmission of the entire Sent_Queue prior to receipt of any acknowledgements, when telecommanding very distant spacecraft (see Section 9, Deep Space Telecommand).

(xii) Transmission_Limit

The Transmission_Limit holds a value which represents the maximum number of times the first frame on the Sent_Queue may be transmitted. This includes the first "transmission" and any subsequent "retransmissions" of the frame.

The value of the Transmission_Limit may be changed by means of the Set Transmission_Limit Directive.

(xiii) Timeout_Type (TT)

The Timeout_Type variable is referred to as TT. It may take one of two values, 0 or 1. It specifies the action to be performed when both the Timer expires and the Transmission_Count (see next variable) has reached the Transmission_Limit.

(xiv) Transmission_Count

When a Type AD or BC frame is lost, the normal recovery procedure is to retransmit it. If there is a serious problem on the underlying physical link, however, no amount of retransmissions will permit an acknowledgement for the frame to appear in the CLCW for the virtual channel.

If nothing were done, there would be no way for COP-1 to detect the error. Therefore all segments containing user data passed from the ground Higher Layer (as well as all directives from the Control Authority in the Higher Layers) have associated with them, at least implicitly, a limit to the number of times the corresponding frame is to be retransmitted.

In order to keep from declaring that the link has failed when it is in fact getting frames into the spacecraft, the Transmission_Limit applies only to the first frame on the Sent_Queue. Once that frame is acknowledged, the Transmission_Count associated to it is reset, even though the remaining frames on the Sent_Queue have been transmitted, possibly more than once. The effect is that the Transmission_Count can be considered to be associated with the Sent_Queue, rather than with each frame.

There are two different sorts of event which may cause the FOP-1 to initiate retransmission of either a BC frame or one or more AD frames:

- A CLCW arrives which negatively acknowledges a frame (Retransmission_Flag = 1).
- The Timer expires before a CLCW positively acknowledging the last frame on the Sent_Queue has been received.

Whenever a CLCW arrives which negatively acknowledges a frame, the FOP-1 checks whether the value of the Transmission_Count has reached the value of Transmission_Limit. If it has not, the FOP-1 increments the count and initiates retransmission of the frames on the Sent_Queue. If it has, the FOP-1 generates an Alert Indication.

Whenever the Timer expires before a CLCW positively acknowledging the last frame on the Sent_Queue has been received, the FOP-1 checks whether the value of the Transmission_Count has reached the value of the Transmission_Limit. If it has not, the FOP-1 increments the count and initiates retransmission of the frames on the Sent_Queue. If it has, the FOP-1 selects one of two possible actions depending on the value of the Timeout_Type variable:

- if TT = 0, the FOP-1 generates an Alert Indication
- if TT = 1, the FOP-1 suspends the AD service, which may be resumed later if so required (see Suspend_State variable, SS, and Resume AD Service Directive). This feature is used, typically, for deep-space telecommanding.

Whenever one or more frames are acknowledged and therefore removed from the Sent_Queue, the Transmission_Count is reset to 1. The Transmission_Count is also set to 1 when the FOP-1 prepares an AD or BC frame for transmission and the Sent_Queue was previously empty. All these actions are defined in detail in Section 6.3.3.6, Actions.

For the Expedited Service (BD), there is no Transmission_Count variable, because each BD frame is transmitted only once.

(xv) Suspend_State (SS)

The Suspend_State variable is referred to as SS. It may take one of five values, from 0 to 4. It records the State that the FOP was in when the AD Service was suspended (as described in Paragraph (xiv) above). This is the State to which the FOP will return should the AD Service be resumed. If SS = 0, the AD Service is deemed not suspended.

(xvi) FOP_Sliding_Window_Width (K)

The value to which the FOP_Sliding_Window_Width is set is referred to as "K" and may be changed by means of the Set FOP Sliding Window Width Directive.

The FOP Sliding Window is a mechanism which limits the number of Transfer Frames which can be transmitted ahead of the last acknowledged frame, i.e. before a telemetered CLCW report is received which updates the status of acknowledged frames.

The value "K" shall be set by the mission operations authority to the required value between the following limits:

$$1 \leq K \leq PW$$
and
$$K < 256$$

where PW is the FARM Positive_Window_Width, as defined in Paragraph (b), FARM-1 Variables, subparagraph (vii).

(b) FARM-1 Variables

For each virtual channel, the receiving-end protocol machine maintains the following variables:

- State
- Lockout_Flag
- Wait_Flag
- Retransmit_Flag
- Receiver_Frame_Sequence_Number (usually referred to as V(R))

- FARM-B_Counter
- FARM Sliding Window Variables:
  - FARM_Sliding_Window_Width (also known as W)
  - FARM_Positive_Window_Width (also known as PW)
  - FARM_Negative_Window_Width (also known as NW)
- Buffer Administration Variables

Finally, each virtual channel must have available some storage for use as buffers. This implies the existence of data structures for administering the buffers.

These variables are described in detail in the following sections.

(i) State

The State may be one of the following:

- Open (S1)
- Wait (S2)
- Lockout (S3)

This variable represents the state of the FARM-1 finite-state automaton which implements the protocol at the receiving end of the virtual channel.

In Open State, the protocol machine accepts in-sequence frames and passes them to the Higher Layer.

In Wait State, there is no buffer space available in which to place any further received data frame of type AD. The protocol machine enters the Wait State when it has received an AD frame but is unable to deliver the segment it contains to the Higher Layer. It leaves the Wait State upon receipt of a buffer release signal from the Higher Layer.

Lockout State is entered if the protocol machine detects an error in the way the ground protocol machine is implementing the protocol. It is a safe state in that no user data will be accepted or transferred to the Higher Layer when in locked state (unless bypass is used). The protocol machine leaves the Lockout State upon receipt of an 'UNLOCK' control command.

(ii) Lockout_Flag

The Lockout_Flag is set to "1" whenever the protocol machine is in Lockout State. When the CLCW is to be encoded for a particular virtual channel, the value of this flag is read out into the CLCW of that virtual channel.

(iii) Wait_Flag

The Wait Flag is set to "1" whenever the protocol machine is in Wait State. When the CLCW is to be encoded for a particular virtual channel, the value of this flag is read out into the CLCW of that virtual channel.

(iv) Retransmit_Flag

The Retransmit_Flag is set to "1" whenever the protocol machine knows that a type AD frame has been lost in transmission or has been discarded because there was no buffer space available. When the CLCW is to be encoded for a particular virtual channel, the value of this flag is read out into the CLCW of that virtual channel. The appearance of the set condition of the flag on the ground forms a negative acknowledgement of all previously transmitted frames with a N(S) equal to or greater than N(R). The flag will be reset to "0" upon successful receipt of a frame with N(S) = V(R), receipt of a 'SET V(R)' control command (unless in Lockout State) or receipt of an 'UNLOCK' control command.

(v) FARM-B_Counter

This variable is incremented whenever a valid BD or BC frame arrives. The value of this variable is read out into the CLCW but is not used by the COP-1 protocol machines at either end of the link. The counter is intended for use by layers above the Transfer Layer to offer a minimal facility for a Higher Layer error-control loop when the Expedited Service (BD) is used.

How the Higher Layers access the CLCW to obtain the value of the FARM-B_Counter is not defined in this specification. It is implementation dependent.

(vi) Receiver_Frame_Sequence_Number V(R)

This variable records the value of the N(S) expected to be seen in the next type AD frame on this virtual channel.

(vii) FARM Sliding Window Variables

The purpose of the COP-1 Sliding Windows is to protect FARM-1 against the unauthorised (uncontrolled) transfer of a sequence of frames such that the Frame Sequence Number, N(S), of one or more of these frames will exceed the current value of the Receiver_Frame_Sequence_Number, V(R), by at least 256.

The purpose of the FOP Sliding Window (defined in terms of its width "K" in paragraph (a), FOP-1 Variables, Subparagraph (xvi)) is to limit the number of frames which can be transmitted safely ahead of the last acknowledged frame.

The purpose of the FARM Sliding Window is to protect FARM-1 against any malfunction or erroneous set-up of FOP-1. The FARM Sliding Window is defined in terms of three variables:

- its total width, referred to as "W"
- the width of its positive part, referred to as "PW"
- the width of its negative part, referred to as "NW"

The three variables are specified in the next subparagraphs, as well as the main related actions. Figure 6.7 illustrates the FARM Sliding Window concept with its different sections and actions.

(viii) FARM_Sliding_Window_Width (W)

The FARM_Sliding_Window_Width is referred to as "W" and gives the range over which the Frame Sequence Numbers of received AD frames may vary without lockout occurring.

The value "W" shall be set by the mission operations authority to the required value between the following limits:

$$2 \leq W \leq 254$$

where W is always an **even integer**.

Unless otherwise specified, the value "W" shall be fixed for the entire duration of the mission. The maximum recommended value is 200.

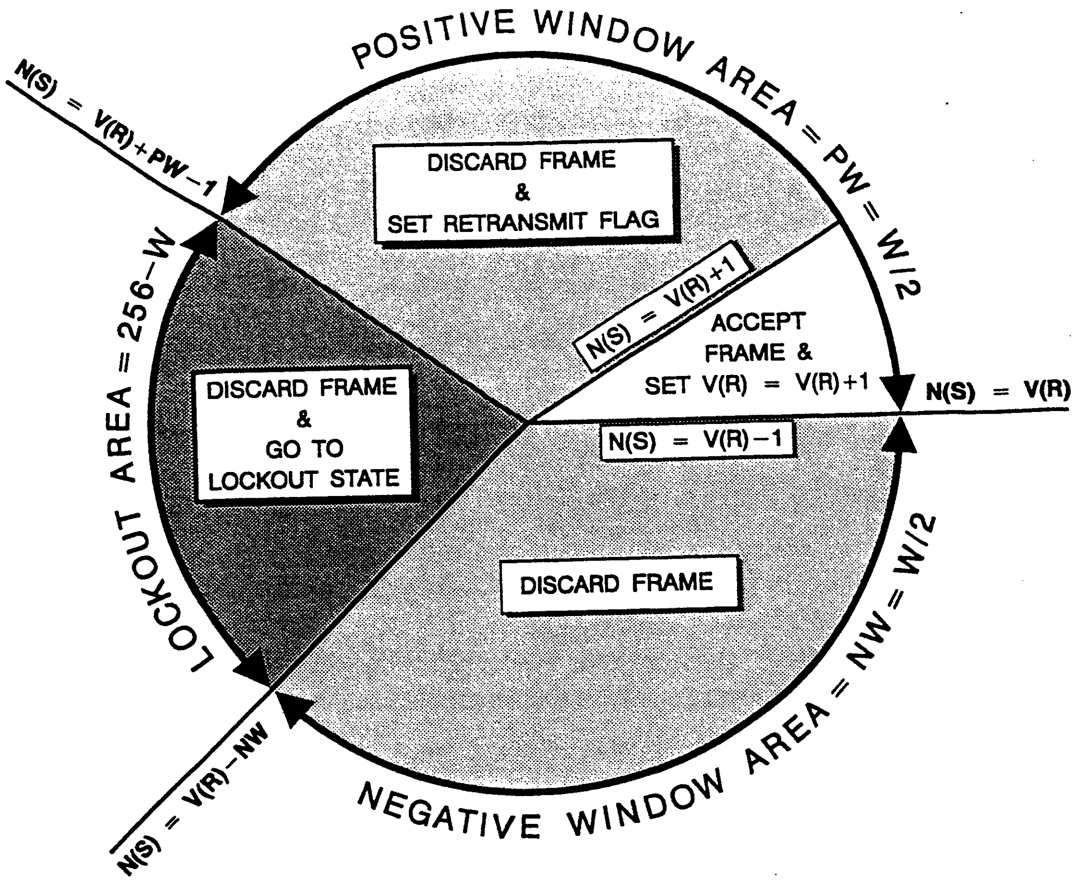

Figure 6.7 FARM SLIDING WINDOW CONCEPT

(ix) FARM_Positive_Window_Width (PW) and FARM_Negative_Window_Width (NW)

As shown in Figure 6.7:

- The FARM Positive Window area starts with V(R) and extends PW frames in the positive direction.
- The FARM Negative Window area starts at V(R)-1 (the number of the last accepted frame) and extends NW frames in the negative direction.

The width of each area is specified as follows:

$$PW = NW = W/2$$

A Frame Sequence Number, N(S), falls outside the FARM Sliding Window, (i.e., into the lockout area of width 256 - W) when:

$$N(S) > V(R) + PW - 1 \quad \text{and} \quad N(S) < V(R) - NW$$

When the frame is in the lockout area, FARM-1 will discard the frame, go into the lockout state and set the Lockout Flag.

When N(S) falls inside the FARM Sliding Window, one of the following three cases will occur:

- FIRST CASE

$$N(S) = V(R)$$

The frame is in the positive window and contains the expected Frame Sequence Number: the frame is accepted.

- SECOND CASE

$$N(S) > V(R) \quad \text{and} \quad N(S) \leq V(R) + PW - 1$$

The Frame is in the positive window and does not contain the expected Frame Sequence Number: the frame is discarded and the Retransmit Flag is set, if it has not already been set.

- THIRD CASE

$$N(S) < V(R) \text{ and } N(S) \geq V(R) - NW$$

The frame is in the negative window and is discarded without any other action being taken.

NOTE: Certain missions, such as those involving spacecraft very distant from the Earth, may require only one transmission of a sequence of AD frames in one COP-1 session (Transmission_Limit = 1), whether in the Suspend/Resume mode of operation or not. For such missions, and in such a mode, it is permitted to select PW > NW, with, ultimately, NW = 0 and PW = W, where W can be any integer between 1 and 256 inclusive. Thus:

$$PW \leq W \text{ and } 1 \leq W \leq 256 \text{ and } 1 \leq PW \leq 256$$

Whatever the value of PW, the value of the FOP_Sliding_Window_Width, K, may never exceed 255.

See also Section 9, Deep Space Telecommand.

(x) Buffer Administration Variables

The receiving end of the Transfer Layer requires storage to process the frames arriving from the ground and to contain data to be passed to the Segmentation Layer.

The actual storage allocation strategy is implementation dependent. However, the way FARM-1 is defined in the state tables implies that certain aspects of this strategy are not implementation dependent. These are described here.

The FARM-1 state tables imply the existence of the following FARM-1 buffers:

- one "front-end" buffer to contain one maximum-length frame for use while the Transfer Frame Validation checks are performed;
- at least one "back end" buffer to contain the data (TC Segments) to be passed to the segmentation layer.

If only one "back-end" buffer is provided, the main requirement is that the data contained in incoming BD frames have priority: if the back-end buffer still contains data, these data shall be erased and the buffer made available to the incoming (BD) segment data.

6.3.3.3 COP-1 Sublayer Interface to Higher Layer at the Sending End

(a) Overview

In addition to the normal data transfer interfaces to the FOP-1 protocol machine, a number of management functions may be performed by the Higher Layers. These may be regarded as either a special set of commands from the Higher Layer (with the Higher Layer description modified to include them) or they may be regarded as a separate higher interface to the Transfer Layer.

In order to describe the way the Transfer Layer responds to requests from the Higher Layers, we consider two separate interfaces:

- a Sequence-Controlled Service Interface
- an Expedited Service Interface

The Sequence-Controlled Service (short name: AD Service) consists essentially of guaranteeing the successful transfer of TC segments by means of AD frames. However, the two BC frames are also generated and serviced when the proper Directive is sent.

The Expedited Service (short name: BD Service) consists essentially of transmitting each TC segment in one BD frame.

The following service primitives, described in detail in the next subsections, are defined for each Service Interface:

- **Sequence-Controlled Service Interface:**
  - many different Directives
  - Accept Response to Directive
  - Reject Response to Directive
  - Positive Confirm Response to Directive
  - Negative Confirm Response to Directive
  - Alert and Suspend Indications
  - Request to Transfer Segment
  - Accept Response to Request to Transfer Segment
  - Reject Response to Request to Transfer Segment
  - Positive Confirm Response to Request to Transfer Segment
  - Negative Confirm Response to Request to Transfer Segment

- **Expedited Service Interface:**
  - Request to Transfer Segment
  - Accept Response to Request to Transfer Segment

(b) Sequence-Controlled Service Management Interface

The Sequence-Controlled Service Management Interface is the service access point for exchanging information between the management functions of the Higher Layers and the Transfer Layer.

This access point serves to permit the Higher Layer to request services from the Transfer Layer in connection with managing a Virtual Channel. These service requests are referred to in this document as **Directives**.

In addition, the access point serves to permit the Transfer Layer to report the status of a Virtual Channel to the Higher Layers. In particular, exception conditions are signalled by means of a service primitive called an **Alert Indication**.

