

# ***Consultative Committee for Space Data Systems***

REPORT CONCERNING SPACE  
DATA SYSTEMS STANDARDS

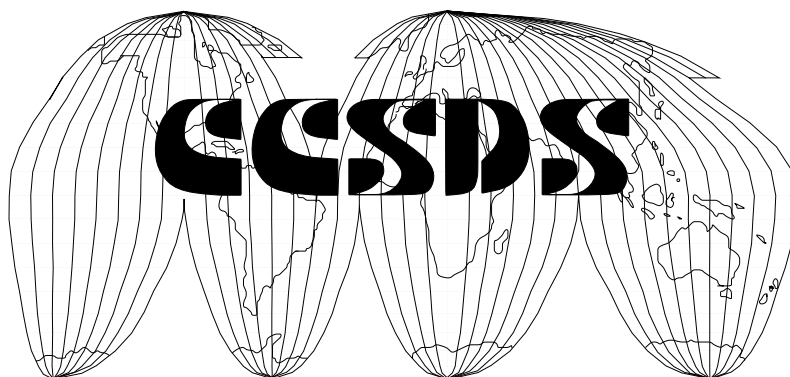
## **ADVANCED ORBITING SYSTEMS, NETWORKS AND DATA LINKS:**

SUMMARY OF CONCEPT,  
RATIONALE, AND PERFORMANCE

CCSDS 700.0-G-3

**GREEN BOOK**

NOVEMBER 1992



## AUTHORITY

Issue:	Green Book, Issue 3
Date:	November 1992
Location:	Annapolis, Maryland, USA

This Report reflects the consensus of the technical panel experts of the following member Agencies of the Consultative Committee for Space Data Systems (CCSDS):

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

- o Chinese Academy of Space Technology (CAST)/People's Republic of China.
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This document is published and maintained by:

CCSDS Secretariat  
Program Integration Division (Code OI),  
National Aeronautics and Space Administration  
Washington, DC 20546, USA

## **FOREWORD**

This document is a CCSDS Report which contains background and explanatory material to supplement the CCSDS Recommendation, “Advanced Orbiting Systems, Network and Data Links: Architectural Specification”, Reference [1].

Through the process of normal evolution, it is expected that expansion, deletion or modification to this Report may occur. This Report is therefore subject to CCSDS document management and change control procedures which are defined in Reference [2].

Questions about the contents or status of this Report should be addressed to the CCSDS Secretariat.

**DOCUMENT CONTROL**

Document/Title	Date	Status and Substantive Changes
CCSDS 700.0-G-1: Report Concerning Space Data System Standards. Advanced Orbiting Systems, Networks and Data Links: Summary of Concept, Rationale, and Performance Issue-1	June 1989	Supported Issue-3 AOS Red Book: Superseded
CCSDS 700.0-G-2: Report Concerning Space Data System Standards. Advanced Orbiting Systems, Networks and Data Links: Summary of Concept, Rationale, and Performance Issue-2	October 1989	Supported Issue 1 AOS Blue Book: Superseded
CCSDS 700.0-G-3: Report Concerning Space Data System Standards. Advanced Orbiting Systems, Networks and Data Links: Summary of Concept, Rationale, and Performance Issue-3	November 1992	Supports Issue 2 AOS Blue Book Current Issue  <ol style="list-style-type: none"> <li>1. Removes superfluous information that is adequately covered in the main Recommendation.</li> <li>2. Updates current status of related AOS work items.</li> <li>3. Adds information on hybrid mission configurations and production data processing.</li> <li>4. Updates encoder verification information.</li> </ol>

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## REFERENCES

- [1] “Advanced Orbiting Systems, Networks and Data Links: Architectural Specification”, Recommendation for Space Data Systems Standards, CCSDS 701.0-B-2, Blue Book, Issue 2, (Washington, D.C.: CCSDS, November 1992 or later issue).
- [2] “The AOS Handbook”, (Noordwijk, Netherlands: ESA Publications Division, ESTEC).
- [3] “Radio Frequency and Modulation Systems; Part 1: Earth Stations and Spacecraft”, Recommendation for Space Data Systems Standards, CCSDS 401.0-B, Blue Book (Washington, D.C.: CCSDS, September 1989 or later issue). Note: Since this Reference does not currently cover data relay satellites, the following document shall be substituted for Reference [3]: STDN 101.2, “Space Network (SN) Users’ Guide” [formerly titled “Tracking and Data Relay Satellite System (TDRSS) Users’ Guide”], Revision 6, (Greenbelt, Maryland: NASA Goddard Space Flight Center, September 1988 or later issue).
- [4] “Telemetry Channel Coding”, Recommendation for Space Data Systems Standards, CCSDS 101.0-B-3, Blue Book, Issue 3 (Washington, D.C.: CCSDS, May 1992 or later issue).
- [5] “Packet Telemetry”, Recommendation for Space Data Systems Standards, CCSDS 102.0-B-3, Blue Book, Issue 3 (Washington, D.C.: CCSDS, November 1992 or later issue).
- [6] “Telecommand Part 1—Channel Service”, Recommendation for Space Data Systems Standards, CCSDS 201.0-B-1, Blue Book, Issue 1 (Washington, D.C.: CCSDS, January 1987 or later issue).
- [7] “Telecommand Part 2—Data Routing Service”, Recommendation for Space Data Systems Standards, CCSDS 202.0-B-2, Blue Book, Issue 2 (Washington, D.C.: CCSDS, November 1992 or later issue).
- [8] “Telecommand Part 2.1—Command Operation Procedures”, Recommendation for Space Data Systems Standards, CCSDS 202.1-B-1, Blue Book, Issue 1, (Washington, D.C.: CCSDS, October 1991 or later issue).
- [9] “Telecommand Part 3—Data Management Service”, Recommendation for Space Data Systems Standards, CCSDS 203.0-B-1, Blue Book, Issue 1 (Washington, D.C.: CCSDS, January 1987 or later issue).
- [10] “Virtual Channel Multiplexing Traffic Simulation”, by J. M. Carra and F. Gomez Molinero (Noordwijk, Netherlands: European Space Agency, ESTEC/WD Division).

- [11] “Audio, Video and Still-Image Communications Services”, Recommendation for Space Data Systems Standards, CCSDS 704.0-R-2, Red Book, Issue 2 (Washington, D.C.: CCSDS, May 1993 or later issue).

## **DOCUMENTATION STATUS**

For completeness, several areas of work which are still under development are detailed in the main Recommendation [1].

The following supplementary AOS reference documents, which are currently available as CCSDS White Books, have been used in the preparation of this document:

- [12] “Advanced Orbiting Systems, Networks and Data Links: Space Link ARQ Procedure”, Draft Recommendation for Space Data Systems Standards, CCSDS 702.0-W-1, White Book, Issue 1 (Washington, D.C.: CCSDS, March 1990 or later issue).
- [13] “Description of CCSDS Ground Infrastructure Cross Support Services” (Draft White Book, 20 April 1992 or later issue); vol. 1, “Service Concept”; vol. 2, “Space Data Services”; and vol. 3, “Ground Domain Services”.



# **1 INTRODUCTION**

## **1.1 PURPOSE**

This Report presents a summary of supplementary information which underlies the main Recommendation for Advanced Orbiting Systems (AOS), Reference [1]. This information may help first-time readers to understand and apply the main Recommendation. Notes on specific topics, such as system performance, are included. Reference [2] also contains information that readers may find useful to augment this report.

## **1.2 SCOPE**

THE INFORMATION CONTAINED IN THIS REPORT IS NOT PART OF THE MAIN CCSDS RECOMMENDATION FOR ADVANCED ORBITING SYSTEMS. In the event of any conflict between the main AOS Recommendation and the material presented herein, the main Recommendation shall prevail.

Insofar as there are areas of related CCSDS “work-in-progress” that are not referenced in the main Recommendation, this Report will identify them.

## **1.3 SUMMARY**

Between 1982 and 1986, in response to the known mission requirements of that era, CCSDS developed a series of technical Recommendations (References [3] to [9]) for the standardization of common data system functions across a spectrum of so-called “conventional” missions. These conventional Recommendations (including Radio Frequency and Modulation, Packet Telemetry, Telemetry Channel Coding, and four volumes associated with Telecommand) provided a broad basis of data-communications standardization for many types of unmanned science and applications spacecraft.

To meet the needs of the “Advanced Orbiting Systems” of the 1990s and beyond, as evidenced by requirements for the international Space Station which began to emerge in 1986, CCSDS decided to upwardly extend its conventional recommendations to provide a more diverse and flexible set of data handling services. Typical Advanced Orbiting Systems include manned and man-tended space stations, unmanned space platforms, free-flying spacecraft and advanced space transportation systems. Many of these systems need services to concurrently transmit multiple classes of digital data (including audio and video—see Reference [11]) through space/ground, ground/space and space/space data channels at relatively high combined data rates. They also need the capability to interface with, and exploit, the rich service environment of worldwide Open Systems Interconnection (OSI).

The principal difference between the conventional and AOS Recommendations is that a much wider repertoire of services is provided for Advanced Orbiting Systems. Because advances in technology now make it possible to consider the space segment as a conceptually symmetric counterpart of its supporting ground network, the conventional concepts of “telemetry” and “telecommand” become blurred. Instead, the forward and return space links

become the vehicles for extensive two-way interchange of many different classes of digital message traffic between ground and space.

Consequently, symmetric services and protocols are provided for AOS so that video, audio, high-rate telemetry, low-rate transaction data, etc., can be exchanged through the space link in either direction. To handle different classes of data that share a single link, various transmission schemes (e.g., asynchronous, synchronous, isochronous) are provided, as are different user data formatting protocols (e.g., bitstreams, octet blocks and packetized data) and different grades of error control. For the first time, capabilities are included to run commercially derived ground network protocols into the space segment. The AOS Recommendation therefore provides a space-adapted analog of the terrestrial concept of an “integrated services digital network”.

Strong efforts were made to ensure that the AOS Recommendation is downward-compatible with the suite of conventional CCSDS protocols. Many of the user-exposed data handling services (e.g., high rate telemetry) are virtually identical. Some small changes were made in the data link protocol to accommodate higher data rates and multiple classes of data sharing the space channel. Maintaining this level of compatibility is essential in order to encourage the widespread deployment of a standard data handling service infrastructure within the ground systems.

Some missions may not require the provision of all of the services supported by AOS. System designers should therefore consider the applicability of the conventional CCSDS Recommendations for Packet Telemetry and Telecommand when selecting from the overall CCSDS protocol suite. Although not formally addressed in the main Recommendation, it is possible to run “hybrid” configurations where the conventional and AOS protocols are mixed, e.g., a conventional Telecommand forward link operating in conjunction with an AOS return link. The various CCSDS Recommendations should therefore be considered as a mix-and-match “toolkit” from which selections may be made so that the data handling requirements of a particular mission may be satisfied.

Note that although the main AOS Recommendation puts forth the notion of a “CCSDS Principal Network” (CPN), it is essentially mute on several topics that must be addressed in a completely defined CPN. These topics include:

- Extending the AOS protocols beyond the termini of the space link. The main Recommendation leaves the extension of these services across onboard and ground networks as a local matter for individual missions and ground networks.
- Providing complete protocols for operating the CCSDS Path service across onboard and ground networks. The Path protocol defined in the main Recommendation is abstract, in that it requires individual onboard and ground networks to provide network-unique protocol elements (such as how the Path service instance is uniquely identified within such a network).

- Addressing real-world situations such as playback and store-and-forward situations. The main Recommendation is written from an on-line perspective and as such does not address these issues.

CCSDS Panel-3 is currently addressing some of these issues as part of an overall ground service infrastructure standardization effort (Reference [13]). More information can be obtained from the CCSDS Secretariat.

## **1.4 ORGANIZATION OF THIS REPORT**

This document is organized as follows:

Section 2 presents an AOS overview in terms of major drivers and user requirements.

Section 3 broadly describes the various AOS services and protocols and suggests their utilization.

Section 4 presents supporting concepts, including description of: data-protection mechanisms, production data processing, CCSDS cross support, hybrid mission configurations, and the Space Link ARQ procedure.

Section 5 contains some notes on hybrid mission configurations, where conventional and AOS services and protocols are mixed.

Section 6 supplies information about the currently suspended CCSDS work in developing a “Space Link ARQ Procedure” (SLAP).

Appendices A, B, and C address specific implementation and performance issues that may be of interest to system designers.

## **2 AOS OVERVIEW**

### **2.1 USER APPLICATIONS**

The AOS Recommendation supports single space vehicles, or constellations of space vehicles, which simultaneously execute a wide spectrum of applications in near-earth orbit, geostationary orbit, or deep space. Primary application areas are categorized as either observational science, experimental science, or the operation of the space vehicle (“core”) systems.

#### **2.1.1 Observational Science**

Observational science is primarily performed from unpressurized platforms in orbits around the Earth or other planetary bodies. Examples include astronomy, space physics, and Earth observation.

Typically, the lifetime of observational payload investigations is in the order of years. The user equipment is relatively stable in terms of location and functionality and usually requires minimal on-orbit human interaction during the life of a mission. There is therefore a relatively static association between a space instrument and its ground processing facility.

Since transmitted data rates are often high, the observational user requires streamlined techniques for flowing large volumes of data from space to ground, with protocols optimized so as to reduce requirements for onboard processing resources and communications bandwidth. Because of the need to share limited onboard resources between many users, observational operations may require extensive preplanning and scheduling. A large degree of protocol flexibility, such as the capability to change addresses dynamically, is therefore unnecessary.

The CCSDS “Path service” was developed to be of particular use in satisfying the data handling needs of the observational user. It is virtually identical to the less-formal “Source Packet” and “Telecommand Packet” services of the conventional Recommendations.

#### **2.1.2 Experimental Science**

Experimental science, such as materials processing and the effects of space on human physiology, is conducted primarily in pressurized space vehicles since a high degree of flight crew interaction may be required.

In contrast to observational science, experimental science investigations are often scheduled for only a limited time duration. General purpose “laboratory” equipment that has been used in one experiment may be almost immediately reconfigured for use in another. A crew member may control an experiment from workstations at different locations, possibly assisted by an investigator on earth. Hence, source-destination data communications pairs may be only temporarily associated with any particular experiment, and these associations will typically exist only for relatively short sessions. The level of human interaction is high

in terms of monitor and control of the experiment and much of the information that is generated will be evaluated on board. Thus, the volume of data that is transmitted to and from the ground may be relatively low.

Experimental users have needs that are quite similar to those of users of a local area network facility located on the ground. In particular, they need data communications protocols which provide routing flexibility by supporting global source and destination addressing, and which support a rich repertoire of upper-layer data handling services.

The CCSDS Internet service was developed to meet the needs of experimental users. It is a new CCSDS service, which opens doors to a much wider level of potential upper-layer standardization than is currently available for conventional systems.

### **2.1.3 Core Operations**

The core infrastructure operates and maintains the space vehicle systems that support the payload users. Core user requirements share attributes that are common to both observational and experimental applications. Since the safety of the space mission (as well as often the safety of human lives) is involved, reliability concerns may strongly influence the selection of services that are used for transmission of core data.

A high degree of interaction is required in order to perform adaptive command and control (similar to experimental users), yet fairly large quantities of systems monitoring data must be repetitively and continuously returned to static locations on Earth in order to support long-term analysis of engineering performance (similar to observational users). Core users are therefore likely to use both the Internet service and the Path service for message exchange. For piloted missions, synchronized digitized audio and video must also be integrated with message traffic between ground controllers and onboard crew; the Path service can often satisfy these needs, but for some applications special CCSDS point-to-point space link data-transfer mechanisms have been provided.

## **2.2 SPACE NETWORKING ENVIRONMENT**

There are unique problems encountered in the space mission environment that have to be addressed in the design of data communications protocols. Considerations include very large propagation delays, weak signal levels, noisy data channels, high Doppler shifts induced by relative vehicle motion, and contact periods between space and ground systems that are often short and subject to interruption.

Space/ground data transmission requires use of high capital-investment tracking facilities that must be shared not only by multiple users, but also by multiple space missions. Onboard resources are almost invariably subject to constraints of power, weight, volume, and the high costs of flight-qualifying hardware and software.

All of these considerations point to the need for robust space data handling services which are optimized for efficiency and low utilization of onboard resources. Because of the

intermittent nature of the space/ground link transmission contacts, onboard data storage and replay must be accommodated. Removing the artifacts of transmission across the space link often requires considerable value-added processing prior to delivery of data to end users.

### 2.3 AOS SERVICE CONCEPT

A “CCSDS Principal Network” (CPN), which is fully described and defined in the main Recommendation, serves as (or is embedded within) the project data handling network that provides end-to-end data flow in support of a particular mission. A CPN supports eight different types of data handling services:

- Internet service;
- Path service;
- Virtual Channel Data Unit service;
- Virtual Channel Access service;
- Bitstream service;
- Insert service;
- Encapsulation service;
- Multiplexing service.

The Internet and Path services conceptually operate end to end across the network. The remaining services operate only point to point across the space link.

Note – All of the AOS services are specified in terms of the stack of raw protocols which exist at the interface between a spacecraft and its supporting ground system, or between two communicating spacecraft. It is very important to note that most of these raw CPN services require augmentation within the ground system before they are finally exposed to end users. CCSDS Panel-3 is currently developing the overall service architecture which allows the underlying AOS CPN services to be extended to the users in a real operational environment of mission cross support. More information on this ground service infrastructure work can be obtained by contacting the CCSDS Secretariat.