The service primitives defined on this interface are described hereafter.

NOTE: Other management information, such as spacecraft identification, TC codeblock length, uplink bit rate etc., which must be provided by the Higher Layers, is not included here for the sake of clarity: their detailed implementation not only reflects the layered nature of the telecommand system, but also the operational philosophy of the network facilities, which is outside the scope of this Standard.

- **DIRECTIVES**

Service Requests from the Higher Layer management function are referred to here as "directives". These are:

- 4 Initiate AD Service Directives
- 1 Terminate AD Service Directive
- 1 Resume AD Service Directive
- 5 FOP-1 Setup Directives

Furthermore, any other undefined Directive will be rejected and reported as:

- an "Invalid" Directive

The 12 directives correspond to Events E23 through E40 in the FOP-1 State Table. They are:

- Initiate AD Service (without CLCW check) Directive
  Parameters:
    - directive identifier
    - Virtual Channel identifier

- Initiate AD Service (with CLCW check) Directive
  Parameters:
    - directive identifier
    - Virtual Channel identifier

- Initiate AD Service (with Unlock) Directive
  Parameters:
    - directive identifier
    - Virtual Channel identifier

- Initiate AD Service (with Set V(R)) Directive
  Parameters:
    - V*(R), the new value for V(R)
    - directive identifier
    - Virtual Channel identifier

- Terminate AD Service Directive
  Parameters:
    - directive identifier
    - Virtual Channel identifier

- Resume AD Service Directive
  Parameters:
  - directive identifier
  - Virtual Channel identifier

- Set V(S) to V*(S) Directive
  Parameters:
  - V*(S), the new value for V(S)
  - directive identifier
  - Virtual Channel identifier

- Set FOP_Sliding_Window_Width Directive
  Parameters:
  - new value for width of FOP Sliding Window (K)
  - directive identifier
  - Virtual Channel identifier

- Set T1_Initial Directive
  Parameters:
  - new value for Timer_Initial_Value (T1_Initial)
  - directive identifier
  - Virtual Channel identifier

- Set Transmission_Limit Directive
  Parameters:
  - new value for Transmission_Limit
  - directive identifier
  - Virtual Channel identifier

- Set Timeout_Type Directive
  Parameters:
  - new value for Timeout_Type (TT)
  - directive identifier
  - Virtual Channel identifier

- Invalid Directive
  Parameters:
  - any invalid directive identifier
  - Virtual Channel identifier

Asynchronously from the directive, the Transfer Layer returns a Response to Directive. This indicates whether FOP-1 will try to execute the directive. This may be one of the following:

- Accept Response to Directive
  Parameters:
    - directive identifier
    - Virtual Channel identifier

- Reject Response to Directive
  Parameters:
    - directive identifier
    - Virtual Channel identifier

After each Accept Response to Directive, but asynchronously from that Response, the Transfer Layer signals to the Higher Layer a Confirm Response referring to the directive. This indicates whether or not COP-1 (including FARM-1 for directives requiring receiving end action) was able to complete the execution of the directive. This may be one of:

- Positive Confirm Response to Directive
  Parameters:
    - directive identifier
    - Virtual Channel identifier

- Negative Confirm Response to Directive
  Parameters:
    - directive identifier
    - Virtual Channel identifier

The Negative Confirm Response to Directive service primitive does not carry a parameter giving the reason for the failure to confirm performance of the service requested by the directive. However, whenever a condition is detected which might give rise to Negative Confirm Response to Directive service primitives, an Alert Indication is signalled from the Transfer Layer to the Higher Layer.

- **ALERT INDICATIONS**

If an unrecoverable error occurs on the link, then the Transfer Layer passes an indication to the Higher Layer.

- Alert indication
  Parameters:
    - reason for alert
    - Virtual Channel identifier

This alert indication serves as notice of the termination of the Sequence-Controlled Service guarantee.

The reason for an Alert Indication may be one of the following:

- Allowed number of transmissions exhausted for an AD frame: Alert [limit]. (NOTE: This Alert Indication cannot occur if the Timer has expired and the Timeout_Type variable is set to "1").
- Allowed number of transmissions exhausted for the BC frame derived from a directive (e.g. Initiate AD Service Directive with "Unlock" or with "Set V(R)"): Alert [limit].
- Lockout detected: Alert [lockout].
- CLCW with Retransmit Flag = 0 and N(R) = NN(R) has arrived when last CLCW seen previously showed Retransmit Flag = 1: Alert [synch].
- All frames sent are acknowledged but Retransmit_Flag = 1: Alert [synch].
- An attempt to acknowledge frames is made during the initialising phase corresponding to State (S4): Alert [synch].
- CLCW with invalid N(R) has arrived: Alert [NN(R)].
- LCW with Wait Flag = 1 and Retransmit Flag = 0 has arrived: Alert [CLCW].
- CLCW with invalid pattern of bits has arrived: Alert [CLCW].
- FOP-1 and Lower Layer are out of synchronisation (Lower Layer rejects frame even though appropriate Out_Flag is set to "Ready"): Alert [LLIF].
- A "Terminate AD Service Directive" has arrived: Alert [term].

The Alert Indication implies the end of the Sequence-Controlled Service guarantee on the error-free transfer of data to the spacecraft. Higher Layer recovery actions are necessary to try to ensure that data are not lost, duplicated or erroneous.

The Alert Indications relating to the transmission count may be the result of a break in the underlying physical link and may therefore be caused by problems outside the Transfer Layer.

All other Alert Indications report the breakdown of the Transfer Layer protocol. This means that some part of the system is not operating to specification (therefore, reports already received by the layers above the FOP-1 are likely to have been incorrect).

In particular, an Alert Indication carries the virtual channel identifier which appeared in the first CLCW in which the error condition occurred, but, given that the protocol mechanism has broken down, it is possible that the virtual channel identifier is incorrect.

A Lockout Detected Alert will not occur if the Lockout was detected and reported by an earlier Alert Indication and it has not changed since that indication.

- **SUSPEND INDICATION**

By setting Timeout_Type to "1" and setting a small value of T1_Initial it is possible to cause FOP-1 to transmit a sequence of AD frames a specified number of times and then suspend its operation, without clearing its buffers. The Suspend Indication is used to notify the Higher Layer that the transmissions have been completed and that the operation has been suspended. A subsequent Resume directive will then cause FOP-1 to resume operations in the same state it was in when it was suspended. See also Section 9 on deep-space telecommanding.

(c) Sequence-Controlled Service Segment Transfer Interface

Data transferred through this interface enjoys the protection of all the Transfer Layer facilities and is covered by the guarantee to deliver data without error, in order and without omission or duplication to the spacecraft.

Only one operation may be performed by the Higher Layer on the interface. This is to present to the Transfer Layer:

- Request to Transfer Segment (AD Service)
  Parameters:
    - request identifier
    - Virtual Channel identifier.
    - TC Segment

In response to this request, the Transfer Layer signals its acceptance or rejection of the Request. However, if the Transfer Layer is unable to accept the segment immediately (for example because the spacecraft has indicated it cannot immediately accept any more data) then the Transfer Layer will delay signalling to the Higher Layer its acceptance of the segment from the Higher Layer. The Higher Layer may not issue another Request to Transfer Segment until the current one has been accepted or rejected.

Whenever it has transfer capacity after a period when there was no extra capacity available, the FOP-1 protocol machine looks at the AD Service interface to see if a Request to Transfer Segment is outstanding. If one is outstanding, the Transfer Layer accepts the segment which is then deemed to be under control of the Transfer Layer.

The two layers need to share a common system of identifiers for use when referring to a particular request (and, therefore, to a particular segment). After each request perhaps immediately, perhaps after a delay, the Transfer Layer returns to the Higher Layer a Response referring to the Request. This may be one of:

- Accept Response to Request to Transfer Segment (AD Service)
  Parameters:
  - request identifier
  - Virtual Channel identifier

- Reject Response to Request to Transfer Segment (AD Service)
  Parameters:
  - request identifier
  - Virtual Channel identifier

After each Accept Response to Request to Transfer Segment (AD Service), but asynchronously from the Response, the Transfer Layer signals to the Higher Layer a confirm response referring to the Request. This may be one of:

- Positive Confirm Response to Request to Transfer Segment (AD Service)
  Parameters:
  - request identifier
  - Virtual Channel identifier

- Negative Confirm Response to Request to Transfer Segment (AD Service)
  Parameters:
  - request identifier
  - Virtual Channel identifier

The Negative Confirm Response to Request to Transfer Segment (AD Service) does not carry a parameter giving the reason for the failure to confirm the requested data-transfer service. However whenever a condition is detected which might give rise to such responses, an Alert Indication is signalled from the Transfer Layer to the Higher Layer (see previous Paragraph (b)).

From the point of view of the Higher Layer, between the time of acceptance of a segment by the Transfer Layer until a positive confirm response is received, the segment is in a "Grey Area" in which whether or not it has been transferred on board cannot be known. Segments which receive a negative confirm response may have been unsuccessfully uplinked or they may not. Therefore a negative confirm response signals a break in the Sequence-Controlled Service guarantee.

If a segment has not been accepted, it is deemed to be still under the control of the Higher Layer and is not covered by the Sequence -Controlled Service guarantee. Once the FOP-1 detects a problem (for example a failure of the automatic error-recovery mechanism to ensure transfer on board) leading to a break in the Sequence-Controlled Service guarantee, it rejects any outstanding Request to Transfer Segment. Therefore a segment which has not been accepted can never be in the "Grey Area".

(d) Expedited Service Interface

The Expedited Service Interface is the service access point used for segments to be transferred via BD frames.

Data transferred through this interface are covered by the Expedited Service guarantee to deliver data without error, in order, without duplication but with possible omissions (the data are not duplicated because there is no automatic retransmission mechanism: the frame is transmitted only once).

If any error recovery is required, it has to be performed by the Higher Layers.

Only one operation is performed by the Higher Layer on this interface. This is to present a segment to the Transfer Layer:

- Request to Transfer Segment (BD Service)
  Parameters:
  - request identifier
  - Virtual Channel identifier
  - TC Segment

After each request, perhaps immediately, perhaps after a delay, the Transfer Layer returns to the Higher Layer a Response referring to the Request. This may be one of:

- Accept Response to Request to Transfer Segment (BD Service)
  Parameters:
  - request identifier
  - Virtual Channel identifier.

- Reject Response to Request to Transfer Segment (BD Service)
  Parameters:
  - request identifier
  - Virtual Channel identifier.

As long as the sending-end Lower Layers are capable of accepting the BD frame, it will be transmitted.

As no error recovery is performed by the COP-1 Sublayer for a BD frame, a copy of the data is not kept by the FOP-1 and no confirmation of its acceptance by the receiving end is signalled on this interface.

6.3.3.4 COP-1 Sublayer Interface to Higher Layer at the Receiving End

At the receiving end of the COP-1 Sublayer (i.e. FARM-1), the user data (TC Segment) are delivered as a buffer of accepted data. The ESA baseline is that no distinction is made between a TC Segment delivered by means of an AD frame and one delivered by a BD frame. However, the management of the common FARM-1 back-end buffer is effected as follows:

- **BD frames**

When a frame of this type is accepted by the FARM-1, the TC Segment it contains shall be placed in the back-end buffer of the FARM-1 even if this buffer still contains data (partially read out or not), in which case these data will be erased, an abort signal sent to the Higher Layer to signal the erasure and the new data signalled as "arrived".

- **AD frames**

When a frame of this type is accepted by the FARM-1, the TC Segment it contains shall be placed in the back-end buffer of the FARM-1 only when the buffer is available (empty). If the buffer still contains data, the newly arrived AD frame shall be discarded (erased) as shown by the FARM-1 State Table (Event E2 in Table 6.3).

Therefore:

- FARM-1 must always know when its back-end buffer still contains data.
- Any new data arrival in the FARM-1 back-end buffer shall be signalled to the Segmentation Layer. When this new data arrival has the effect of erasing any data still present in this buffer (case of the BD type of data transfer), this erasure shall be signalled to the Higher (Segmentation) Layer.

All this can be expressed by the following service primitives:

- **From FARM-1 to Segmentation Layer**

- Segment Arrived Indication
  Parameters:
    - Virtual Channel identifier
    - segment aborted indication
    - TC Segment

The virtual channel identifier is normally implicit.

- **From Segmentation Layer to FARM-1**

No specific service primitive is defined. Any required data flow control signalling may be defined, as long as the back pressure is felt by the FARM-1, i.e. the FARM-1 must always know whether its back-end buffer is empty or not.

No interface with the Higher Layer exists for control frames (BC): control commands are activated only **within** the COP-1 Sublayer.

Finally, data link service anomalies may result in discontinuities in the data transfer service. This may or may not require erasing incomplete data in the Higher Layers. This problem is mentioned in Section 6.3.3.6 (Actions; Note of Paragraph (b)) and resolved in Section 7.

6.3.3.5 Service Primitives of Interface between COP-1 Sublayer and Frame Header Sublayer

These service primitives and their related actions are already defined in Sections 6.3.2.2 and 6.3.2.4 respectively.

6.3.3.6 Actions

(a) At the Sending End : FOP-1

The actions related to the interface between the FOP-1 and the Higher Layer have been covered in Section 6.3.3.3.

Although some actions have already been introduced when the FOP-1 variables, all FOP-1 actions are specified by the FOP-1 State Table (See Table 6.2) which expresses the operations to be performed for each event/state combination. However because of space considerations in the table and in order to avoid repetition of the text of this section, certain abbreviations have had to be used. These are listed below:

- **"Purging the Sent_Queue"** includes clearing the Sent_Queue by generating a Negative Confirm Response for each frame on the queue and deleting the frame.
  (Note: Purge Sent_Queue only occurs as part of the termination of an AD Service).
- **"Purging the Wait_Queue"** includes clearing the Wait_Queue by generating a Reject Response for the queued segment.
- **"Transmit"**, for an AD or BC Frame **(i.e. for the Sequence-Controlled Service)**, includes all the functions necessary to prepare the frame for transmission. In particular it includes:
  - inserting the current value of V(S) into the N(S) value of the frame and then incrementing V(S) (for AD frames only);
  - adding the master copy of the frame to the Sent_Queue (for AD and BC frames) with the To_Be_Retransmitted_Flag NOT set;
  - if the Sent_Queue was previously empty, setting the Transmission_Count to 1 (for AD and BC frames);
  - starting the Timer (for AD and BC frames);
  - setting the AD_Out (or BC_Out) flag to Not_Ready;
  - passing a copy of the frame (AD or BC) to the Lower Layer as a parameter of a Transmit Request for (AD or BC) Frame.

- **"Transmit"**, for a BD Frame **(i.e. for the Expedited Service)**, includes all the functions necessary to prepare the frame for transmission. In particular it includes:
  - setting the BD_Out flag to Not_Ready;
  - passing a copy of the BD frame to the Lower layer as a parameter of a Transmit Request for (BD) Frame.

- **"Initiate AD (or BC) Retransmission"** includes:
  - passing an Abort Request to the Lower Layer;
  - incrementing the Transmission_Count;
  - starting the Timer;
  - marking all AD frames (or the BC frame) on the Sent_Queue as "To_Be_Retransmitted".

- **"Remove Acknowledged Frames from Sent_Queue"** includes:
  - generating a Positive Confirm Response to Request to Transfer Segment for each acknowledged frame and deleting the frame;
  - updating the value of NN(R);
  - setting the Transmission_Count to 1.

- **"Alert"** includes:
  - cancelling the Timer;
  - purging the Sent_Queue;
  - purging the Wait_Queue;
  - completing the processing of any Initiate AD Service Directive by generating a Negative Confirm Response for the Directive;
  - generating an Alert signal to the Higher Layer.

- **"Look for Directive"** includes:
  - checking if the BC_Out_Flag is set to Ready. If not, no further processing can be performed for retransmitting the BC frame until an Accept Response is received for the outstanding Transmit Request for (BC) Frame, setting the BC_Out_Flag to Ready;
  - if the BC_Out_Flag is set to Ready, checking if the BC frame on the Sent_Queue is flagged "To_Be_Retransmitted". If so, the flag is set to Not_Ready and a copy of the BC frame is passed to the Lower Layer as a parameter of a Transmit Request for (BC) Frame.