All of the CPN protocols conceptually operate bi-directionally (i.e., from space to ground, from ground to space, or from space to space). However, when data are transmitted from space to ground, some value-added “production data processing” services may be performed at the receiving end of the CPN data flow prior to delivery of data to users. For instance, network-induced artifacts produced by the onboard storage and replay of data must be removed by appropriate preliminary ground processing before telemetry data are forwarded to the end user. A discussion of production data processing is contained in section 4.2.

### **3 AOS SERVICES AND PROTOCOLS**

#### **3.1 CPN END-TO-END SERVICES**

The two CPN end-to-end services (Path and Internet) both conceptually correspond to the Network layer of the OSI Reference Model of Open Systems Interconnection. They are fully complementary services that are designed for different applications.

The Path service supports a space-unique enhanced performance architecture that allows the user Application layer to directly access the space Data Link layer without providing formal Presentation, Session, or Transport services. The Path protocol is multi-layered, wrapping functions at Layer-2 (delimiting), Layer 3 (addressing), Layer 4 (sequence control), and Layer 7 (application data unit delimiting, naming and numbering) into one very lean and compact data structure.

The Internet service, on the other hand, maps directly into the Network layer of the OSI protocol stack in a strictly layered manner, interfacing to the Data Link layer below and the Transport layer above.

##### **3.1.1 Path Service**

The CCSDS Path service is implemented using a special-purpose protocol, developed by the CCSDS, which is optimized to handle the “telemetry” data type. Path service supports high processing speed and efficiency, at the expense of flexibility. The Path service uses a “CCSDS Packet” as its protocol data unit.

The CCSDS Packet structure is similar to that used for telemetry and telecommand applications within “conventional” space missions (i.e., the large family of free-flying space vehicles which fall outside the characteristics of Advanced Orbiting Systems). It was selected because of its lean structure and its ability to provide a consistent user interface as a bridge between conventional missions and Advanced Orbiting Systems.

To support the Path service, “Logical Data Paths” (LDPs), which identify fixed routing relationships between the source/destination pairs in a flow of telemetry, are preconfigured by network management. Data are then relayed across the CPN by tagging each CCSDS Packet with the thin “Path Identifier”, rather than extensive global source and destination addresses. Routing decisions are made by examining the Path ID and, using tables supplied by network management, deriving the next point in the data flow. In this way the Path service provides multiple arterial “trunks” for the efficient transmission of large volumes of telemetry-type data between relatively static endpoints.

In order to conserve communications overhead, the Path ID naming space is kept small (nominally, 11 bits). Within one onboard subnet, the Path IDs are locally unique since they are named by the identifier of the subnet through which they flow. When the Path service data units flow out of a particular onboard subnet, they must be “qualified” with some external identification to make them unique. Normally, the individual spacecraft subnetwork

names are used in the onboard relaying nodes as the qualifier; the spacecraft identifier (SCID) is used after the data cross the space link. This all sounds more complex than it really is; these kinds of techniques have in fact been used by space missions for decades.

### **3.1.2 Internet Service**

The CCSDS Internet service complements the Path service by providing a large degree of flexibility in support of interactive applications, at the expense of speed and efficiency. The CCSDS has selected the commercially supported ISO 8473 connectionless network protocol for use within the Internet service, thus allowing space missions to exploit the rich upper-layer-service infrastructure of OSI. The ISO 8473 Internet packet provides global end-point addressing and is compatible with standard OSI subnetwork routing techniques.

If an application uses the full OSI stack, then the Internet packets will probably carry protocols associated with the ISO Transport, Session, Presentation and Application layers. In addition to concerns over the large integrated communications overhead and processing requirements associated with such a stack, there may be problems associated with operating through very large propagation delays. For this reason, the main CCSDS Recommendation stops short at the ISO 8473 protocol.

CCSDS is currently examining the requirements for a “skinny stack” which may eliminate these concerns; information relative to this new activity may be obtained from the CCSDS Secretariat. In the interim, implementers are cautioned that the flexibility provided by the Internet service and the access to the rich OSI service infrastructure must be balanced against overall performance.

## **3.2 POINT-TO-POINT SPACE LINK SERVICES**

Transmission of data through the Layer 1/2 space-to-ground and space-to-space communications channels is a problem that is unique to the space mission environment. CCSDS has therefore expended considerable resources in designing customized protocols which can both efficiently use these channels and make their error characteristics invisible to higher layers. In the process, capabilities have been provided to support specialized users who do not need end-to-end CPN services, but who instead require only point-to-point data transmission through the space channel.

The CCSDS Data Link layer protocol uses fixed-length frames of data. Boundaries between frames are delimited by pseudonoise-encoded synchronization markers. A “Virtual Channel” identifier, inserted into the frame header, allows a particular frame to be allocated to a particular flow of data, thus supporting multiple different types of traffic on a single digital channel. The basic protocol data unit of the space link is therefore known as a “Virtual Channel Data Unit”, or VCDU.

Two optional layers of error correction are provided to clean up the noise introduced by the weak-signal Physical layer; a standard Convolutional code may be applied to the entire data stream, and/or a block-oriented Reed-Solomon code may be applied to selected Virtual



Channels. A Reed-Solomon encoded VCDU is known as a “Coded Virtual Channel Data Unit”, or CVCDU, and it supports basically error-free transmission through the space link.

A particular spacecraft creates a serial stream of VCDUs/CVCDUs containing a unique “Spacecraft Identifier” (SCID) that is inserted into each of the frame headers. These SCIDs therefore name the Virtual Channels.

### **3.2.1 Virtual Channel Data Unit (VCDU) Service**

In some configurations a spacecraft which is creating its own stream of VCDUs/CVCDUs, named by its SCID, may wish to accept a stream of VCDUs or CVCDUs that has been created by another spacecraft (or module of itself) which has a different SCID. These two streams may then be merged for transmission through a common channel, and separated again at the receiving end.

The Virtual Channel Data Unit service allows such independently created VCDUs/CVCDUs from a guest spacecraft to be transferred across the space link by a host spacecraft, which simply interleaves them frame by frame with its own VCDUs/CVCDUs. This service is available only to “trusted” guest users who are certified during the design process to ensure that the independently created protocol data units do not violate the operational integrity of the data link created by the host spacecraft.

### **3.2.2 Virtual Channel Access (VCA) Service**

The VCA service allows a user to format a fixed-length block of octets for point-to-point transmission across the space link on a dedicated Virtual Channel. The fixed-length data field of a VCDU or CVCDU is allocated for this purpose.

The VCA service is likely to be used to transmit high rate video (Reference [11]), a stream of time-division multiplexed telemetry, or a privately encrypted data block.

### **3.2.3 Bitstream Service**

The Bitstream service allows serial strings of user-defined bits, whose internal structure and boundaries are unknown to the data transmission system, to be transferred across the space link. The bitstream is simply clocked into the fixed-length data field of a VCDU or CVCDU. A Bitstream Protocol Data Unit (B\_PDU) is provided for this purpose, which includes a pointer to delimit the end of the valid user data in the event that the frame is released for transmission before its data field is full.

The Bitstream service was originally intended primarily to support the bit-oriented replay of onboard tape recorders. High-rate video (Reference [11]) may also use the service.

### 3.2.4 Insert Service

The Insert service allows small fixed-length, octet-aligned service data units to be transferred isochronously across the space link under conditions where the overall transmitted link data rate is low. A small data carrying space is reserved just after the header of *every* frame that is transmitted on the link, into which a few octets of data may be inserted. Since the frames are of fixed length, a regular sampling interval is provided.

The most likely use of the Insert service is to support digitized audio (see Reference [11]) over low rate space links. More information about isochronous services is presented in Appendix B.

### 3.2.5 Encapsulation Service

The Encapsulation service supports end-to-end services by allowing variable-length, octet-aligned service data units (SDUs), that are not formatted as CCSDS Packets, to be transferred transparently through the space link. The incoming SDU is simply encapsulated within a special CCSDS Packet, which is the protocol data unit (PDU) of the Encapsulation service. The CCSDS Internet service uses this service to enable SDUs formatted as ISO 8473 packets to be multiplexed onto the space link; other Network-layer SDUs could also be conceptually supported.

### 3.2.6 Multiplexing Service

The Multiplexing service allows variable-length, octet-aligned SDUs, that are preformatted as CCSDS Packets, to be multiplexed together for efficient transfer across the space link. Since the space link protocol uses a fixed-length transmission scheme, the Multiplexing service is required to allow variable-length CCSDS Packets to be mapped in and out of the data fields of CVCDUs. (Note that Data Link layer Reed-Solomon encoding is almost always required to support packetized data transfer, since examination of packet headers is an error-intolerant process.)

The mechanism for implementing the Multiplexing service is the Multiplexing Protocol Data Unit (M\_PDU). Incoming CCSDS Packets are simply concatenated, back-to-back, until they fill a fixed-length block which can occupy the data field of a CVCDU. The header of the M\_PDU contains a pointer which delimits the boundary between the first Packet pair; the individual Packet length fields then delimit the other boundaries.

The Path service (which uses the CCSDS Packet as its PDU) provides an SDU which is directly compatible with the Multiplexing service. The Internet service must first have its ISO 8473 PDU wrapped within a CCSDS Packet by the Encapsulation service; the Multiplexing service can then mix Path and Internet SDUs together on a common Virtual Channel.

### 3.3 GRADES OF SERVICE

Since many different types of digital data are multiplexed together for transmission over a single space link, it is reasonable to recognize that they may not all have the same requirements for data quality. For instance, asynchronous packetized data transmission requires virtually error free service (since in-line protocol must be examined), whereas other data types (such as uncompressed video using the VCA service) may be able to tolerate a fairly high error rate as a consequence of their inherent oversampling.

CCSDS therefore provides three different “Grades of Service” during transmission through the space link. Note that these Grades of Service are local *only* to the space link and they are not end-to-end services; additional mechanisms are needed to provide a particular service quality on an end-to-end basis.

The error control for the Grades of Service is provided using a combination of error detection, error correction and (though only partially developed) retransmission control. Each Virtual Channel supports a single Grade of Service. Different types of error control mechanisms are used to provide the different Grades of Service.

#### 3.3.1 Grade-3 Service

Grade-3 service provides the lowest quality of service. Data transmitted using Grade-3 service may be incomplete and there is a moderate probability that errors induced by the Space Link Subnet are present and that the sequence of data units is not preserved.

The raw VCDU, without Reed-Solomon coding, supports Grade-3 service. The error rate is therefore that of the underlying Physical channel. To protect critical VCDU Header routing information, a special header error correction field is provided. To detect other errors occurring within the VCDU, a cyclic redundancy code error control field (using a polynomial which covers the entire VCDU) is inserted into the VCDU trailer.

Grade-3 service is not suitable for transmission of asynchronous packetized data because of insufficient protection of control information that is contained in the packet headers. Current experience indicates that very few missions in fact end up implementing a Grade-3 service.

#### 3.3.2 Grade-2 Service

To provide Grade-2 service, a block of Reed-Solomon check symbols is appended to the VCDU to form a Coded Virtual Channel Data Unit (CVCDU). The Reed-Solomon encoding provides extremely powerful error correction capabilities. Data transmitted using Grade-2 service may be incomplete, but data sequencing is preserved and there is a very high probability that no data errors have been induced by the Space Link Subnet.

Because the Reed-Solomon overhead is low and is fully compensated by the huge coding gain, many current missions implement an entirely Grade-2 service.

### 3.3.3 Grade-1 Service

Data transmitted using Grade-1 service are delivered through the Space Link Subnet complete, in sequence, without duplication and with a very high probability of containing no errors induced by the Space Link Subnet. Grade-1 service is the highest quality of service available and relies on the implementation of an Automatic Repeat Queuing (ARQ) retransmission scheme in conjunction with the Reed-Solomon encoding.

CCSDS began the development of a “Space Link ARQ Procedure” (SLAP) to provide Grade-1 service, using two paired Reed-Solomon-encoded Virtual Channels operating in opposite directions. However, it became clear that a primary customer for AOS (the Space Station program) did not intend to use it; instead, an end-to-end ARQ scheme was proposed for that program, using the ISO TP4 Transport protocol running over CCSDS Internet service. Lacking an immediate customer, and facing severe resource constraints, CCSDS shelved the development of the SLAP. However, the work that was performed is documented in the form of a mature “White book” (Reference [12]), and some further information is contained in section 4.5 for those readers interested in its concept of operation.

A unidirectional (forward link only) equivalent of Grade-1 service may be supported by running a hybrid configuration using the existing CCSDS Telecommand “Command Operation Procedure” (COP). Implementers needing this service should refer to section 4.4, Hybrid Mission Configurations.

## **4 SUPPORTING CONCEPTS**

### **4.1 DATA PROTECTION**

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

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

The necessarily open nature of most space data networks (especially in cross support configurations) makes physical protection of the entire network impractical. In this environment, the Data Protection mechanisms must permit operation identical to “clear-text” communications to flow through the mission’s data networks insofar as provision of normal network telecommunications services are concerned. Two techniques exist which would facilitate providing logical Data Protection; these are “Encrypted Authentication” and “Data Encryption”.

Encrypted Authentication techniques ensure that a message comes from an authorized source and that an unauthorized party cannot modify the information contained therein. Data Encryption techniques ensure that an encrypted message is unintelligible to an unauthorized user. A given implementation may use Encrypted Authentication only, or both Encrypted Authentication and Data Encryption together.

#### **4.1.1 Authentication**

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

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

The parameters which control how the authentication algorithm computes the authentication word before transmission are set by programming a “key” into the sending end of the

authentication system. The constantly changing nature of the encryption process assures that no two encrypted authentication words will be alike for the duration of the mission. The distribution and management of the key may require that physical security measures be implemented within the sending end of the appropriate layer, and that Data protection measures be implemented when transferring key changes to the spacecraft.

During processing at the receiving end of the authentication process, the authentication word is passed through an algorithm into which is programmed a key that matches the one at the sending end, and the decryption process is synchronized with the sending end. Thus the user data unit will be executed only if the received authentication word meets these requirements.

#### **4.1.2 Data Encryption**

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

#### **4.1.3 Selection of Data Protection Technique**

The CCSDS makes no recommendation for the choice of an Encrypted Authentication or Data Encryption algorithm, or for the associated management procedures. However, to ensure that algorithms selected by individual Projects are consistent with inter-Agency cross support across the Space Link Subnetwork of the CPN, the following implementation guidelines are provided.

- (1) The Encrypted Authentication or Data Encryption system should operate within or above the Virtual Channel Access sublayer of the Space Link Subnet. A standardized mechanism for implementing the system at the sending and receiving ends of the Virtual Channel Access sublayer is suggested as being the most secure and manageable.
- (2) The Encrypted Authentication or Data Encryption mechanism should not interfere with the standard Space Link Subnet verification techniques, including the SLAP, and should permit recovery from the effects of errors or interruptions in the communications process.
- (3) If implemented within the Virtual Channel Access sublayer of the Space Link Subnet, the Encrypted Authentication word or transformed portion of the data should be included completely within the data field of the Virtual Channel protocol data units (VCDUs and CVCDUs), and should not interfere with the processing of header or trailer information. One possible location for the Encrypted Authentication word is within the Insert Zone.

- (4) If implemented outside of the Space Link Subnet, the Encrypted Authentication word or transformed portion of the data should be included completely within the user data field of the CCSDS Packet (Path service), or completely within the user data field of the Internet packet (Internet service).
- (5) The selected Encrypted Authentication or Data Encryption technique should be transparent to the data-routing, error-control and transmission functions in the lowest layers of the Space Link Subnet, i.e., the Virtual Channel Access and Physical Channel layers. The Encrypted Authentication or Data Encryption technique should not require the implementation of any physical security mechanisms within these lowest layers.
- (6) Note that since bulk encryption of space mission data at the Physical Channel layer does not allow any cross support except at the bit level, it is NOT a recommended technique.

## **4.2 PRODUCTION DATA PROCESSING**

The intervening communications system between a data source in space and the data user on the ground should ideally be transparent. In the real world of spacecraft communications it is currently necessary for the ground system to carry out many operations on the data to ensure they reach their destination in as complete and unadulterated a form as possible. The removal of all of the induced communications artifacts is known as “Production Data Processing” (PDP).

Spacecraft in near-earth orbit often have visibility of their ground station for only 10 to 20 minutes per orbit. Deep space missions have longer contact periods (hours), but they may occur only once per day or even once per week. Even with the introduction of data relay satellite service, only manned spacecraft have been provided with virtually constant ground contact, and even these are subject to interruption caused by unavoidable coverage gaps (e.g., “Zones of Exclusion”).

Accordingly, in order to provide complete and continuous data sets to the mission users, data are stored on board for transmission during the next contact period. To protect against loss of data, some of the data generated during the spacecraft’s period of contact are stored as well, leading to data overlap between real-time and stored data. Since technology and cost may dictate that data are stored by recording them on tape, and reliability and operational simplicity requirements (and the need to extend the operational life of the recorder) may rule against rewinding the tapes before playback, the replayed data are often transmitted in reverse order.

Continuous ground contact during critical mission periods may involve a sequence of ground stations. To ensure no loss of data during handover from one ground station to the next, contact may be maintained simultaneously with both, which results in overlapping data also being collected.