- **"Look for Segment"** includes:
  - checking if the AD_Out_Flag is set to Ready. If not, no further processing can be performed for transmitting AD frames until an Accept Response is received for the outstanding Transmit Request for (AD) Frame, which causes the FOP to set the AD_Out_Flag to Ready;
  - if the AD_Out_Flag is set to Ready, checking if an AD frame on the Sent_Queue is flagged "To_Be_Retransmitted". If so,

the flag is set to Not_Ready and a copy of the AD frame is passed to the Lower Layer as a parameter of a Transmit Request for (AD) Frame and its To_Be_Retransmitted Flag is reset;

- if no AD frame is marked "To_Be_Retransmitted", checking if both $V(S) < NN(R) + K$ and a segment is available at the AD Service Interface on the Wait_Queue. If so:
  - removing the segment from the Wait-Queue;
  - generating the Accept Response to Request to Transfer Segment;
  - performing a "Transmit" action (see above) for AD Frame.

- if no segment is available on the Wait_Queue, no further processing is performed.

- "**Initialise**" includes:
  - purging the Sent_Queue;
  - purging the Wait_Queue;
  - setting the Suspend_State variable (SS) to 0.

- "**Suspend**" includes:
  - generating a Suspend signal to the Higher Layer

- "**Resume**" includes:
  - starting the Timer;
  - setting the Suspend_State variable (SS) to 0.

The State Tables show the new state value at the bottom of each box (for example "(S1)").

References to:

- Lockout_Flag
- Wait_Flag
- Retransmit_Flag
- N(R)

pertain to the values in the current CLCW.

The FOP-1 table is large and the state transitions complex. The newcomer may therefore find it helpful to consider initially only the state changes relating to the main protocol. This is shown, for the normal situation in which no exception conditions occur, in Figure 6.8. This protocol is capable of automatically handling flow control and error control (providing the quality of the link is not so low that a maximum of Transmission_Limit transmissions fail to transfer a frame on board). It is not capable of handling improper operation of the spacecraft link, caused for example by two ground stations simultaneously sending Transfer Frames to the same spacecraft.

Next consideration should be given to the initialisation protocol used, for example, to initiate and terminate a session using the AD Service. This is shown in Figure 6.9 and shows the main protocol States (S1), (S2) and (S3) coalesced into a single state. The FOP-1 State Table distinguishes between many events, all of which should never occur. If one of these situations is detected, an Alert signal is passed to the Higher Layer and the FOP-1 enters the Initial State (S6). Except for Alert [term] after a "Terminate AD Service Directive', all these traps are grouped under "Exceptions" in Figure 6.9.

A detailed summary of the way the FOP-1 moves between all states is given in Figure 6-10.

(b) At the Receiving End : FARM-1

The actions related to the interface between the FARM-1 and the Higher Layer have been covered in Section 6.3.3.4.

Various abbreviations are used in the FARM-1 State Table (see Table 6.3). These are listed below:

- **"Valid frame arrives"** means that the lower sublayer (Legal Frame Validation) has placed a "legal" frame in the front-end buffer. If the frame is a data frame (AD or BD) and if the FARM-1 **"accepts"** it, the back-end buffer is allocated for the data (TC Segment).
- **"Accept"** for an AD frame may be subject to a buffer release signal from the Higher Layers if the MAP interface of the Segmentation Layer is implemented to take advantage of the "Wait" concept. When no back-end buffer is available (Event E2), the frame must be discarded.
- **"Accept"** for a BD frame means that the data contents of the frame (TC Segment) are placed in the back-end buffer even when this buffer still contains data, in which case these previous data are erased. The "Wait" concept does not apply to BD frames: the data are deemed to have unimpaired access to the Higher Layers and the necessary interfaces must be implemented to this effect (recovery requirements specific to the mission).

A summary of the way the FARM-1 moves between states is given in Figure 6.11.

In Table 6.3, events E7 and E8 are concerned with the execution of an "UNLOCK" Control Command and a "SET V(R)" Control Command, respectively. The specification of each action in each box is self-explanatory. The action described for event E8 in state (S3) means that the **Control Command "SET V(R)" is not executed (FARM-1 must be "unlocked" first), but accounted for by means of the FARM-B Counter** since it was validated as "legal" and found "executable".

NOTE: The execution of an "UNLOCK" Control Command resets only FARM-1, not the Higher Layers. Section 7.3 defines a standard procedure which allows the data management function of the Higher Layers, at the receiving end, to purge/reset their buffers as required for the spacecraft operations.

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State Name							ACTIVE	RETRANSMIT WITHOUT WAIT	RETRANSMIT WITH WAIT	INITIALISING WITHOUT BC FRAME	INITIALISING WITH BC FRAME	INITIAL
Main Feature of State							Last CLCW showed: Lockout_ Flag = 0, Retransmit_ Flag = 0, Wait_ Flag = 0	Last CLCW showed: Lockout_ Flag = 0, Retransmit_ Flag = 1, Wait_ Flag = 0	Last CLCW showed: Lockout_ Flag = 0, Retransmit_ Flag = 1, Wait_ Flag = 1	Initiate AD Service (with CLCW check) Directive received and "clean" status not seen since	BC frame transmitted and "clean" status not seen since	Not configured for AD Service
State Number							S1	S2	S3	S4	S5	S6
Event Conditions						Event Number						
CLCW arrives formed from a valid COP-1 pattern of bits	Lockout_ Flag = 0	N(R) = V(S) ie: Valid N(R) and all out-standing AD frames acknow-ledged	Retransmit_ Flag = 0	Wait_ Flag = 0	N(R) = NN(R) ie no new frames acknow-ledged	E1	Ignore (S1)	Alert [synch] (S6)	Alert [synch] (S6)	Confirm, Cancel Timer (S1)	Confirm, Release copy of BC frame, Cancel Timer (S1)	Ignore (S6)
					N(R) < > NN(R) ie some new frames acknow-ledged	E2	Remove acknow-ledged frames from Sent_ Queue, Cancel Timer, Look for Segment (S1)	Remove acknow-ledged frames from Sent_ Queue, Cancel Timer, Look for Segment (S1)	Remove acknow-ledged frames from Sent_ Queue, Cancel Timer, Look for Segment (S1)	Not Applicable	Not Applicable	Ignore (S6)
				Wait_ Flag = 1		E3	Alert [CLCW] (S6)	Alert [CLCW] (S6)	Alert [CLCW] (S6)	Alert [CLCW] (S6)	Alert [CLCW] (S6)	Ignore (S6)
			Retransmit_ Flag = 1			E4	Alert [synch] (S6)	Alert [synch] (S6)	Alert [synch] (S6)	Alert [synch] (S6)	Ignore (S5)	Ignore (S6)

Table 6.2 FOP-1 STATE TABLE (PART 1)

					State Number	S1	S2	S3	S4	S5	S6
Continued: CLCW arrives formed from a valid COP-1 pattern of bits	Continued: Lockout_ Flag = 0	N(R) < V(S) and N(R) > = NN(R) ie: Valid N(R) and some outstanding AD frames not yet acknow-ledged	Retransmit_ Flag = 0	Wait_ Flag = 0	N(R) = NN(R) ie no new frames acknow-ledged — E5	Ignore (S1)	Alert [synch] (S6)	Alert [synch] (S6)	Not applicable	Not applicable	Ignore (S6)
					N(R) < > NN(R) ie some new frames acknow-ledged — E6	Remove acknow-ledged frames from Sent_Queue, Look for Segment (S1)	Remove acknow-ledged frames from Sent_Queue, Look for Segment (S1)	Remove acknow-ledged frames from Sent_Queue, Look for Segment (S1)	Alert [synch] (S6)	Ignore (S5)	Ignore (S6)
				Wait_ Flag = 1	E7	Alert [CLCW] (S6)	Alert [CLCW] (S6)	Alert [CLCW] (S6)	Alert [CLCW] (S6)	Alert [CLCW] (S6)	Ignore (S6)
			Retransmit_ Flag = 1	N(R) < > NN(R) ie some new frames acknow-ledged	Wait_ Flag = 0 — E8	Remove acknow-ledged frames from Sent_Queue, Initiate AD Retrans-mission, Look for Segment (S2)	Remove acknow-ledged frames from Sent_Queue, Initiate AD Retrans-mission, Look for Segment (S2)	Remove acknow-ledged frames from Sent_Queue, Initiate AD Retrans-mission, Look for Segment (S2)	Alert [synch] (S6)	Ignore (S5)	Ignore (S6)
					Wait_ Flag = 1 — E9	Remove acknow_ ledged frames from Sent_Queue (S3)	Remove acknow_ ledged frames from Sent_Queue (S3)	Remove acknow_ ledged frames from Sent_Queue (S3)	Alert [synch] (S6)	Ignore (S5)	Ignore (S6)

Table 6.2 FOP-1 STATE TABLE (PART 2)

									State Number	S1	S2	S3	S4	S5	S6
Continued: CLCW arrives formed from a valid COP-1 pattern of bits	Continued: Lockout_ Flag = 0	Continued: N(R) < V(S) and N(R) > = NN(R) ie: Valid N(R) and some outstanding AD frames not yet acknow_ ledged	Continued: Retransmit_ Flag = 1	N(R) = NN(R) ie no new frames acknow-ledged	Trans-mission_ Count < Trans-mission_ Limit	Wait_ Flag = 0	E10			Initiate AD Retrans-mission, Look for Segment (S2)	Ignore (S2)	Initiate AD Retrans-mission, Look for Segment (S2)	Not applicable	Not applicable	Ignore (S6)
						Wait_ Flag = 1	E11			Ignore (S3)	Ignore (S3)	Ignore (S3)	Not applicable	Not applicable	Ignore (S6)
					Transmission_Count ≥ Transmission_Limit		E12			Alert [Limit] (S6)	Alert [Limit] (S6)	Alert [Limit] (S6)	Not applicable	Not applicable	Ignore (S6)
		Invalid N(R) ie N(R) < NN(R) or N(R) > V(S)					E13			Alert [NN(R)] (S6)	Alert [NN(R)] (S6)	Alert [NN(R)] (S6)	Alert [NN(R)] (S6)	Ignore (S5)	Ignore (S6)
	Lockout_ Flag = 1						E14			Alert [Lockout] (S6)	Alert [Lockout] (S6)	Alert [Lockout] (S6)	Alert [Lockout] (S6)	Ignore (S5)	Ignore (S6)
CLCW arrives with pattern of bits invalid under COP-1							E15			Alert [CLCW] (S6)	Alert [CLCW] (S6)	Alert [CLCW] (S6)	Alert [CLCW] (S6)	Alert [CLCW] (S6)	Ignore (S6)

Table 6.2 FOP-1 STATE TABLE (PART 3)

				State Number	S1	S2	S3	S4	S5	S6
Timer Expires	FOP_ Transmission_ Count < Transmission_ Limit		E16		Initiate AD Retrans- mission, Look for Segment (S1)	Initiate AD Retrans- mission, Look for Segment (S2)	Ignore (S3)	Alert [limit] (S6)	Initiate BC Retrans- mission, Look for Directive (S5)	Not applicable
	FOP_ Trans- mission_ Count ≥ Trans- mission_ Limit	Timeout_Type (TT) = 0	E17		Alert [Limit] (S6)	Alert [Limit] (S6)	Alert [Limit] (S6)	Alert [Limit] (S6)	Alert [Limit] (S6)	Not applicable
		Timeout_Type (TT) = 1	E18		SS: = 1 Suspend (S6)	SS: = 2 Suspend (S6)	SS: = 3 Suspend (S6)	SS: = 4 Suspend (S6)	Alert [Limit] (S6)	Not applicable
Receive Request to Transfer Segment from Higher Layer	AD Service	Wait_Queue empty	E19		Add to Wait_Queue, Look for Segment (S1)	Add to Wait_Queue, Look for Segment (S2)	Add to Wait_Queue, (S3)	Reject (S4)	Reject (S5)	Reject (S6)
		Wait_Queue not empty	E20		Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Reject (S6)
	BD Service	BD_Out = Ready	E21		Accept, BD_Out = Not_Ready, Transmit BD frame (S1)	Accept, BD_Out = Not_Ready, Transmit BD frame (S2)	Accept, BD_Out = Not_Ready, Transmit BD frame (S3)	Accept, BD_Out = Not_Ready, Transmit BD frame (S4)	Accept, BD_Out = Not_Ready, Transmit BD frame (S5)	Accept, BD_Out = Not_Ready, Transmit BD frame (S6)
		BD_Out = Not_Ready	E22		Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Reject (S6)

Table 6.2 FOP-1 STATE TABLE (PART 4)

State Number			S1	S2	S3	S4	S5	S6
Receive Directive from Management Function: Initiate AD Service (without CLCW check) Directive		E23	Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Accept, Initialise, Confirm (S1)
Initiate AD Service (with CLCW check) Directive		E24	Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Accept, Initialise, Start Timer (S4)
Initiate AD Service (with Unlock) Directive	BC_Out = Ready	E25	Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Accept, Initialise, BC_Out = Not_Ready, Transmit Unlock BC Frame (S5)
	BC_Out = Not_Ready	E26	Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Reject (S6)
Initiate AD Service (with Set V(R)) Directive	BC_Out = Ready	E27	Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Accept, Initialise, V(S) := V*(R), NN(R) := V*(R), BC_Out = Not_Ready, Transmit Set V(R) BC Frame (S5)
	BC_Out = Not_Ready	E28	Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Reject (S6)

Table 6.2 FOP-1 STATE TABLE (PART 5)

State Number			S1	S2	S3	S4	S5	S6
Continued: Receive Directive from Management Function								
Terminate AD Service Directive		E29	Accept, Alert [term], Confirm (S6)	Accept, Alert [term], Confirm (S6)	Accept, Alert [term], Confirm (S6)	Accept, Alert [term], Confirm (S6)	Accept, Alert [term], Confirm (S6)	Accept, Confirm (S6)
Resume AD Service Directive	Suspend_State (SS) = 0	E30	Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Reject (S6)
	Suspend_State (SS) = 1	E31	Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Accept, Resume, Confirm (S1)
	Suspend_State (SS) = 2	E32	Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Accept, Resume, Confirm (S2)
	Suspend_State (SS) = 3	E33	Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Accept, Resume, Confirm (S3)
	Suspend_State (SS) = 4	E34	Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Accept, Resume, Confirm (S4)

Table 6.2 FOP-1 STATE TABLE (PART 6)

		State Number		S1	S2	S3	S4	S5	S6
Continued: Receive Directive from Management Function	Set V(S) to V*(S) Directive	E35		Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Accept, V(S) := V*(S), NN(R) := V*(S), Confirm (S6)
	Set FOP_Sliding Window_Width Directive	E36		Accept, Set K, Confirm (S1)	Accept, Set K, Confirm (S2)	Accept, Set K, Confirm (S3)	Accept, Set K, Confirm (S4)	Accept, Set K, Confirm (S5)	Accept, Set K, Confirm (S6)
	Set T1_Initial Directive	E37		Accept, Set T1_Initial, Confirm (S1)	Accept, Set T1_Initial, Confirm (S2)	Accept, Set T1_Initial, Confirm (S3)	Accept, Set T1_Initial, Confirm (S4)	Accept, Set T1_Initial, Confirm (S5)	Accept, Set T1_Initial, Confirm (S6)
	Set Transmission_Limit Directive	E38		Accept, Set Trans-mission_ Limit, Confirm (S1)	Accept, Set Trans-mission_ Limit, Confirm (S2)	Accept, Set Trans-mission_ Limit, Confirm (S3)	Accept, Set Trans-mission_ Limit, Confirm (S4)	Accept, Set Trans-mission_ Limit, Confirm (S5)	Accept, Set Trans-mission_ Limit, Confirm (S6)
	Set Timeout_Type Directive	E39		Accept, Set TT, Confirm (S1)	Accept, Set TT, Confirm (S2)	Accept, Set TT, Confirm (S3)	Accept, Set TT, Confirm (S4)	Accept, Set TT, Confirm (S5)	Accept, Set TT, Confirm (S6)
	Invalid Directive	E40		Reject (S1)	Reject (S2)	Reject (S3)	Reject (S4)	Reject (S5)	Reject (S6)

Table 6.2 FOP-1 STATE TABLE (PART 7)

				State Number	S1	S2	S3	S4	S5	S6
Receive Response from Lower Layer	AD_Accept	E41			AD_Out = Ready, Look for Segment (S1)	AD_Out = Ready, Look for Segment (S2)	AD_Out = Ready (S3)	AD_Out = Ready (S4)	AD_Out = Ready (S5)	AD_Out = Ready (S6)
	AD_Reject	E42			Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)
	BC_Accept	E43			BC_Out = Ready (S1)	BC_Out = Ready (S2)	BC_Out = Ready (S3)	BC_Out = Ready (S4)	BC_Out = Ready, Look for Directive (S5)	BC_Out = Ready (S6)
	BC_Reject	E44			Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)
	BD_Accept	E45			BD_Out = Ready, Accept (S1)	BD_Out = Ready, Accept (S2)	BD_Out = Ready, Accept (S3)	BD_Out = Ready, Accept (S4)	BD_Out = Ready, Accept (S5)	BD_Out = Ready, Accept (S6)
	BD_Reject	E46			Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)	Alert [LLIF] (S6)