Fairly comprehensive processing is therefore needed after the raw data reach the ground, and before they are delivered to the user, to remove network-induced artifacts such as data reversal and data overlap. Some spacecraft may also have multiple links to the ground, for example separate spacecraft system and payload channels, which may result in contemporaneous data of different kinds being collected separately. Some users may require such data sets to be merged.

The specific functions included in PDP are unique to the particular space agency involved, but usually include:

- reversal of onboard tape-recorded data;
- removal of overlaps between the stored and real-time data;
- removal of duplicate data sets;
- restoration of data to their as-generated sequential order;
- generation of data-quality and audit-trail information.

Several mechanisms are available to support PDP, including:

- a Replay Flag within the VCDU header which enables the identification of tape playback data;
- a sequence count within the VCDU header which enables identification of duplicate and out-of-sequencing data;
- ground timestamping of VCDUs on reception which enables correct data correlation;
- sequence numbering and onboard timestamping of CCSDS Packets, which enables data set reassembly.

### **4.3 CCSDS CROSS SUPPORT**

The term “CCSDS cross support” is applied when one agency uses part of another agency’s data communications resources to complement its own system. Multiple Agencies can therefore confederate their resources to execute missions that would otherwise be unaffordable.

Cross support allows access to additional resources such as ground stations or data relay satellites, thus extending the technical reach and capability of a Project. Sharing of these expensive capital resources also has the benefit of increasing their utilization.

In the main AOS Recommendation, both symmetric and asymmetric cross support of the CPN protocols is described. Symmetric cross support means that the data structure passed from the requester agency to the provider agency is exactly the same data structure that is passed back to the requester after transmission through the cross support service interface. Asymmetric cross support means that the requester agency receives a different data structure than it submitted to the provider agency; i.e., data are passed to the provider agency at one layer and returned to the requester agency at a different layer.



In order to achieve unlimited cross support between agencies, both the requester and the provider of the cross support would have to implement the full set of protocols contained in the AOS Recommendation. For agencies that do not implement the full set of AOS protocols, only partial cross support is possible.

Cross support agreements between the requester and the provider are therefore needed which precisely define the common services and protocols that each is to implement. Symmetric cross support of a particular service is relatively easy to provide; only the common data structures need to be agreed upon. Asymmetric cross support requires that the requester and provider agree on more layers of protocol.

Section 7 of the main AOS Recommendation discusses the implications of cross support insofar as the stack of raw space link protocols is concerned. However, in a real cross support environment many more aspects are involved. CCSDS Panel 3 is currently defining the overall architecture by which Agencies can offer cross support service interfaces in an operational mission environment (see Reference [13]). A real cross support interface not only includes delivery of the raw space link service data unit, but it must provide annotation of the data with ancillary information (such as quality, audit trail and timetagging) and must deliver it via a specific communications network. Mechanisms must also be provided to schedule the cross supported session, monitor and control its overall progress, and debrief when it is over.

As a result of the CCSDS Panel-3 work, it is expected that a comprehensive infrastructure of standard cross support services will be developed by CCSDS Agencies and offered for use by Project organizations. The CCSDS Secretariat can provide up-to-date information on the status of this work.

#### **4.4 HYBRID MISSION CONFIGURATIONS**

The AOS Recommendation has been specifically designed to be downward-compatible with earlier CCSDS Recommendations, such that investments already made in space mission equipment will not be wasted. Thus the AOS Recommendation draws heavily upon previous CCSDS Recommendations for the asymmetric flow of Telemetry and Telecommand data within conventional space systems.

Wherever technically feasible, appropriate elements of the conventional Recommendations have been used directly. In other cases, upward-compatible extensions of the conventional Recommendations have been defined to support new services, such as the integration of digitized audio and video into space data streams.

The AOS Recommendation assumes the use of symmetric data link services and protocols; i.e., the forward and return space links provide identical services to users and operate using the same data structures. However, some missions may wish to operate a “hybrid” configuration; for instance, a conventional CCSDS Telecommand forward link might be paired with an AOS return link, thereby benefiting from the fully specified “COP” ARQ capability supported by conventional Telecommand. Such a configuration would not support

the integration of digitized audio and video into the uplink data stream; however, it would allow utilization of the rich set of AOS services on the return link.

The most common application for a hybrid system will be during communications between a control node on the ground and a spacecraft. However, use of such a configuration for space-to-space commanding is not precluded.

Since hybrid configurations are not specifically addressed in the AOS recommendation, they are necessarily the subject of detailed negotiations between Projects and CCSDS cross support organizations. However, the following implementation notes are provided to help steer such negotiations.

In a hybrid configuration which pairs a conventional Telecommand forward link with an AOS return link, variable-length Telecommand (TC) Frames are transmitted to the receiving spacecraft under retransmission control of a "Command Operation Procedure" (COP). The COP consists of a pair of cooperating procedures: a Frame Operations Procedure (FOP) at the ground sending node, coupled with a Frame Acceptance and Reporting Mechanism (FARM) at the receiving node on the spacecraft.

In order for the COP to operate, a Command Link Control Word (CLCW) must be formulated by the FARM and transmitted to the FOP. The CLCW is a 32-bit word. When operating a Telecommand forward link in conjunction with a conventional Packet Telemetry return link (Reference [5]), the CLCW is returned from the FARM to the FOP in the trailer of a Version-1 Telemetry Transfer Frame.

In a hybrid telecommanding configuration the CLCW should be returned from the FARM to the FOP in the Trailer of the Version-2 (AOS) Coded Virtual Channel Data Unit (CVCDU), by formatting it into the 32-bit Operational Control Field. The presence or absence of the CLCW within this field is a managed parameter for a particular Virtual Channel.

The mechanisms for inserting the CLCW into the CVCDU trailer for transmission on the return link, and its corresponding extraction and relay to the FOP, are handled as local matters which are defined via a cross support agreement.

The Version-1 CCSDS Packet structure, which is used for telemetry and telecommand applications both within Advanced Orbiting Systems and conventional space missions, is inherently compatible with a hybrid commanding configuration. Note that since AOS protocols do not use the "Type" bit in the Packet header, it is ignored. Note also that the Version-2 CCSDS Packet cannot be supported on an AOS return link.

## 4.5 SPACE LINK ARQ PROCEDURE

Note – The CCSDS has currently suspended its work on the Space Link ARQ Procedure. The material included here has no formal status within CCSDS and is included for information ONLY. The current “White book” specification of SLAP is contained in Reference [12].

In its current state of development, the Space Link ARQ Procedure (SLAP) is intended to be used to provide guaranteed Grade-1 delivery of data *only* across the space link which interconnects the space and ground systems. Provision of Grade-1 service across the entire CPN is necessarily a responsibility of Project organizations.

The SLAP is very closely patterned after, and based upon, the connection-oriented procedures of ISO 8802.2 Logical Link Control (Type 2 operation).

The SLAP provides Grade-1 space link communications service in support of applications in which completeness and sequentiality of delivered data are essential. Such applications may include transfer of computer programs, transfer of data bases (e.g., star catalogs, mission timelines), transfer of communications control parameters and tables for network management (e.g., telemetry format definitions), diagnostic computer memory dumps, historical data retrieval, electronic mail, transfer of computer data bases, and transfer of system fault messages.

The SLAP incorporates the following features:

- (1) It provides delivery of a single stream (in each direction) of user data across a space/ground or space/space link.
- (2) It provides delivery of the user data in the order received, without omissions or duplication.
- (3) It provides a full duplex service using a pair of Virtual Channels dedicated to Grade-1 service. Once a connection is established (via the network management and signalling system), data transfers on the forward and return links are asynchronous with respect to each other. (Typically, unrelated applications are using the two directions of transfer.)
- (4) It provides for automatic recovery from routine space link transmission errors.
- (5) It provides for automatic re-establishment of the link connection after an interruption, with notification to the user.
- (6) It provides the means to acknowledge one or more transmissions in a single report.
- (7) It provides the means to test the space link before sending data.

- (8) It provides the means to request the status of a remote receiver.
- (9) It provides the opportunity for a receiver to report status to a sender at some minimum period.
- (10) It conserves link bandwidth, including the original transmission, retransmission and transfer of supervisory and reporting data.
- (11) It is dimensioned to support transfer rates of up to 100 Mb/s.
- (12) It can accommodate a loop time (source to destination and return) in the range of up to 2.0 seconds. This assumes use of one, or possibly two, data relay satellites to communicate between ground and space or space and space applications.
- (13) It is expandable to accommodate selective retransmission for use with higher data rates or for long-delay applications.

The SLAP provides connection-oriented service for the space link transmission of Multiplexing Protocol Data Units (M\_PDUs), Bitstream Protocol Data Units (B\_PDUs), or private fixed-length VCA service data units. The arriving data unit, which must consist of a fixed number of octets, is referred to as a Service Data Unit (SDU) from the point of view of the SLAP. The fixed size of the SDUs, for a particular connection, is determined by the presence of optional fields in the fixed-length CVCDU which carries the SDU.