Table 6.2 FOP-1 STATE TABLE (PART 8)

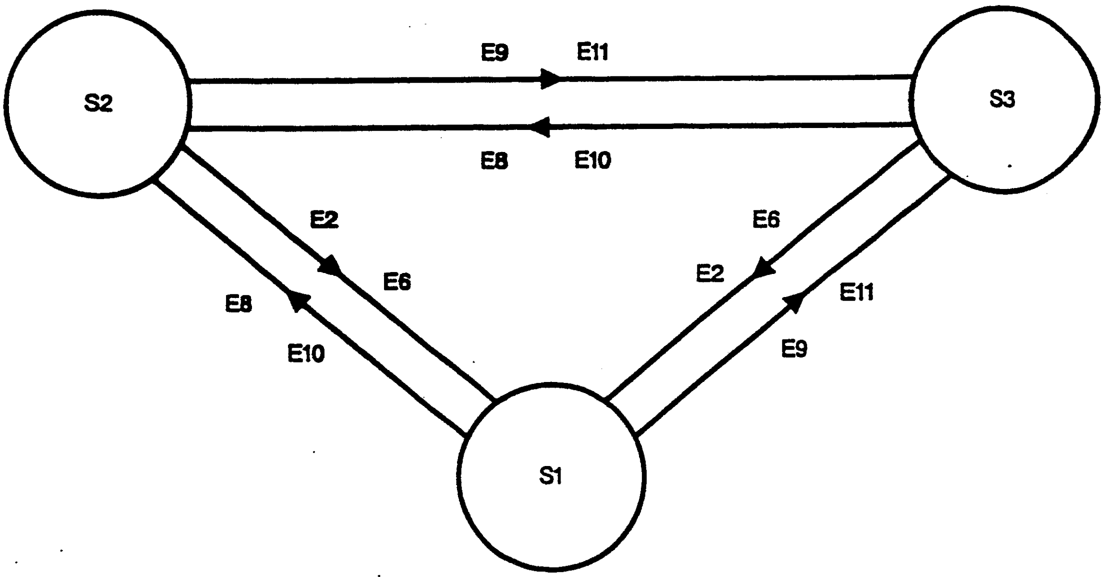

Figure 6.8 FOP-1 STATE TRANSITIONS: MAIN PROTOCOL

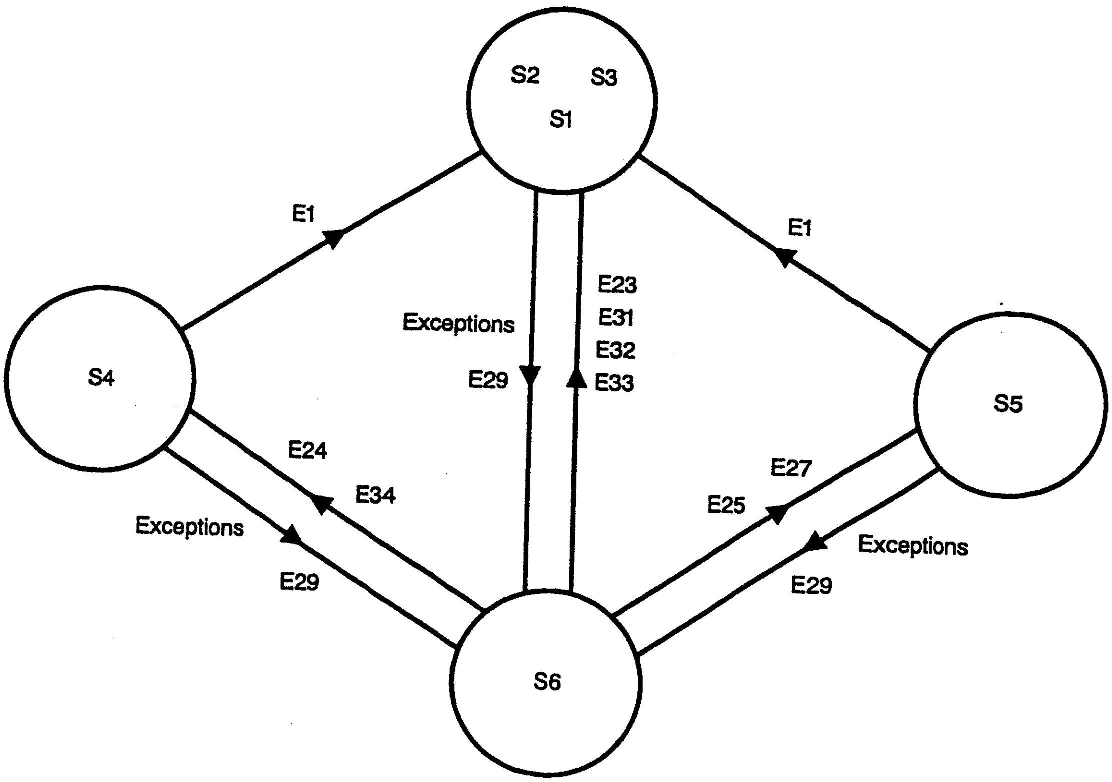

Figure 6.9 FOP-1 STATE TRANSITIONS: INITIALISATION PROTOCOL

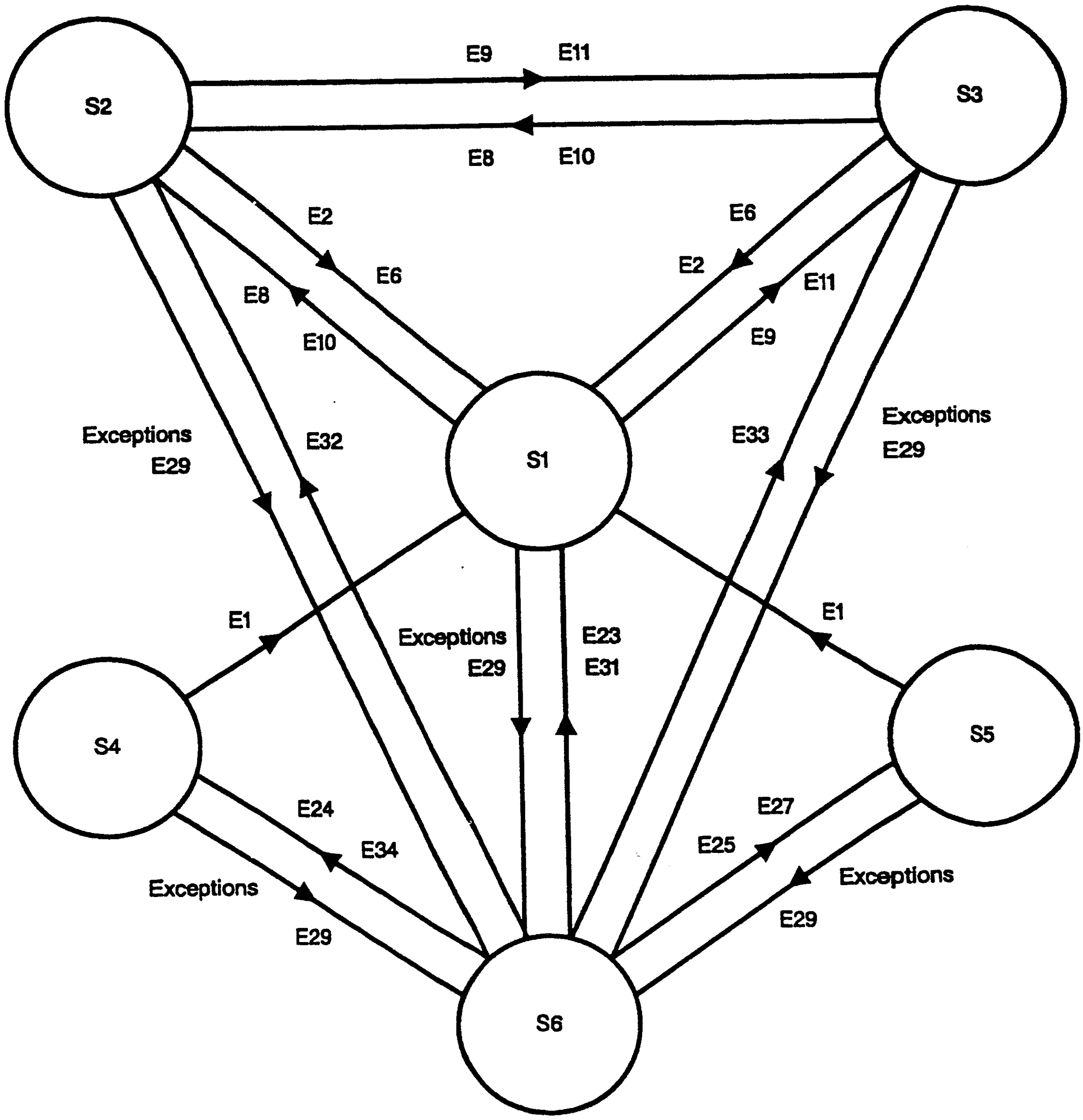

Figure 6.10 FOP-1 STATE TRANSITIONS

State Name				OPEN	WAIT	LOCKOUT
Main Feature of State				Normal state to accept frames	Wait_Flag is on	Lockout_ Flag is on
State Number				S1	S2	S3
Event Conditions			Event Number			
Valid AD frame arrives	N(S) = V(R)	A buffer is available for this frame	E1	Accept frame, V(R) := V(R) + 1, Retrans-mit_ Flag := 0 (S1)	Not applicable	Discard (S3)
		No buffer is available for this frame	E2	Discard, Retrans-mit_ Flag := 1, Wait_Flag := 1 (S2)	Discard (S2)	Discard (S3)
	N(S) > V(R) and N(S) ≤ V(R) + PW-1 i.e. inside positive part of sliding window and N(S) < > V(R)		E3	Discard, Retrans-mit_ Flag := 1 (S1)	Discard (S2)	Discard (S3)

Table 6.3 FARM-1 STATE TABLE (PART 1)

State Number				S1	S2	S3
Continued: Valid AD frame arrives	N(S) < V(R) and N(S) ≥ V(R)-NW i.e inside negative part of sliding window	E4		Discard (S1)	Discard (S2)	Discard (S3)
	N(S) > V(R)+PW-1 and N(S) < V(R)-NW i.e. outside sliding window	E5		Discard, Lockout_ Flag := 1 (S3)	Discard, Lockout_ Flag := 1 (S3)	Discard (S3)
Valid BD frame arrives		E6		Accept, Increment FARM-B_ Counter (S1)	Accept, Increment FARM-B_ Counter (S2)	Accept, Increment FARM-B_ Counter (S3)
Valid Unlock BC frame arrives		E7		Increment FARM-B_ Counter, Retrans- mit_ Flag := 0 (S1)	Increment FARM-B_ Counter, Retrans- mit_ Flag := 0, Wait_Flag := 0 (S1)	Increment FARM-B_ Counter, Retrans- mit_ Flag := 0, Wait_Flag := 0, Lockout_ Flag := 0 (S1)

Table 6.3 FARM-1 STATE TABLE (PART 2)

State Number			S1	S2	S3
Valid Set V(R) to V*(R) BC frame arrives	E8		Increment FARM-B_ Counter, Retrans-mit_ Flag := 0, V(R) := V*(R) (S1)	Increment FARM-B_ Counter, Retrans-mit_ Flag := 0, Wait_Flag := 0, V(R) := V*(R) (S1)	Increment FARM-B_ Counter (S3)
Invalid frame arrives	E9		Discard (S1)	Discard (S2)	Discard (S3)
Buffer release signal	E10		Ignore (S1)	Wait_Flag := 0 (S1)	Wait_Flag := 0 (S3)
CLCW report time	E11		Report value of: V(R), Lockout_ Flag, Wait_Flag, Retrans-mit_Flag, FARM-B Counter (S1)	Report value of: V(R), Lockout_ Flag, Wait_Flag, Retrans-mit_Flag, FARM-B Counter (S2)	Report value of: V(R), Lockout_ Flag, Wait_Flag, Retrans-mit_Flag, FARM-B Counter (S3)

Table 6.3 FARM-1 STATE TABLE (PART 3)

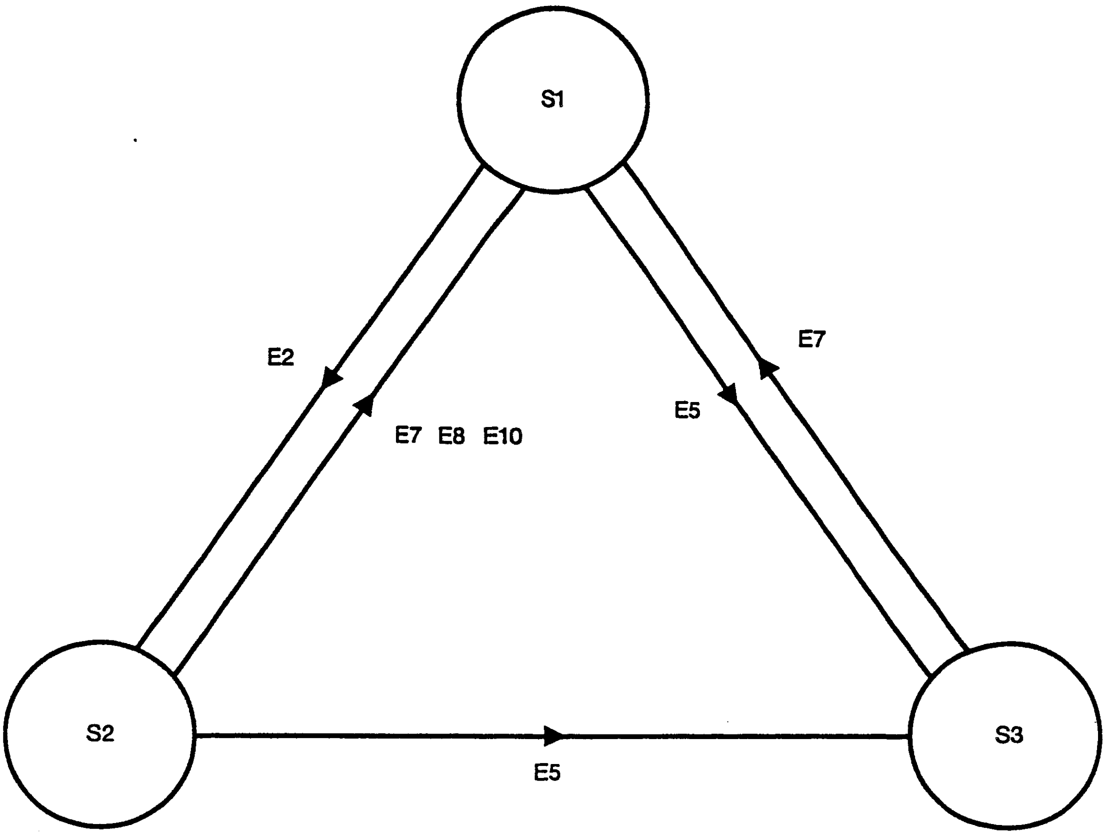

Figure 6.11 FARM-1 STATE TRANSITIONS

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7. SEGMENTATION LAYER

7.1 OVERVIEW OF THE LAYER

The Segmentation Layer provides the Higher Layers with the means to interface several distinct streams of variable-length data units (e.g., the TC Packets) to the single virtual channel transmission process of the layers below.

Inputs to the sending end of the Segmentation Layer are TC Packets, and the protocol data unit of the Segmentation Layer is the TC Segment. The services offered by the layer are:

(a) Segmentation and Re-assembly Service

The Service consists of:

- at the sending end: segmentation of the TC Packets which are too large for direct insertion into a TC Transfer Frame.
- at the receiving end: re-assembly of each TC Packet.

The service draws normally upon the Sequence-Controlled Service of the Transfer Layer (AD Service) to ensure the maintenance of the sequence of TC Segments.

(b) Multiplexing Service

This service consists in multiplexing multiple connections (e.g. distinct streams of TC Packets) onto a single Virtual Channel, so that the services of the Transfer Layer may be shared by multiple processes of the Higher Layers. Typical applications at the receiving end are:

- implementation of physical connections for the selection of alternative "routes" to circumvent spacecraft subsystem failures (e.g. redundancy interfaces);
- implementation of multiple logical connections in data management processes for operational purposes (such as multiplexing two distinct streams of TC Packets while providing an AD Service to both streams);
- implementation of physical or logical connections for the organisation of bandwidth-sharing schemes on the capacity- limited data uplink (this is a generalisation of the preceding multiplexing scheme).

To achieve this, the Segmentation Layer provides a number of service access points called the "Multiplexer Access Points" (MAPs).

(c) Data Flow Control Service

One of the services of the COP-1 Sublayer consists of a back-pressure data flow control mechanism, the main protocol elements of which are the "Wait" state in the FARM-1 and the "Wait_Queue" in the FOP-1. This data-flow control only applies to segments transferred via AD frames (and called AD segments hereafter) and can be implemented for each MAP connection at the receiving end if so required. (NOTE: In some systems, it may not be acceptable that excessively slow traffic on one particular MAP connection be "shared", in terms of inacceptable access times, by the other MAP connections. In such a case, this type of back-pressure control may have to be abandoned for that particular MAP connection, and be replaced by a similar function in the Higher Layers.)

A TC Segment consists of three distinct protocol data elements:

- An 8-bit Segment Header, the purpose of which is to identify the MAP connection and flag the sequential position of the segment relative to the complete TC packet.
- A Segment Data Field, of maximum length 248 octets, which contains all or a portion of a TC packet.
- An **(optional)** Segment Trailer of variable length specific to the **(optional)** service defined in Section 10: the Encrypted Authentication of Telecommand Data.

At the receiving end, a TC Segment is delivered by the FARM-1 of the particular Virtual Channel to the Segmentation Layer which consists essentially of two functions:

- **MAP Selection** - This can take the form of hardware (decoding matrix for implementing each MAP output) or software.
- **Packet Assembly** - This takes the form of a Packet Assembly Controller (PAC) the purpose of which is to control the assembly of each TC Packet on a particular MAP connection.

Protocols for the operation of the PACs are defined in the next sections, including the handling of exceptions (recovery in case of anomaly) and the standard reporting data.

7.2 STANDARD DATA STRUCTURES WITHIN THE LAYER

The TC Segment is the protocol data unit of the Segmentation Layer. Figure 7-1 shows the format of the TC Segment.

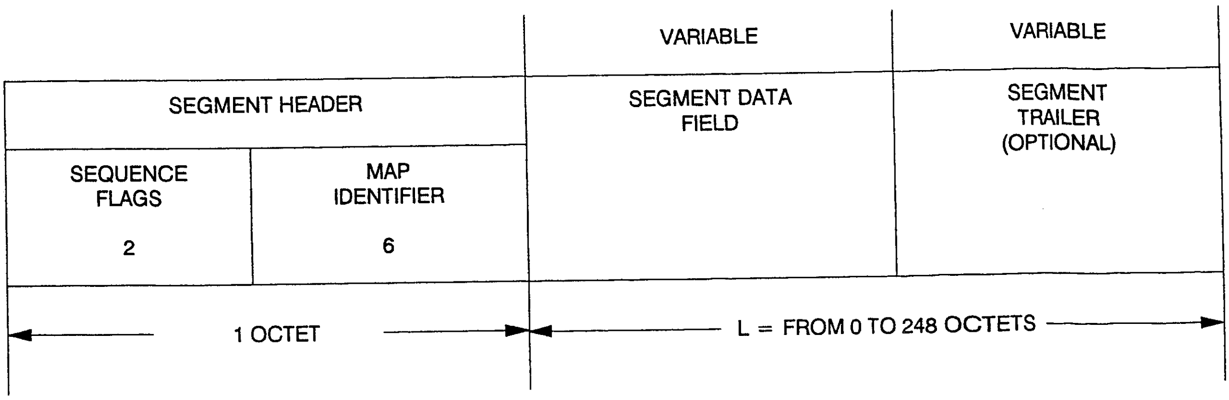

Figure 7.1 TELECOMMAND SEGMENT FORMAT

When the Segment Trailer option is not retained, the Segment Data Field may have a maximum length of 248 octets.

7.2.1 Segment Header

The Segment Header is a single-octet structure occupying the first octet (octet "0") of the TC Segment structure. The Segment Header is divided into two major fields as follows:

(a) Sequence Flags (Bits 0,1)

This field is used by the segmentation protocol to indicate the sequential position of the segment relative to the complete user data unit (e.g. the TC Packet). This technique requires that the Sequence-Controlled Service of the Transfer Layer be used.

The flags are interpreted as follows:

Bit 0	Bit 1	Interpretation
0	1	First segment
0	0	Continuation segment
1	0	Last segment
1	1	Unsegmented

The interpretation of the Sequence Flags **must be consistent with the indicated MAP Identifier,** since distinct streams of segmented TC packets may be interleaved.

When the flags are set to "11" this means that the TC Segment Data Field contains an entire TC Packet.

(b) Multiplexed Access Point (MAP) Identifier (Bits 2 through 7)

This 6-bit field enables up to 64 MAP connection addresses to be associated with a single Virtual Channel.

In this Standard, a further subdivision is defined which associates MAP connections by pair when packet re-assembly is required, with one pair of MAPs for each implemented PAC. This system may, ultimately, divide the 64 MAPs into 32 data MAPs and 32 control MAPs. This is done by using Bit 2 as a control flag, as shown in Figure 7.2.

SEQUENCE FLAGS	MAP IDENTIFIER	
	CONTROL FLAG	ACTUAL MAP ADDRESS
2 BITS	1 BIT	5 BITS

Figure 7.2 SEGMENT HEADER SUBDIVISIONS

- When Bit 2 = 0, the next 5 bits of the MAP Identifier indicate one of 32 user data (e.g. Packet) connections.
- When Bit 2 = 1, the next 5 bits of the MAP Identifier indicate one of 32 control data (e.g. Control Segment) connections.

The Control Segments are described in Section 7.3.

7.2.2 Segment Data Field

The Segment Data Field may vary from 0 to 248 octets maximum. The Segment Data Field may not be present (zero-octet length) when the TC Segment is used to carry Segmentation Layer protocol control information only (e.g. Control Segments; see Section 7.3). In such a case the Sequence Flags shall always be set to "11" (Unsegmented).

When the optional Segment Trailer is used, the maximum length of the Segment Data Field will be reduced accordingly.

7.2.3 Segment Trailer

The Segment Trailer is optional. In this Standard, it is used to provide the function described in Section 10.

7.3 STANDARD PROCEDURES WITHIN THE LAYER

The following procedures do not include the optional processes related to the Segment Trailer.

7.3.1 Segmentation Procedure (Sending End)

At the sending end, the Segmentation Layer performs the following processing steps:

(a) It allocates the user data to a particular MAP according to the mission-specific scheme. The allocation is specified by the layer above.

(b) If the user data unit (e.g. the TC Packet) exceeds a predetermined maximum length "L", the Segmentation Layer divides it into portions that are compatible with insertion into the protocol data unit of the layer below (e.g. the TC Transfer Frame) and attaches a Segment Header to each portion. If the user data unit is a TC Packet, the first octet of the TC Packet shall appear in the leading octet of the first corresponding Segment Data Field. The first and continuing segments may each have a length equal to the maximum length "L". The last segment shall have a length equal to the residue of the user-data unit.

(c) The Segmentation Layer multiplexes together up to 64 distinct streams of TC Segments (64 MAPs) onto one Virtual Channel, according to the particular mission's multiplexing scheme, and passes the multiplexed stream to the layer below.

The maximum length "L" is 248 octets unless the optional Segment Trailer is present, in which case "L" equals 248 octets minus the length of the trailer.

7.3.2 Re-assembly Procedure (Receiving End)

At the receiving end, the Segmentation Layer performs the following processing steps:

(a) accepts a stream of multiplexed TC Segments on one Virtual Channel from the layer below (Transfer Layer);
(b) sorts the segments according to the MAP IDs which appear in their Segment Headers;
(c) re-assembles the segments (less the headers) for each MAP connection, using the Sequence Flags of the Segment Headers, in order to recreate the original user data unit (e.g., the TC Packet);
(d) passes the resulting user data unit to the layer above (Packetisation Layer).

These steps are carried out by a function called the Packet Assembly Controller (PAC). When packet re-assembly is required for a given mission, there will be one PAC for each pair of MAP connections, with one MAP for data and the other for control (MAP Bits 3 through 7 are identical). When packet re-assembly is not required, it is not necessary to implement the PAC function.

- Step (a) implies a service guarantee which is that of the Sequence-Controlled Service (AD segment data). It is not possible to re-assemble successfully BD segment data, unless a similar guarantee is provided (this can only be obtained through Higher-Layer verification procedures which are not covered by this Standard).
- Step (c) implies that the number of octets in each segment is known by the PAC, since the process **shall not make use of the Packet**

Length field : the PAC function need not have any knowledge of the user-data-unit structure, and shall offer the same service to any type of user-data-unit structure.

- Step (d) can be combined with step (c) by making direct use of the user's memory to store the segments. This technique implies, however, the existence of a control protocol between the PAC and the user's memory.

The PAC shall report by telemetry the following information to the TC Packet Management layers at the sending end:

- MAP ID
- Reassembly status (Completed = "0", In Progress = "1")
- Lockout status (Lockout = "1")

The "Lockout" state shall be entered for the following protocol errors:

- Incorrect sequence of data segments, as indicated by the Sequence Flags.
- Incorrect Control Segment format.

Removal of the "Lockout" state of the PAC shall be performed by means of a specific Control Segment called "Reset Command". This Control Segment consists of a single octet (the Segment Header) with no Segment Data Field. The format is as follows:

```
Bit 0 |       | Bit 7
      111XXXXX
```

The unspecified bits represent the MAP address of the PAC.

The "Reset Command" shall be used:

- to unlock the PAC (when in "Lockout");
- to set/reset the PAC to the "Completed" state and erase any partially re-assembled data unit (therefore, a PAC can only be reset when in the "In Progress" state).

When Bit 2 = 1, a Control Segment format is assumed and verified as follows:

- bits 0,1 must both be set to "1";

- the Control Segment must consist of only one octet.

If the Control Segment does not conform to the format rules above, it will be ignored by the PAC, which will enter the "Lockout" state.

The "Reset Command" will be used, typically, to recover from data delivery "discontinuities" that may occur because of link difficulties or data link protocol anomalies.

Note that a Control Segment may be transferred by using either service of the Transfer Layer (i.e. AD Service or BD Service), as required.

7.3.3 Service Primitives of Interface between Segmentation Layer and Higher Layers

7.3.3.1 At the Sending End

(a) Management Interface with the Higher Layers

- **From the Higher Layers**

- COP-1 Initiate and Set-up Directives
  Parameters:
  - directive identifier
  - Virtual Channel identifier
  - spacecraft identifier
  - codeblock length
  - etc. (not exhaustive)

- Segmentation and Multiplexing Directives
  Parameters:
  - directive identifier
  - maximum length of segment
  - network service number (1, 2 or 3)
  - multiplexing scheme (MAP-based multiplexing information, TBD)

- **From the Segmentation Layer**

Because of the complexity of this interface, the list above is not exhaustive, only indicative. The same applies to the response interface which shall consist of the same basic set of accept, reject, positive confirm and negative confirm responses as defined for the interface between the Segmentation Layer (the Higher Layer) and the Transfer Layer (COP-1 sublayer).

(b) Data Interface with the Higher Layers

- **From the Higher Layers**

– Request to Transfer Packet (AD Service)
  Parameters:
  - request identifier
  - MAP identifier
  - Virtual Channel identifier
  - TC Packet

– Request to Transfer Segment (BD Service)
  Parameters:
  - request identifier
  - Virtual Channel identifier
  - data of segment length (e.g. TC Segment)

- **From the Segmentation Layer**

Because of the complexity of the Segmentation Layer functions as regards the handling of data units (e.g. packets or segments), the following text is not exhaustive, only indicative:

The response interface should consist of the same basic set of accept, reject, positive confirm and negative confirm responses as defined for the interface between the Segmentation Layer and the COP-1 Sublayer. The essential service response is, for the AD service, to confirm the successful transfer of each entire packet. Should the transfer be unsuccessful, the exact specification of the reason for failure or of the current transfer status at the time of failure (e.g. the number of successfully transferred segments belonging to an incompletely transferred packet) is left to the network interface designer. For the BD Service, the interface is identical to that between the Segmentation Layer and the COP-1 Sublayer.

7.3.3.2 At the Receiving End

(a) From the Segmentation Layer to the Packetisation Layer

- Packet Arrived Indication
  Parameters:
  - MAP identifier
  - TC Packet

In an actual implementation, the MAP identifier may be implicit.

(b) From the Packetisation Layer to the Segmentation Layer

- Buffer Available Indication

7.3.4 Service Primitives of Interface between Segmentation Layer and Transfer Layer

This interface is fully described in Sections 6.3.3.3 and 6.3.3.4.

7.3.5 Actions

(a) At the Sending End

The interface actions related to the interface with the Higher Layers are in principle identical to those with the Lower Layer (COP-1 Sublayer of the Transfer Layer). The two main functions of the Segmentation Layer dictate its actions. They are essentially related to the AD Service:

- segmentation of each packet.
- multiplexing of the segmented packets belonging to distinct MAP-identified streams.

For the BD Service case, the Segmentation Layer only verifies that the length of the segment of data conforms to the maximum segment length set-up by the Higher Layers.

(b) At the Receiving End

If segmentation is effectively used, the various PACs will carry out their re-assembly task, as specified in Section 7.3.2.

8. PACKETISATION LAYER

8.1 OVERVIEW OF THE LAYER

The primary objective of the Packetisation Layer is to provide the Higher Layers of the system with data transportation at a required quality of service and in an optimum manner. Since, as far as this Standard is concerned, such terms as "required quality of service and in an optimum manner" are undefined (these qualifiers are mission - and even subsystem - specific, or are to be found in Reference [6]), this section will provide the protocol elements on which to build the required, complete data transport protocol.

The protocol data unit of the Packetisation Layer is the TC Packet. The format of the TC Packet is nearly identical to that of the TM Source Packet (see Reference [7]). The TC Packet is a standard, variable-length data structure which can be used to encapsulate the user application data to be uplinked. Depending on the requirements of the mission (or, even, the specific spacecraft subsystem), TC Packets may exist as stand-alone, executable data entities, or may be batched together into sequences (or files) of interdependent data entities.

Error detection is an optional service of the Packetisation Layer. This may be required for two reasons:

- possibility of an undetected error in the packet at the final delivery location (i.e. in the memory) rather than on the link.
- improvement of operational command data verification procedures (e.g. dumping memory contents via telemetry is replaced by telemetering a "no error" status).

The error-detection protocol will involve an error-control field in the last octets of the TC packet.

All other protocol functions will be performed by means of the fields of the Packet Header. Therefore, although the users will have some latitude in using these fields, they should not lose sight of the fact that they have been placed there to fulfil a transport function that cannot be ignored.

8.2 STANDARD DATA STRUCTURES WITHIN THE LAYER

The TC Packet is the standard transport data structure of the Packet Telecommand System.

The TC Packet format, which is shown in Figure 8.1, consists of two major fields:

- the Packet Header, with a fixed length of 48 bits (6 octets).
- the Packet Data Field, with a variable length from 1 to 65536 (2^{16}) octets.

PACKET HEADER (48 BITS)							PACKET DATA FIELD (VARIABLE)		
PACKET IDENTIFICATION				PACKET SEQUENCE CONTROL		PACKET LENGTH	DATA FIELD HEADER (OPTIONAL)	APPLICATION DATA	PACKET ERROR CONTROL (OPT.)
Version Number	Type	Data Fields Header Flag	Appli-cation Process ID	Sequence Flags	Packet Name or Sequence Count		May contain o S/C Time o Packet format o Ancillary data		
3	1	1	11	2	14				
16				16		16	Variable	Variable	16

Figure 8.1 TELECOMMAND PACKET FORMAT

8.2.1 Packet Header

The Packet Header shall consist of 48 bits subdivided into the following fields:

FIELD	LENGTH (BITS)
Packet Identification - Version Number (3) - Type (1) - Data Field Header Flag (1) - Application Process ID (11)	16

FIELD	LENGTH (BITS)
Packet Sequence Control	16
- Sequence Flags (2)	
- Packet Name or Sequence Count (14)	
Packet Length	16
Total =	48

8.2.1.1 Packet Identification (16 Bits)

Packet identification is a 16-bit field divided into four subfields, namely Version Number (3 bits), Reserved Bit (1 bit), Data Field Header Flag (1 bit) and Application Process Identifier (11 bits).