The operation of the SLAP is described in Section 6.2 of the main Recommendation. Basically, the data flowing in one direction carry "Link ARQ Control Words" (LACWs) that report progress on receipt of data flowing in the opposite direction. The SLAP accepts an SDU from a layer above and creates a SLAP Protocol Data Unit (SLAP\_PDU) that contains the SDU and an LACW. This LACW contains a sequence number that is used to track the SLAP\_PDU until it is delivered at the other end. The SLAP passes the assembled SLAP\_PDU to the sublayer below, which encapsulates it within a CVCDU that includes Reed-Solomon coding for error detection/correction. The completed CVCDU is then transmitted through the space channel to the other end of the connection.

Upon arrival at the receiving end, the LACW is extracted from the SLAP\_PDU and the sequence number is checked to assure that no data have been lost or duplicated. In the event of a sequence error, LACWs carried by SLAP\_PDUs traveling in the opposite direction are used to signal that a retransmission is required. This retransmission begins with the first SLAP\_PDU that was not received in sequence, and all subsequent SLAP\_PDUs are retransmitted in the order in which they were originally provided to the SLAP from the layer above.

The error detection/correction process assures that, with very high probability, only error-free SLAP\_PDUs are passed up to the receiving SLAP. This hybrid ARQ approach, combining forward error correction with sequence checking and ARQ, provides the Grade-1 guarantee of delivery of SDUs across the connection error free, in order, without omission or

duplication. Note that only the SLAP data unit zone is subject to retransmission. If the VCDU Insert Zone is included, contents of that zone are given Grade-2 service.

Assignment of Virtual Channels to be used for Grade-1 service, and the initiation and termination of connections on these Virtual Channels, is the responsibility of CPN management. This managed approach avoids the waste of bandwidth that would result from performing these functions in-band.

CPN management is responsible for connection setup, monitoring, and shutdown. It must also react to status indications from the SLAP that indicate a breakdown of the Grade-1 guaranteed delivery service.

Management functions are carried out at each end of the connection by management entities that directly control the SLAP process at that location. The action of the management entities is coordinated through management procedures that are external to the connection between the SLAP protocol entities at either end of the link. This coordination may provide for mutually agreeable transmission rates, time-out periods, retry counts, and other parameters that affect performance of the connection. Management may also provide schedule coordination.

The degree of SLAP control exercised by management may vary from mission to mission. In one implementation, connection may be permitted only when prescheduled, while in another, connections may be permitted at any time the Grade-1 Virtual Channel is available, without intervention by management. Likewise, the setting of SLAP parameters might be carefully tuned by one Project for maximum throughput under prevailing link conditions, while another Project might opt for minimal management control, e.g., by setting timers more loosely.

## APPENDIX A SPACE LINK SUBNET PERFORMANCE NOTES

### A.1 Purpose

This Appendix presents background performance information which may be useful to designers of CCSDS Advanced Orbiting Systems, but which is otherwise too implementation oriented to be appropriate for inclusion in a CCSDS Recommendation.

### A.2 Scope

This Appendix describes the rationale for the performance specifications that have been established for the Space Link Subnetwork, in particular the Grade of Service specifications.

### A.3 Performance of the Virtual Channel Access Sublayer

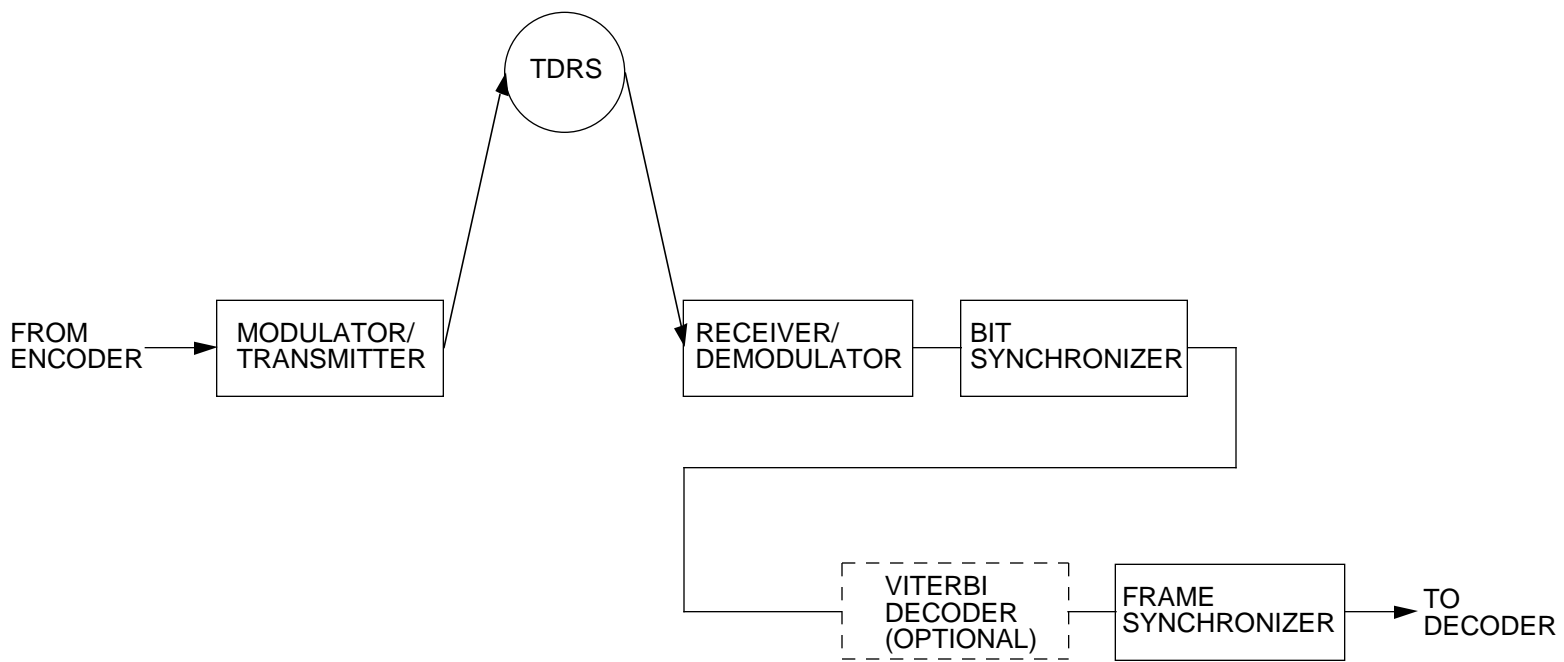
The case that will be analyzed considers a spacecraft using a TDRSS KSA forward/return link (DG2 mode, as defined in the NASA Space Network Users' Guide, Reference [3]), i.e., a single data source using SQPSK modulation. The noise on the channel is assumed to be of the Additive White Gaussian Noise (AWGN) variety. The TDRSS channel reference diagram is shown in Figure A-1. It is assumed that:

- (1) Performance specifications are given after initial acquisition (i.e., receiver lock and bit synchronization are declared).
- (2) The receiver working point is equivalent to a BER of  $1 \times 10^{-5}$ , which can theoretically be achieved at an information bit energy-to-noise ratio ( $E_b/N_o$ ) = 9.6 dB for the uncoded channel and  $E_b/N_o$  = 4.4 dB for the Rate 1/2 convolutional coding case.

Table A-1 summarizes the required performance in terms of  $E_b/N_o$  and also gives an indication of lock performance.

Figure A-2 shows a block diagram of the generalized TDRSS coding concept for Grade-2 and Grade-3 Virtual Channel data, transmitted in this case via a Ku-band physical space channel. Grade-1 data are handled the same as Grade-2, except for the additional SLAP protocol which provides retransmission control of Virtual Channel Data Units initially received with detectable but uncorrectable errors. Figure A-3 relates BER and  $E_b/N_o$  for coded and uncoded PSK modulation.

If the convolutional coding is employed, it is important to note that errors from the Viterbi decoder will occur in bursts. This burst distribution is shown in Figure A-4, and Table A-2 provides the Viterbi decoder burst statistics to be expected when operating at an  $E_b/N_o$  of 4.4 dB.