(a) Version Number (Bits 0 through 2)

The Version Number is a 3-bit field occupying the three most significant bits of a packet structure. The Version Numbers are defined by the CCSDS. **IN THIS STANDARD, ONLY ONE VERSION NUMBER (VERSION 1) IS PERMITTED,** and this specifies the packet format described in this Section. This number is:

Bits 0 through 2 = 000

(b) Type (bit 3)

Packets may be identified to be either telemetry type (Bit 3 = 0) or telecommand type (Bit 3 = 1). All TC Packets shall have this bit set to "1".

(c) Data Field Header Flag (Bit 4)

The Data Field Header Flag indicates the presence (Bit 4 = 1) or absence (Bit 4 = 0) of a Data Field Header within the Packet Data Field.

(d) Application Process Identifier (Bits 5 through 15)

The Application Process Identifier is an 11-bit field uniquely identifying both the physical "sink" (instrument or subsystem unit) and the particular application process within this physical sink to which is sent the TC Packet. A physical "sink" may 'own' more than one application process. Unless otherwise specified, any A.P. Identifier is unique on board a given spacecraft, regardless of the number of Virtual Channels or MAP connections used (1).

The Application Process Identifiers are tailored to the mission needs in general, and to the overall data management system requirements in particular. They are ultimately assigned by the Mission Control authority. Each Application Process Identifier is logically associated with the Packet Name or Sequence Count subfield of the Packet Sequence Control field.

8.2.1.2 Packet Sequence Control (16 Bits)

Packet Sequence Control is a 16-bit field which is subdivided into separate fields, namely Sequence Flags (2 bits) and Packet Name or Sequence Count (14 bits).

(a) Sequence Flags (Bits 0,1)

The Sequence Flags which occupy the two most-significant bits of the 16-bit Packet Sequence Control field, provide a method for defining whether this packet is a first, last or intermediate component of a higher-layer data structure, such as a sequence of packets which are addressed to one particular Application Process.

The assignment of the Sequence Flags is as follows:

- Last Sequential Component (Bit 0)
  When Bit 0 is set to value "1", it indicates that this packet is the last component of a higher-layer data structure which is addressed to one particular spacecraft Application Process.

NOTE (1): The space vehicle itself is identified by the Spacecraft Identifier in the TC Transfer Frame Header, as described in Section 6.

- First Sequential Component (Bit 1)
  When Bit 1 is set to value "1", it indicates that this packet is the first component of a higher-layer data structure which is addressed to one particular spacecraft Application Process.

Based on the above assignments, the Sequence Flags may be interpreted as follows:

Bit 0	Bit 1	Interpretation
0	1	First component of higher-layer data structure
0	0	Continuation component of higher-layer data structure
1	0	Last component of higher-layer data structure
1	1	Stand-alone TC Packet

(b) Packet Sequence Count (Bits 2 through 15)

This 14-bit subfield allows a particular TC Packet to be identified with respect to others occurring within a Telecommand Session. The technique consists of placing a straight sequence number within this field. This capability permits the packet to be traced and supervised prior to its release for execution.

Complete Standards for the use of the Packet Sequence Control field are to be found in Reference [6].

8.2.1.3 Packet Length (16 Bits)

The Packet Length is a 16-bit field which specifies the number of octets contained within the Packet Data Field. The number is a binary value "C" expressed as follows:

C = [(Number of octets in Data Field)-1]

Therefore, it should be noted that the **actual** length of the entire TC Packet will **implicitly** be 6 octets longer, since the standard 48-bit Packet Header always precedes the Packet Data Field. Also, the smallest possible TC Packet length is 7 octets and the largest possible is 65542 octets.

8.2.2 Packet Data Field

8.2.2.1 General

The Packet Data Field contains the information which is specific to the destination Application Process on board the spacecraft.

The Packet Data Field is subdivided into the following subfields:

- Data Field Header (optional and variable)
- Application Data (variable)
- Packet Error Control (optional, 16 bits)

8.2.2.2 Data Field Header

The Data Field Header is an optional subdivision of the Packet Data Field.

The purpose of the Data Field Header is to provide a standard means for inserting within the first octets of a TC Packet Data Field any ancillary data (time, additional packet type identification, internal data field format identification etc) which may be necessary to permit the interpretation of the data contained within the packet.

The presence or absence of a Data Field Header must be signalled by the Data Field Header Flag in the Packet Header.

The length of the Data Field Header shall be a multiple (integer) of octets. Comprehensive standards for the format of the Data Field Header are the subject of Reference [6].

8.2.2.3 Application Data

The Application Data field is a subdivision of the Packet Data Field. It is the user data in the form of a sequence of octets.

8.2.2.4 Packet Error Control

The Packet Error Control field is an optional subdivision of the Packet Data Field.

The purpose of the Packet Error Control field is to contain an error detection code (checksum or CRC) so that the ultimate recipient of the packet is able to verify that the integrity of the **complete TC Packet structure** has been preserved during the entire transport process and that this packet **is now available and correct in the memory of the Application Process**.

The presence of the Packet Error Control Field is defined **implicitly** by means of the A.P. Identifier.

The length of the Packet Error Control field is 16 bits.

Two error-control techniques are recommended:

(a) Cyclic Redundancy Code (CRC)

The CRC shall be that defined for the Transfer Frame in Section 6.2.

(b) Checksum

The optimum 16-bit error detection code is the CRC, which should be the preferred option whenever feasible.

For some processor-based systems, a CRC may not be appropriate, although it is the better technique in terms of error-detection performance. Therefore it is possible to select instead a 16-bit checksum that will be found easier to compute by some processors.

The checksum is specified in Reference [6].

8.3 STANDARD PROCEDURES WITHIN THE LAYER

8.3.1 Protocol Elements

This section only defines the minimum protocol elements of the layer at the receiving end. These elements are supplemented by Reference [6].

In a typical implementation on board a spacecraft, the PAC will be assisted by a Packet Distribution Function which will deliver each TC packet to its designated Application Process. To do this, the Packet Distribution Function may temporarily use the A.P. ID and the Packet Length fields, until the checks defined below are carried out.

(a) When a TC Packet is delivered complete into memory, the Application Process shall perform the following checks sequentially:

- CRC (or checksum) error syndrome verification. The verification process may make use of the Packet Length field.
- If the Packet is "clean", the following fields are verified for conformity:
  - Version Number
  - Type
  - AP ID
  - Packet Length (against actual number of octets received).

(b) If the Packet "conforms" to the above checks, a report shall be sent to ground by telemetry (via a TM Source Packet) to state:

- clean and conforming packet
- A.P. ID
- Packet Sequence Count

(c) If the Packet is clean but does not conform, a report shall be sent by telemetry to state:

- clean, but not conforming
- AP ID
- Packet Sequence Count

The packet data may then be erased automatically, or on command from ground, as required (Reference [6]).

(d) If the Packet is not clean, a report shall be sent by telemetry to state:

- rejected, dirty.

The data may be erased automatically, or on command from ground, as required (Reference [6]).

8.3.2 Service Primitives of Interface between Packetisation Layer and Higher Layers

These service primitives are not covered by this Standard.

8.3.3 Service Primitives of Interface between Packetisation Layer and Segmentation Layer

These service primitives have been described in Section 7.3.3.

8.3.4 Actions

As specified in Section 8.3.1 and Reference [6].

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9. DEEP-SPACE TELECOMMAND

9.1 OVERVIEW

In Reference [5], the deep-space class of missions begins at a distance of 2×10^{6} km from Earth. This boundary rules the choice of the radio-frequency bands, i.e. the Physical Layer. For what concerns the other layers of the Telecommand system, there are no such clear-cut rules.

The layer most likely to be affected, however, is the Transfer Layer. The error-correction function of the Coding Layer allows the selection of acceptable data rates on the long-range uplink with probabilities of Transfer Frame rejection better than (typically) one in 10^{5}. The Sequence-Controlled Service(COP-1/AD) of the Transfer Layer can be provided satisfactorily at such rejection rates, provided there are no more than 100 frames to be transmitted. For sequences of frames larger than 100, the FOP-1 Sliding Window will prevent any further transmission until a clear positive acknowledgement is received by the FOP-1. This feature, although not apparent when telecommanding near-Earth orbiters, may become an operational hindrance when the round-trip propagation delay of the radio waves exceeds the transmission time of 100 frames.

Section 9.2 describes how the deep-space performance of the AD service of COP-1 can be improved by systematic retransmission of the sequence of frames without waiting for a positive CLCW acknowledgement.

9.2 SYSTEMATIC RETRANSMISSION WITH COP-1/AD

When confronted with round-trip propagation delays much larger than the transmission time of 100 frames, it is possible to obtain the systematic retransmission of the complete sequence of frames before any positive acknowledgement has been received by the FOP-1 process on ground. To achieve this, it is sufficient to set the FOP-1 Timer to the shortest possible value, the number of retransmissions being specified by the selected FOP-1 Transmission Limit.

With such a set-up, the AD Service can be made to be suspended after the required number of transmissions (event E18 in the FOP-1 State Table with a return to the Initial state S6). Should further retransmission be required, this shall be assessed and initiated by the Data Management Layers above the FOP-1 (e.g. the Mission Control Centre) by means of the Resume AD Service Directive.

This procedure can provide operational advantages in most deep-space telecommanding scenarios, mainly by lowering the probability of frame retransmission after the effective CLCW acknowledgements have been received.

NOTE (1): This procedure may also be used in the near-Earth environment, particularly during launching operations, when the fastest access time for the loading of commands on board the spacecraft is desired. For instance, during the precarious communication period when the spacecraft appears over the Earth horizon, telecommands can be actually loaded faster with this method since the ARQ mechanism, with its inevitable time losses, is effectively by-passed.

NOTE (2): Data flow control by means of the "Wait" mechanism of COP-1 is not appropriate in a deep-space telecommanding environment where both the uplink and the spacecraft data-acceptance rates should be matched (see also Section 7.1, Paragraph (c), on MAPs and data flow control).

10. ENCRYPTED AUTHENTICATION OF TELECOMMAND DATA

10.1 CONCEPT OVERVIEW

The telecommand system, as it is currently understood by ESA (i.e. as a spacecraft **control** system), may require message authentication. There is however, no recognized need for secrecy of the telecommand message.

The selected telecommand authentication technique consists of appending a digital signature at the end of the relevant telecommand data structure (the TC Segment). The telecommand data is not scrambled. It is a "plain-text-with-appended-signature" system. The digital signature is an 'n-bit' string, (n = 40 bits in the currently proposed system) built up by an authentication algorithm from a secret key, the command data and a count number. The spacecraft authentication unit compares the received digital signature with the one it has constructed using the same algorithms. When the two signatures are equal, the command is assumed authentic, with a probability of a successful random attack of less than 1 in 2^n. The inclusion of a count number in the signature construction on ground guarantees that the authenticated TC Segment is unique over very large periods of time, thus providing protection against certain modes of attack (such as recording of transmitted signal, for instance). Each time a TC Segment is successfully authenticated the variable count number reference is incremented on board the spacecraft.

The choice of the TC Segment as the authenticated data structure is linked to that of the Sequence-Controlled Service of COP-1. These two choices are conveniently compatible with the synchronisation requirements of the authentication count number. Thus the signature is placed at the end of the TC Segment structure, which effectively means placing an Authentication Sub-layer between the Transfer Layer and the Segmentation Layer.

An immediate consequence is that the authentication processes both on ground (Control Centre) and on board the spacecraft (TC decoder) can be centralised and, therefore standardised. Key and protocol management is facilitated and the overall security improved. Furthermore, the executable command data unit (e.g. the TC Packet) may have any format.

Another consequence is that the Mission Control Centre shall be responsible for segmenting the TC packets and appending the authentication signatures, if required. The TC Packets are then delivered to the transmitting

Ground Station as Service 2 TC Packets (i.e. TC Packets reformatted to contain the required Authentication Tails, as described in Section 3.3).

For operational flexibility, three counters are selectable. These three counters effectively provide three "Logical Authentication Channels" (LACs). The first two LAC counters ("Principal LAC" and "Auxiliary LAC") make it possible to multiplex two independent streams of authenticated data on two independent sets of MAP connections without discontinuities (one LAC for each set of MAPs). With this system, it is now possible to uplink dynamically independent authenticated data from two distinct Control Centres, e.g. one Spacecraft Control Centre and one Payload Control Centre. Although both Centres must have full knowledge of the same operating key, they do not need to synchronise their authentication algorithms. It should also be noted that, if so required, more system flexibility can be obtained by preselecting (both on ground and on board) those MAPs which must be authenticated (e.g. spacecraft control data MAPs) and those which do not need to be (e.g. payload control data MAPs).

The third LAC counter is foreseen for recovery ("Recovery LAC"): its contents are nonvolatile. Transmission operations (under COP-1) are carried out by the Ground Station as for a nonencrypted link: Transfer Layer Control Frames ("Unlock" and "Set V(R)") are **not authenticated** since they belong to the Transfer Layer. They contain no data and have no effect on the data distribution system data. Unauthorised attempts to damage the spacecraft via COP-1 Control Commands would only upset the FARM-1 setting on board the spacecraft and disturb operations in the same way a jamming system would, but no data will be allowed to reach the spacecraft data system.

Telemetry reporting of on-board authentication events will be done via mission-specific data (Source Packets, in the case of Packet Telemetry), not via the CLCW. Such telemetry information does not need to be encrypted.

The following sections describe the general layout and interface of the authentication system at the receiving end.

The detailed specification of the full authentication system can be found in Reference [8] where the authentication algorithm, the implementation considerations, the TC Segment formats (such as the various Authentication Control Commands), the operational loading and recovery procedures are described.

It is expected that, in view of the rapid evolution of the encrypted authentication techniques, several authentication algorithms, with their particular formats and procedures, will be defined in the future. Therefore this Standard only specifies the essential features of the system (layout, interfaces) so that any new authentication technique can easily be accommodated to the existing standardised system implementation.

10.2 GENERAL LAYOUT AND INTERFACE

The optional Authentication Layer is placed between the Transfer Layer and the Segmentation Layer. That part of the TC decoder which is concerned with the Authentication Layer is called the Authentication Unit (A.U.). Figure 10.1 diagrammatically shows the general layout and interface of the A.U. Both the functions and the interface of the A.U. are standardised so as to permit future evolution of authentication algorithms and methods.

When the Authentication Option is not retained the "AUTHORISED/ NON-AUTHORISED" line is permanently set to the "AUTHORISED" level. If the mission requires that the A.U. be by-passed in flight, the "AUTHORISED" level can be provided by the spacecraft Data Management System, on command.

All TC Segments are verified by the Authentication Processor.

Only the specific TC Segments carrying Authentication Control Commands are accepted by the Supervisor after authorisation by the Authentication Processor. These specific TC Segments are distinguished by the "all ones" Segment Header, which is reserved to this usage exclusively (MAP number 63, plus the two Sequence Flags set to "Unsegmented")

Authentication Control Commands are used to reconfigure the A.U., for key management and recovery operations.