**Figure A-1: TDRSS Channel Model for Return Services**

**Table A-1: Required Performances to Achieve a BER of  $1 \times 10^{-5}$  for the KSA Operations**

Mode	Required $E_b/N_0$ (dB)	Carrier Slip Rate (at data rate = 300 Mb/s)	Bit Slip Rate
UNCODED	9.6 <sup>1</sup>	$6.17 \times 10^{-13}$ <sup>1</sup>	$10^{-12}$ <sup>2</sup>
CODED (Viterbi decoder, rate=1/2, K=7)	4.4	N/A <sup>4</sup>	$10^{-12}$ <sup>3</sup>
<p>NOTES:</p> <p>1 This value applies at carrier tracking threshold (i.e., 3dB fade relative to the minimum power received for signal tracking). For balanced QPSK, a single cycle slip will interchange the I and Q demodulator outputs and invert one of the outputs.</p> <p>2 This value applies for data bit jitter of &lt;1.20 rad (rms).</p> <p>3 This value applies for data bit jitter of &lt;0.45 rad (rms).</p> <p>4 Maximum data rate 10 Mb/s for Viterbi decoder.</p>			

**Table A-2: Tabulation of the Viterbi Decoder Output Burst Error Statistics Operating at  $E_b/N_0 = 4.4$ dB (Output BER =  $1 \times 10^{-5}$ )**

Length (bits)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
No. of events	5	6	10	14	14	7	17	15	3	12	2	2	3	2	1
Length (bits)	16	17	18	19	20	21	22	23	24	25	26	27	28	29	
No. of events	0	1	1	1	1	0	0	0	0	1	0	0	0	1	



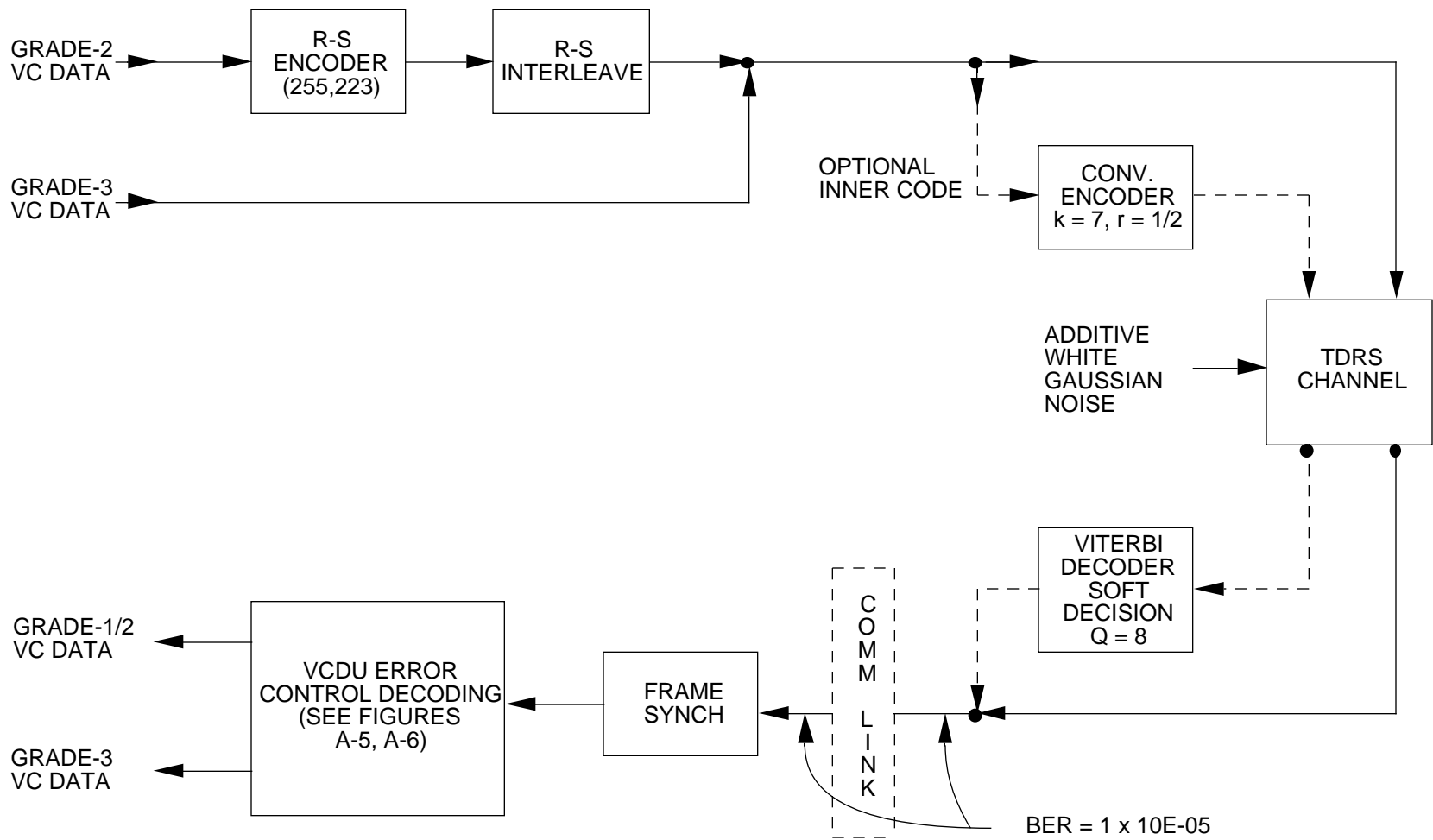
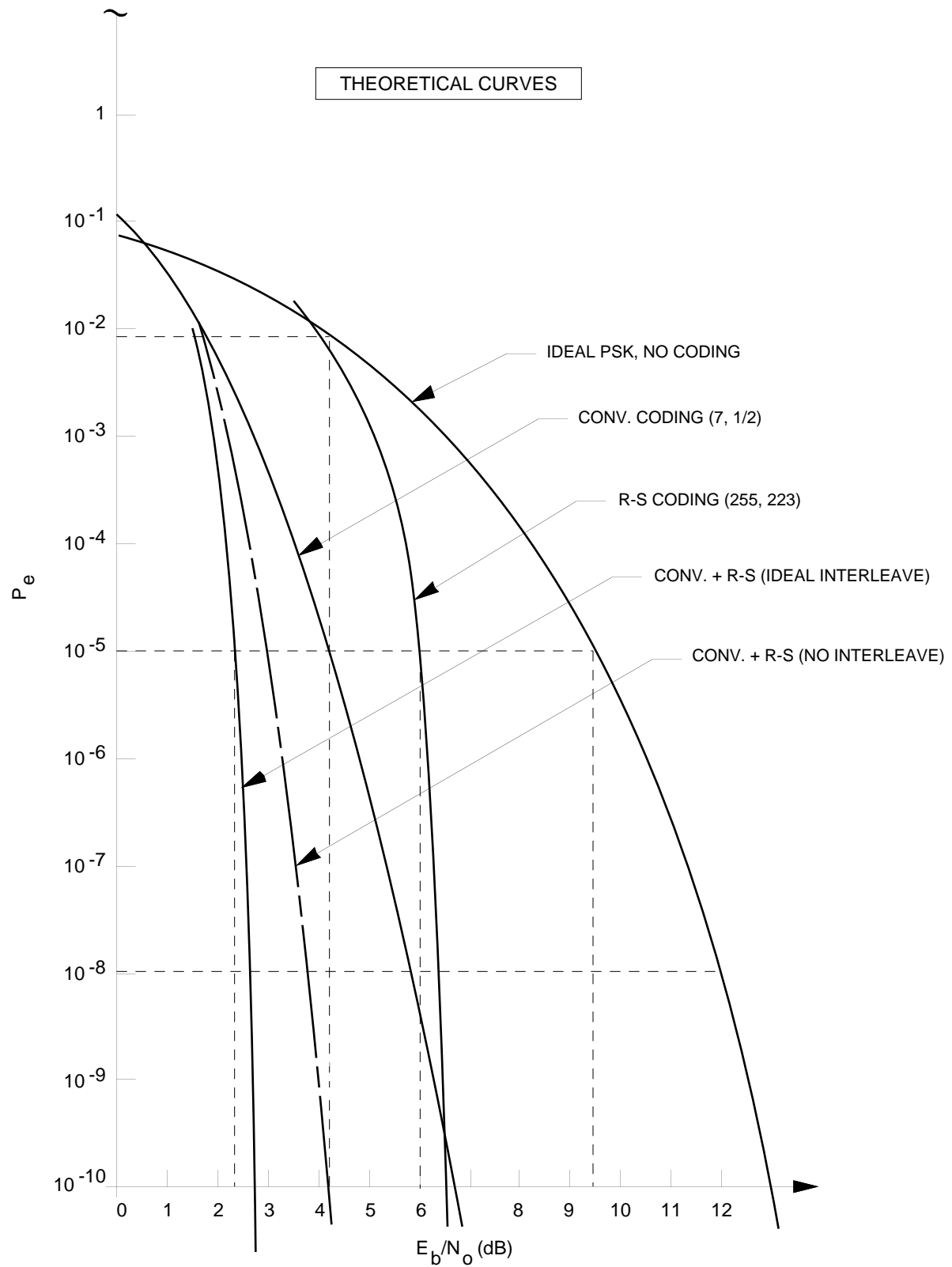
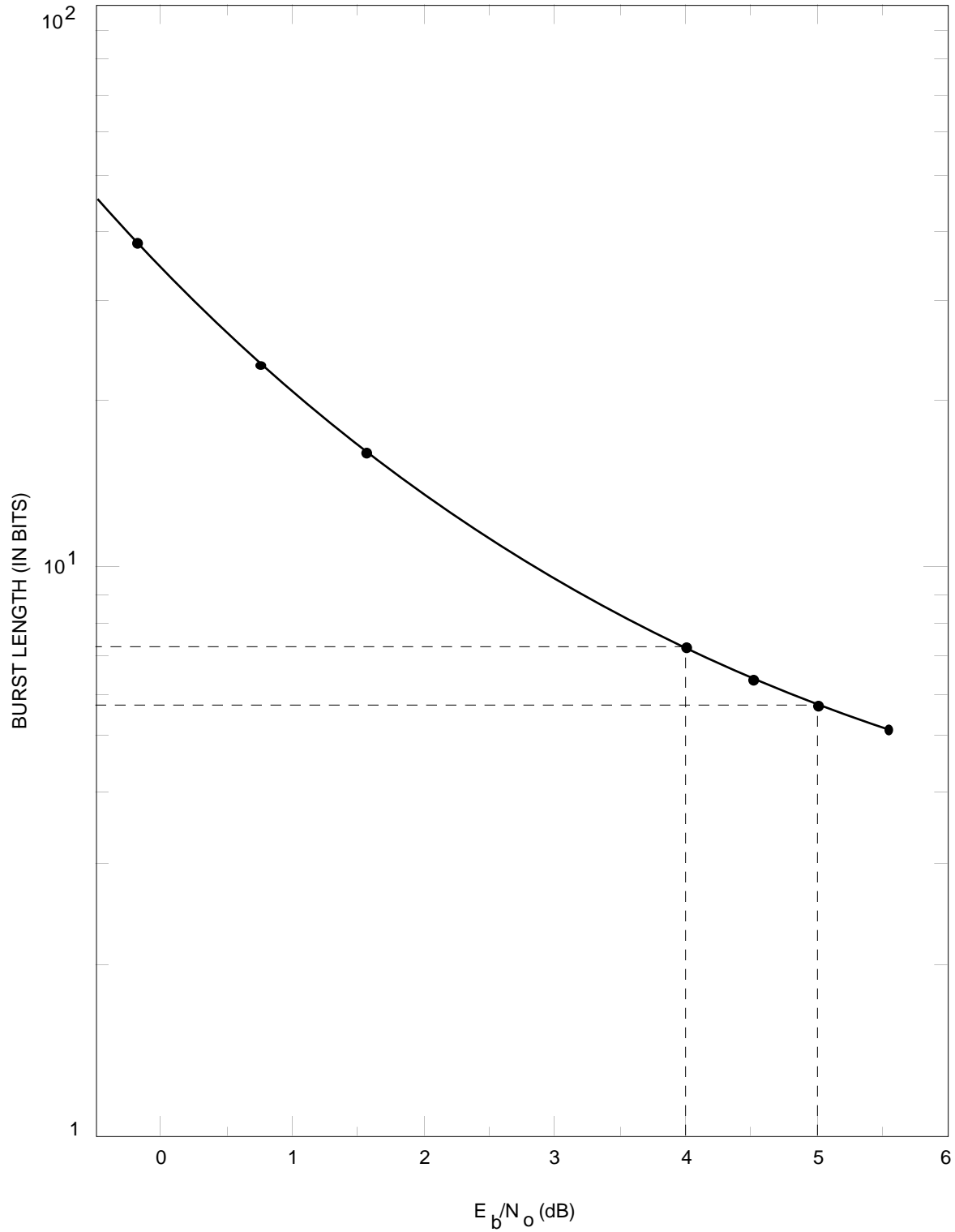