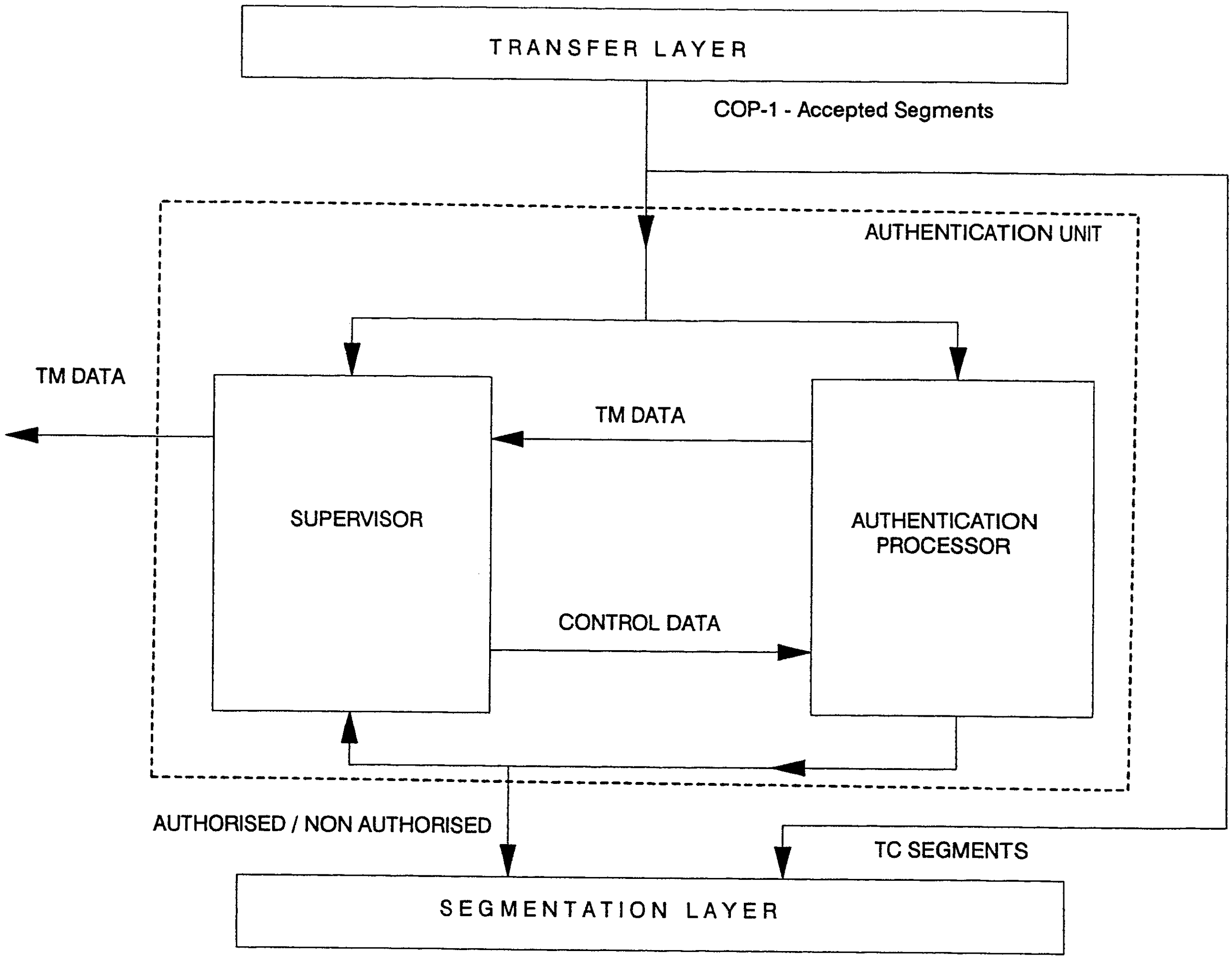

Figure 10.1 AUTHENTICATION UNIT LAYOUT AND INTERFACE

NOTE: This is a conceptual layout. The actual routing and connection of the Authentication Control Data depend on the design options (e.g. MAP selection).

10.3 THE LAC COUNTERS

A LAC Counter is basically a 30-bit counter which is used to associate every TC Segment with an authentication sequence number. The purpose of this number is to protect the system against attacks by ensuring that identical TC Segments will not produce the same signature except at very large intervals of time. With a 30-bit counter it generally amounts to one counter cycle in the mission lifetime, thus making it impossible for an attacking party to record TC frames and play them back later with effect.

The procedure is forced by incrementing the LAC Counter by 'one' every time a TC Segment is successfully authenticated (and only then). As introduced in Section 10.1, two such LAC Counters have been foreseen (plus a special third counter for recovery purposes), each counter allowing an independent, distinct sequence of authenticated TC Segments.

The contents of the LAC Counters need not be secret.

This characteristic is advantageous from an operational point of view. Firstly, the values of the various LAC Counters maintained by the on-board system can be telemetered with no need for secrecy. Secondly, the LAC Counter values used for authenticating each TC Segment can be uplinked, in plain text, with each signature. This, while having no impact on security, brings the following system benefits:

- easy selection of each LAC on board the spacecraft.
- identification of protocol rejections versus signature rejections (e.g. case of an attack with recorded segment data being played back).

10.4 STANDARD DATA STRUCTURES WITHIN THE LAYER

The general structure of an authenticated TC Segment is shown in Figure 10.2.

In Reference [8], the length of the signature field is 5 octets (N=5) and, therefore, the length of the Authentication Tail is 9 octets.

The general structure of the Authentication Tail is given in Figure 10.3.

249 OCTETS MAXIMUM			
SEGMENT HEADER		SEGMENT DATA FIELD	SEGMENT TRAILER
SEQ. FLAGS 2 BITS	MAP IDENTIFIER 6 BITS		AUTHENTICATION TAIL
1 OCTET		FROM 0 TO (244-N) OCTETS	(4 + N)OCTETS

Figure 10.2 GENERAL STRUCTURE OF AN AUTHENTICATED ESA TC SEGMENT

LOGICAL AUTHENTICATION CHANNEL (LAC)		SIGNATURE
LAC ID (2 BITS)	LAC COUNT (30 BITS)	
4 OCTETS		N OCTETS

Figure 10.3 GENERAL STRUCTURE OF THE AUTHENTICATION TAIL

11. TELECOMMAND SERVICES AND PERFORMANCE REQUIREMENTS

11.1 SUMMARY OF THE SERVICES

The telecommand services defined in this Standard are essentially those provided by the lower layers of the telecommand system (i.e. the data link layers). The services provided by the higher layers of the telecommand system (i.e. the data management layers) are defined in Reference [6].

From a purely data-link standpoint, two services are offered:

- **The Sequence-Controlled Service**

This service guarantees that TC Segments are delivered to the receiving end of the data link layers in the same sequential order in which they were received from the layer above at the sending end (possibly with some variable delay), with no omissions, no duplications and no errors (within the probability of undetected frame error discussed in the next section).

The short name of the service is "**AD Service**", as it consists essentially of transmitting TC Transfer Frames of the type AD. However, the full service includes two "AD Service Initialisation Directives" which involve the controlled transmission of the two standard TC Transfer Frames of the type BD (Control Frames): "Unlock" and "Set V(R).

- **The Expedited Service**

The service guarantees that TC Segments are delivered at the receiving end of the data link layers in the same sequential order in which they were received from the layer above at the sending end, with no errors, no duplications **but with possible omissions**.

The short name of the service is "**BD Service**". Since the main data link service used for the mission is the AD Service, the BD Service shall normally be considered for recovery operations exclusively (e.g. in the absence of telemetry, when in "lockout", etc.).

Because of its particular location in the Segmentation Layer (i.e. before MAP demultiplexing, at the receiving end), the "**Authentication Service**" can be considered as an **option** of the data link services above. Use of the AD Service provides an efficient operational platform for the smooth control of the Authentication Sublayer processes. Use of the BD Service is safe, but requires more activity in the Higher Layers when a TC Segment is lost (retransmission "Go-back-N" decision).

Finally, reference is made to the "**Network Interface Services**" described in Section 3.3:

- **Service 1:** **Sequence-Controlled Service for Packets (without Authentication of Segments)**
- **Service 2:** **Sequence-Controlled Service for Packets (with Authentication of Segments)**
- **Service 3:** **Expedited Service**

11.2 PERFORMANCE REQUIREMENTS

The TC transfer Frame is the accounting entity for telecommand data link performance. This performance is described by two probabilities:

- **P_{FR}** : this is the probability that any one frame will be rejected
- **P_{FU}** : this is the probability that the contents of any one accepted frame will contain an undetected error.

The various factors affecting these two probabilities are discussed in detail in **Appendix D : Data Link Performance: Rationale and Guidelines.**

This Standard **recommends** that a channel bit error rate (BER) on the telecommand uplink **be guarantees under all operating conditions to** be better than 10^{-5}. For this value of BER, this Standard **guarantees** a P_{FR} better than 1 in 10^{5} frames and a P_{FU} better than 1 in 10^{19} frames.

The full significance of the selected value for the channel BER is discussed in Appendix D.

12. COMPATIBILITY WITH OTHER GROUND NETWORKS

This Standard is a derived subset of References [1], [2], [3] and [4]. At the time of issue of this Standard, the various Agencies participating in the CCSDS have only recently started their plans for defining compatible agency-specific standards. It is expected that the potential for cross-support will considerably increase during the coming decades.

ESA missions requiring support from other agencies' ground networks are cautioned to negotiate the exact level of compatibility between these networks and their spacecraft systems.

Non-ESA missions conforming to CCSDS-derived telecommand standards issued by other Agencies and requiring support from the ESA ground network are also cautioned to negotiate the exact level of compatibility between their spacecraft systems and the ESA network. In many instances, the ESA network may readily (or at little cost) cover aspects of the CCSDS Recommendations which have not been retained in this Standard.

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APPENDIX A

GLOSSARY OF ACRONYMS

AD: One of three abbreviations (AD, BD, BC) used in this standard and which reflect the state of the "Bypass" and "Control Command" flags in the Transfer Frame Header:

- Bypass Flag = 0 = A = Acceptance Check of N(S)
- Bypass Flag = 1 = B = Bypass of A
- Command Control Flag = 0 = D = Data
- Command Control Flag = 1 = C = Control

It should be noted that only AD, BD and BC are legal: AC is an illegal combination since Control Commands cannot reliably use a transfer service which they are meant to modify.

ARQ: Automatic Request for Retransmission

BC: See AD

BCH: Bose-Chaudhuri-Hocquenghem

BD: See AD

BER: Bit Error Rate

CCSDS: Consultative Committee for Space Data Systems

CLCW: Command Link Control Word

CLTU: Command Link Transmission Unit

CMM: Carrier Modulation Mode

COP: Command Operation Procedure

CRC: Cyclic Redundancy Code

DED: Double Error Detection

FARM: Frame Acceptance and Reporting Mechanism

FCS: Frame Check Sequence (e.g. a CRC)

FEC: Forward Error Correction

FOP: Frame Operation Procedure

ID: Identifier

K: The "FOP_Sliding_Window_Width": this is a variable of the FOP

LLIF: Lower Layer Interface

MAP: Multiplexed Access Point

N(R): The "Next Expected Frame Sequence Number" in a CLCW

NN(R): The "Expected Acknowledgement Frame Sequence Number": this is a variable maintained by the FOP containing the value of N(R) from the previously received CLCW

N(S): The "Frame Sequence Number" in a transmitted TC Frame

NW: The "FARM_Negative_Window_Width": this is a variable of the FARM

PLOP: Physical Layer Operation Procedure

PW: The "FARM_Positive_Window_Width": this is a variable of the FARM

RF: Radio Frequency

S/C: Spacecraft

SEC: Single Error Correction

SS: The "Suspend_State": this is a variable of the FOP

TC: Telecommand

TM: Telemetry

TT: The "Timeout_Type": this is a variable of the FOP

VC: Virtual Channel

V(R): The "Receiver_Frame_Sequence_Number": this is a variable maintained by the FARM containing the sequence number of the next expected frame

V(S): The "Transmitter_Frame_Sequence_Number": this is a variable maintained by the FOP containing the sequence number to be assigned to the next frame to be transmitted

W: The "FARM_Sliding_Window_Width": this is a variable of the FARM

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APPENDIX B

POSSIBLE REALISATION OF A FRAME CHECK SEQUENCE ENCODER - DECODER

This Appendix describes two possible arrangements, based on a shift register, for encoding and decoding a Transfer Frame according to the Frame Check Sequence procedures defined in Section 6.

B.1 ENCODER

Figure B.1 shows a possible arrangement for encoding with the aid of a shift register. To encode, the storage stages are set to "one", gates A and B are enabled, gate C is inhibited, 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.

B.2 DECODER

Figure B.2 shows a possible arrangement for decoding with the aid of a shift register. To decode, the storage stages are set to "one", and gate B is enabled.

The received n bits (i.e. the (n-16) message bits plus the 16 bits of FCS) are then clocked into the input and 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 contents indicates an erroneous block.

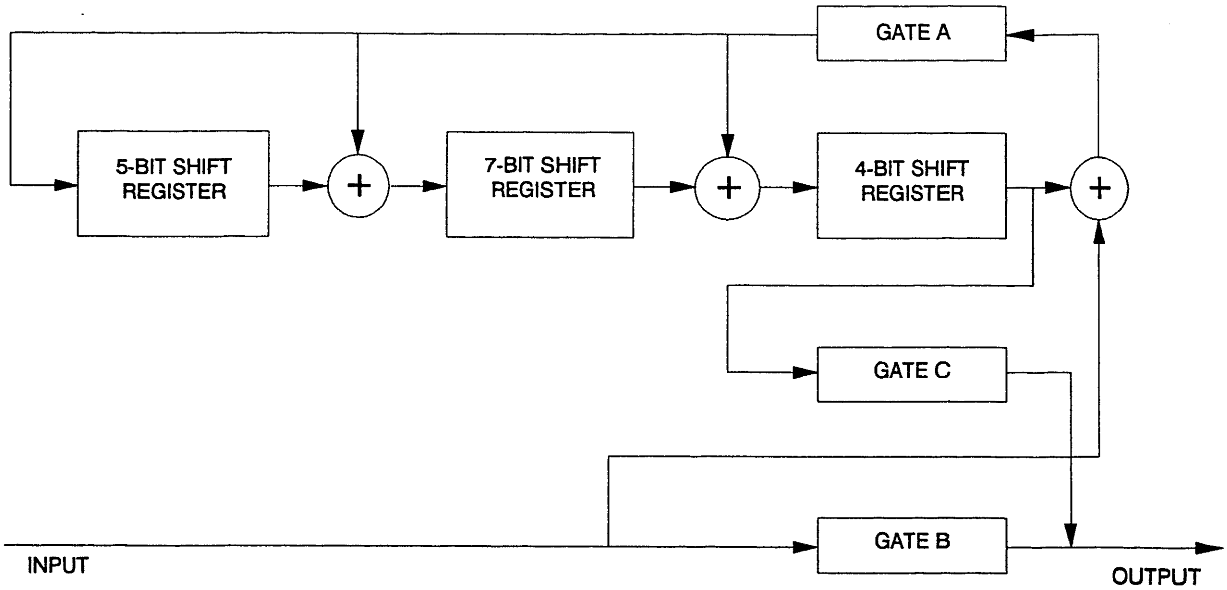

Figure B.1 ENCODER

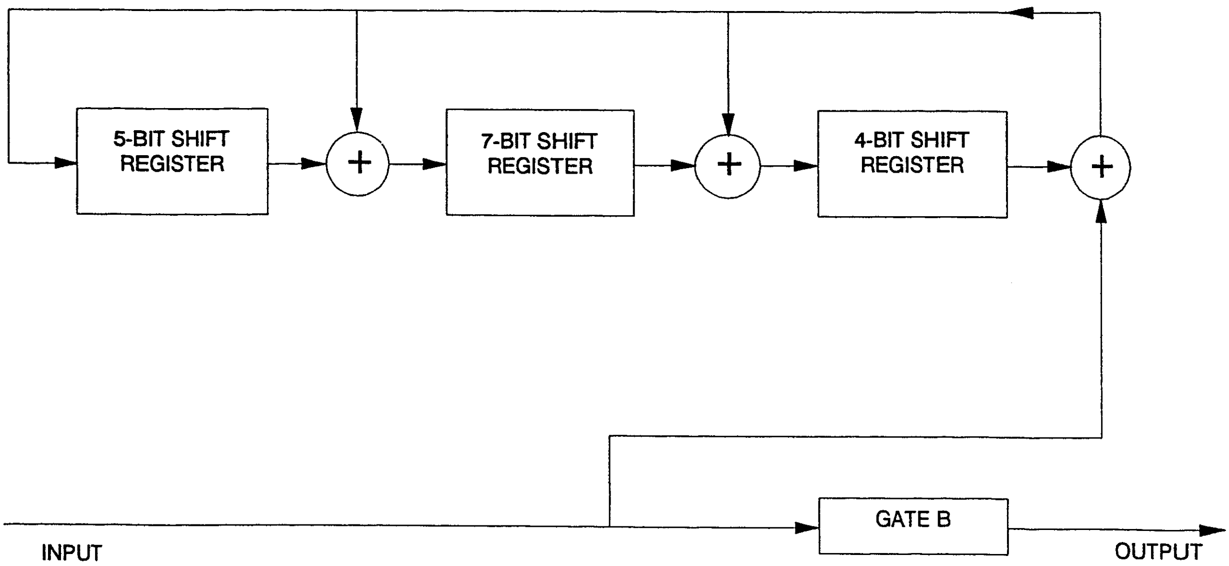

Figure B.2 DECODER

APPENDIX C

DATA LINK MANAGEMENT AND MONITORING

C.1 INTRODUCTION

The data link protocols specified in this Standard are strictly limited to the operation of the uplink. To achieve the proper operation of the telecommand data link, only one telemetry data structure is defined: the CLCW. This appendix discusses the recommended method for multiplexing on the telemetry downlink the CLCW data from (typically) two telecommand Virtual Channel processes.

Furthermore, this appendix introduces the concept of Data Link Management and points at some current and future system developments.

C.2 CLCW MULTIPLEXING

Typically, all ESA spacecraft will carry two telecommand front-end units traditionally called "TC decoders".

The TC decoder is specified in detail in Reference [8]. Each TC decoder is in a constant state of readiness, i.e. it is always powered and in the "Open" state. Each TC decoder delivers CLCW data to the spacecraft telemetry system, typically only the last 16 bits, the other 16 bits being either reconstructed by the telemetry system (VC ID, COP-IN-EFFECT, etc) or obtained from other units (NO RF AVAILABLE flag, for example).

Therefore, the telemetry system completes the two received CLCWs and inserts them into the telemetry Transfer Frames according to one of the following schemes:

(a) Standard Insertion Scheme No. 1

Either CLCW No. 0 or CLCW No. 1 will be inserted in all telemetry frames, but not both. The selection shall be carried out by means of two "CLCW Select" commands which will equip the telemetry system. In the case of failure of the selected TC decoder, the Expedited Service (COP-1/BD) shall be used to select the insertion of the other CLCW through the redundant TC decoder.

(b) Standard Insertion Scheme No. 2

CLCW No. 0 and CLCW No. 1 are alternately inserted in the telemetry Transfer Frames. This method has two drawbacks:

- The effective CLCW rate on the downlink is halved;
- Should the contents of one CLCW become erratic (failure), the consequences on the behaviour of the ground station equipment must be investigated (a false VC value may disrupt the FOP-1 of that VC). A possible solution is to place CLCW No. 0 in the even telemetry frames and CLCW No. 1 in the odd telemetry frames.

On the other hand, this solution requires no specific "Select CLCW" commands, as the Standard Insertion Scheme No. 1 does.

C.3 DATA LINK MANAGEMENT

It is recommended that the TC decoders be equipped to provide sufficient diagnostic information to enable an accurate survey of the performance of each TC decoder to be made on ground throughout the life time of the spacecraft and from a specifically data-link standpoint.

The aim is to:

- survey the actual performance of the data link, accumulate history data and be able to detect any degradation of the TC decoder circuitry;
- survey the overall performance of the data link, from an operational point of view (e.g. detection of interfering telecommand uplinks), and integrate the results with the survey data from all other spacecraft in operation.

Reference [8] proposes a telemetry data structure of 32 bits called "Frame Analysis Report" which, when combined with the relevant ground telecommand traffic data, can yield essential mission and network management tools in a not-so-distant future of crowded spacelanes, both physically and electromagnetically.

APPENDIX D

DATA-LINK PERFORMANCE : RATIONALE AND GUIDELINES

This appendix supplements Section 11 (Telecommand Services and Performance Requirements).

D.1 RATIONALE OF THE DATA-LINK SYSTEM

The telecommand data-link system defined in the Standard makes use of two types of error-control techniques:

- Forward Error Correction (FEC), including error detection only.
- Automatic Request for Retransmission (ARQ)

COP-1/AD uses a hybrid of both error-control techniques, while COP-1/BD only uses FEC.

(a) FEC

FEC is used at two levels:

- Single-Error Correction and Double-Error Detection (SEC/DED) for the process of TC Codeblocks in the CLTU.
- Error detection in the TC Transfer Frame by means of the 16-bit Frame Check Sequence (FCS) placed at the end of the frame.

At the channel bit error rates (BER) considered in the next section, these two FEC methods improve the data link performance as follows:

- SEC/DED lowers substantially the probability of rejecting a TC Transfer Frame;
- The FCS (which is a CRC) lowers considerably the probability of an undetected error occurring in the TC Transfer Frame.

Low frame-rejection rates result in higher data throughputs and improved operational conditions, owing to the reduced amount of time devoted to retransmissions. Very low probabilities of undetected frame error are essential in that they offer the possibility to operate two (or more) redundant telecommand decoders, each decoder being in a state of readiness (Virtual

Channel always in the "Open" state) and operating on the same physical channel (same radio and modulation frequencies).

This possibility can also be envisaged for "families " of spacecraft, with the same physical channel characteristics for the uplink of each spacecraft. Such a concept, however, must be backed-up by specific studies, since the risks involved are difficult to assess (not to mention the associated channel "jamming" aspects which are out of the scope of this Standard).

(b) ARQ

The ARQ technique is used to provide the main service of COP-1: the Sequence-Controlled Service (COP-1/AD). The ARQ technique uses a "Go-back - N" strategy. This is consistent with the low frame-rejection rate capability of the system as will be shown in the next subsections.

D.2 FACTORS AFFECTING THE FRAME REJECTION RATE

As specified in Section 5 (Coding Layer), the basic strategy used for processing a CLTU can be summarised as follows:

- START : Start Sequence accepted with 0 or 1 bit in error
- DECODE : SEC/DED with codeblock fill bit test
- FINISH : Rejection of Tail Sequence as uncorrectable codeblock

Assuming that bit synchronisation has been achieved, one can write:

(a) Start Sequence Factor

The probability P_S of rejecting a Start Sequence is:

$$P_S = 1 - [(1 - p)^{16} + 16p\,(1-p)^{15}] \qquad \text{(E.1)}$$

where p is the channel BER.

Table D.1 provides values of P_S for three typical values of BER.

BER	10^{-4}	10^{-5}	10^{-6}
P_S	1.20×10^{-6}	1.20×10^{-8}	1.20×10^{-10}

Table D.1 PROBABILITY P_S OF START SEQUENCE REJECTION

(b) TC Codeblock Factor

The probability P_C of one or more TC Codeblocks of the CLTU being in error AND uncorrectable (and therefore rejected) is:

$$P_C = 1 - [(1-p)^n + (1-p) np (1-p)^{n-1}]^N$$

which can be simplified as:

$$P_C = 1 - [(1-np) (1-p)^n]^N \quad \text{(E.2)}$$

where:

p is the channel BER
n is the number of bits in the TC Codeblock, minus the fill bit
N is the number of TC Codeblocks in the CLTU

Table D.2 provides values of P_C for three typical channel bit error rates and some representative values of N.

(c) Tail Sequence Factor

The performance of the system relies finally on the probability P_T of missing a Tail Sequence, i.e. of not rejecting it. This probability is:

$$P_T = [1 - (1 - p)^n] p \quad \text{(E.3)}$$

where:

p is the channel BER
n is the number of bits in the TC Codeblock, minus the fill bit

Table D.3 provides values of P_T for three typical values of channel BER.

N	P_C with BER (p) of:		
	10-4	10-5	10-6
1	2.01×10^{-5}	2.02×10^{-7}	2.00×10^{-9}
2	4.02×10^{-5}	4.03×10^{-7}	4.00×10^{-9}
12	2.42×10^{-4}	2.42×10^{-6}	2.40×10^{-8}
24	4.82×10^{-4}	4.84×10^{-6}	4.80×10^{-8}
37	7.43×10^{-4}	7.45×10^{-6}	7.40×10^{-9}

Table D.2 PROBABILITY P_C OF CODEBLOCK REJECTION AS A FUNCTION OF N FOR 64-BIT CODEBLOCKS (n = 63)

Codeblock Length (Bits)	n (Bits)	P_T with BER (p) 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}

Table D.3 PROBABILITY P_T OF MISSING A TAIL SEQUENCE

D.3 FRAME REJECTION PROBABILITIES

The probability P_{FR} of rejecting a stand-alone TC Transfer Frame is determined from:

- the probability of missing a CLTU Start Sequence
- the probability of finding a CLTU Start Sequence AND the probability of rejecting one or more TC Codeblocks

The P_{FR} for a stand-alone TC Transfer Frame is thus:

$$P_{FR} = P_S + (1 - P_S) P_C \quad (E.4)$$

When several frames are transmitted continuously, the probability P_T of missing a Tail Sequence must be considered. Thus the probability P_{SFR} of rejecting a subsequent frame is:

$$P_{SFR} = P_T + (1 - P_T) P_{FR} \quad (E.5)$$

In practice P_{SFR} equals P_{FR}. As an example, the probability of frame rejection for two maximum length frames (n = 63, N = 37) and a BER of 10^{-5} is:

First Frame : 7.47×10^{-6}
Second Frame : 7.47×10^{-6}

Table D.4 provides values of P_{SFR} for three typical channel bit error rates and some representative values of N.

N	P_{SFR} with BER (p) of:		
	10^{-4}	10^{-5}	10^{-6}
1	2.19×10^{-5}	2.20×10^{-7}	2.18×10^{-9}
2	4.20×10^{-5}	4.21×10^{-7}	4.18×10^{-9}
12	2.43×10^{-4}	2.44×10^{-6}	2.42×10^{-8}
24	4.84×10^{-4}	4.86×10^{-6}	4.82×10^{-8}
37	7.44×10^{-4}	7.47×10^{-6}	7.42×10^{-8}

Table D.4 PROBABILITY P_{SFR} OF FRAME REJECTION AS A FUNCTION OF N FOR 64-BIT CODEBLOCKS (n = 63)

Finally, a measure of the influence of the TC Codeblock length on P_{SFR} is given in Table D.5. As can be seen, the performance improves when the codeblock length is shortened. However, the values of Table D.5 do not take into account the increased overhead occasioned by this shortening and its negative impact on the effective data throughput. (NOTE: The reason behind the codeblock length options is a technological one rather than a purely performance one. The equipment designer may find one codeblock length more suitable than the others when using a given microcircuitry architecture.)

Codeblock Length (Bits)	Number of Codeblocks (N)	P_{SFR} with BER (p) of:		
		10^{-4}	10^{-5}	10^{-6}
64	2	4.20×10^{-5}	4.21×10^{-7}	4.18×10^{-9}
	37	7.44×10^{-4}	7.47×10^{-6}	7.42×10^{-8}
56	2	3.24×10^{-5}	3.25×10^{-7}	3.18×10^{-9}
	43	6.61×10^{-4}	6.64×10^{-6}	6.47×10^{-8}
48	2	2.41×10^{-5}	2.42×10^{-7}	2.38×10^{-9}
	52	5.86×10^{-4}	5.88×10^{-6}	5.73×10^{-8}
40	2	1.71×10^{-5}	1.72×10^{-7}	1.76×10^{-9}
	64	5.00×10^{-4}	5.00×10^{-6}	5.14×10^{-8}

Table D.5 PROBABILITY P_{SFR} OF FRAME REJECTION AS A FUNCTION OF CODEBLOCK LENGTH FOR MINIMUM AND MAXIMUM FRAME LENGTHS

D-4 UNDETECTED FRAME ERROR PROBABILITIES

Most of the errors not detected by the Coding Layer will be eliminated by the Transfer Layer (Clean Frame Validation process). Figure D.1 illustrates the performance of these processes for a BER of 10^{-5}:

- The top curve shows the probability of undetected frame error when there is no CRC in the frame (this is given for comparative purposes).
- The bottom curve shows the probability of undetected frame error (P_{FU}) when there is a CRC in the frame (as specified in this Standard).

Section 11 of this Standard recommends that a BER of 10^{-5} be guaranteed on the uplink channel. For this value of BER, a P_{FR} of 10^{-5} and a P_{FU} of 10^{-19} are guaranteed at the output of the Clean Frame Validation process. The

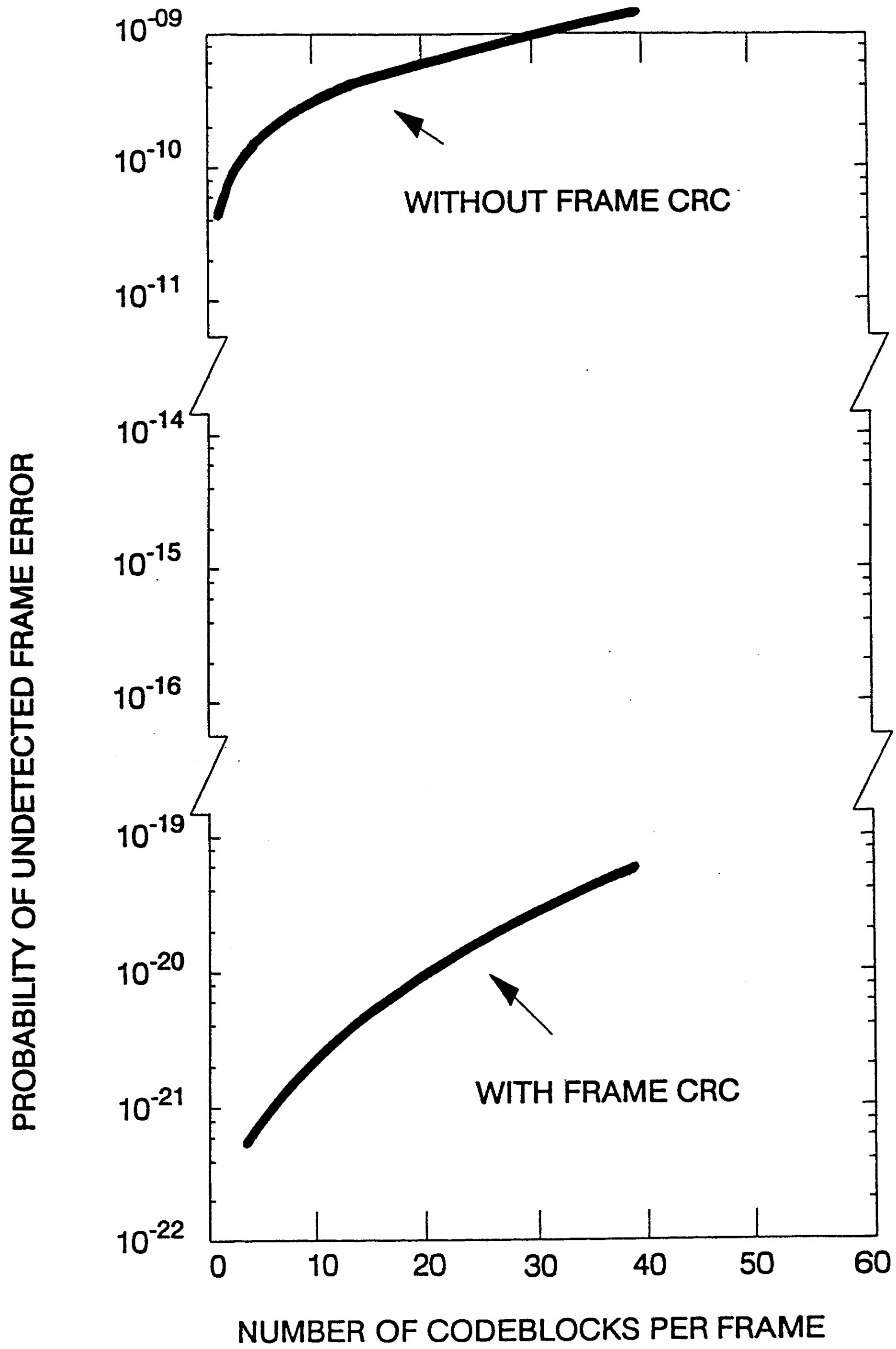

Figure D.1 PROBABILITY P_{FU} OF UNDETECTED FRAME ERROR AT A BER OF 10^{-5}

significance of this recommendation is best illustrated by the following "worst case" example:

- Mission bit rate : 10^3 bps
- Average frame length considered : 10^3 bits (about 128 octets)
- Amount of time spent transmitting data at BER of 10^{-5} (worst case) : 100% of every day
- Occurrence of rejected frame : one every day
- Occurrence of an erroneously accepted frame : one every 3 X 10^{11} years

For a BER of 10^{-4}, a P_{FR} of 10^{-3} and a P_{FU} of 10^{-16} can be expected. For the example considered above, this amounts to 10^2 frames rejected per day and one erroneous frame accepted every 3 X 10^8 years.

For a BER of 10^{-3}, a P_{FR} between 10^{-1} and 10^{-2} can be expected, while a P_{FU} of 10^{-10} can be guaranteed. For the example considered above, this amounts to more than 10^4 frames rejected per day (i.e. the link can hardly be operated) and one erroneous frame accepted every 300 years.

For a BER of 10^{-2}, the number of rejected frames is nearly that of the transmitted frames, and a P_{FU} of 10^{-7} can be expected. For the example considered above, this signifies that the link cannot be operated and that one erroneous frame will be accepted every 4 months.

These "worst cases" examples show that, in all practicality, a BER of 10^{-5} should be recommended as the worst acceptable value to operate the link. This recommendation is also valid for those instances when the link is not being operated. In such cases, the characteristics specific to the mission must be assessed against **the possibility of detecting interfering telecommand signals conforming to the same CCSDS standards**. As a result, a BER worse than 10^{-5} may be found acceptable (in terms of probability of occurrence of an erroneously accepted frame) if this can lead to easier (or improved) implementation on board the spacecraft. In case of doubt, however, a BER of 10^{-5} should be preferred as the worst limit.

[redacted]