Figure A-2: Generalized TDRSS Coding Concept



**Figure A-3: Relative Performance of Concatenated Coding with R-S Outer Code (R-S Ideal Interleaving and No-Interleaving Comparison)**



\* \* AVERAGE DENSITY OF ERRORS IN BURST – 0.5 TO 0.6

**Figure A-4: Average Burst Length Versus Signal-to-Noise Ratio  
at the Viterbi Decoding Output (with Soft Bit Decision)**

#### A.4 Error Control Considerations and Options

The generalized TDRSS concept shown in Figure A-2 is designed using a centrally located data processing center (DPC). The first task of the front end of the DPC is to synchronize to the boundaries of the incoming data and to read the VCDU Primary Header. To accomplish this, the DPC requires that:

- (1) The TDRSS ground station network has achieved receiver lock, bit synchronization and node synchronization (in the case of convolutional coding), before the DPC acquires frame synchronization.
- (2) A communications link has been established between the TDRSS ground station and the DPC. A typical commercial-grade communications link is assumed to have a BER performance of better than  $1 \times 10^{-7}$  for one hop and  $1 \times 10^{-6}$  for two hops; i.e., the TDRSS channel error rate of  $1 \times 10^{-5}$  predominates at the input to the frame synchronizers.

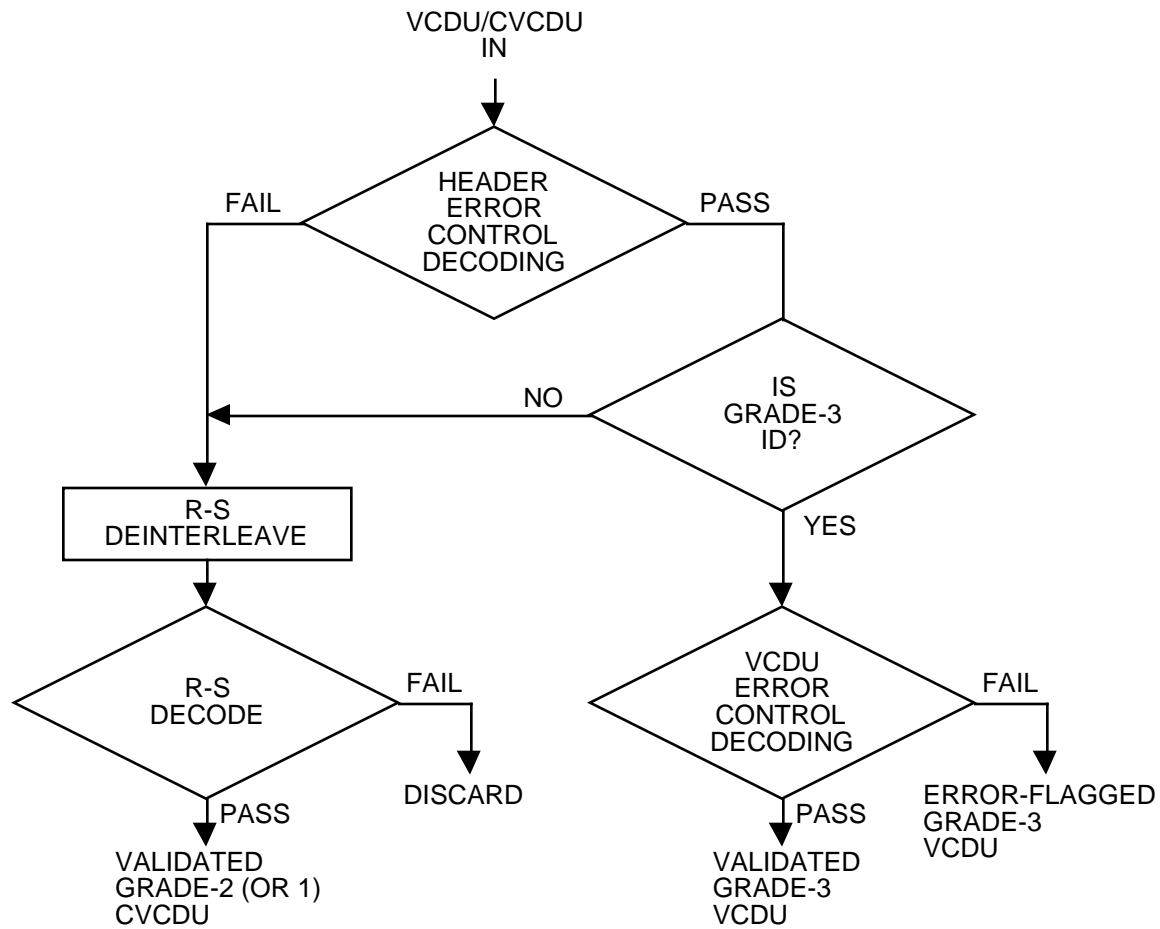
The probability of false acquisition is  $1.6 \times 10^{-5}$ . Once acquired, the strategy allows three consecutive erroneous frame sync patterns before declaring an "out-of-frame-sync" condition. The probability of going out of frame sync (in the absence of carrier bit slippage) is  $1 \times 10^{-28}$ .

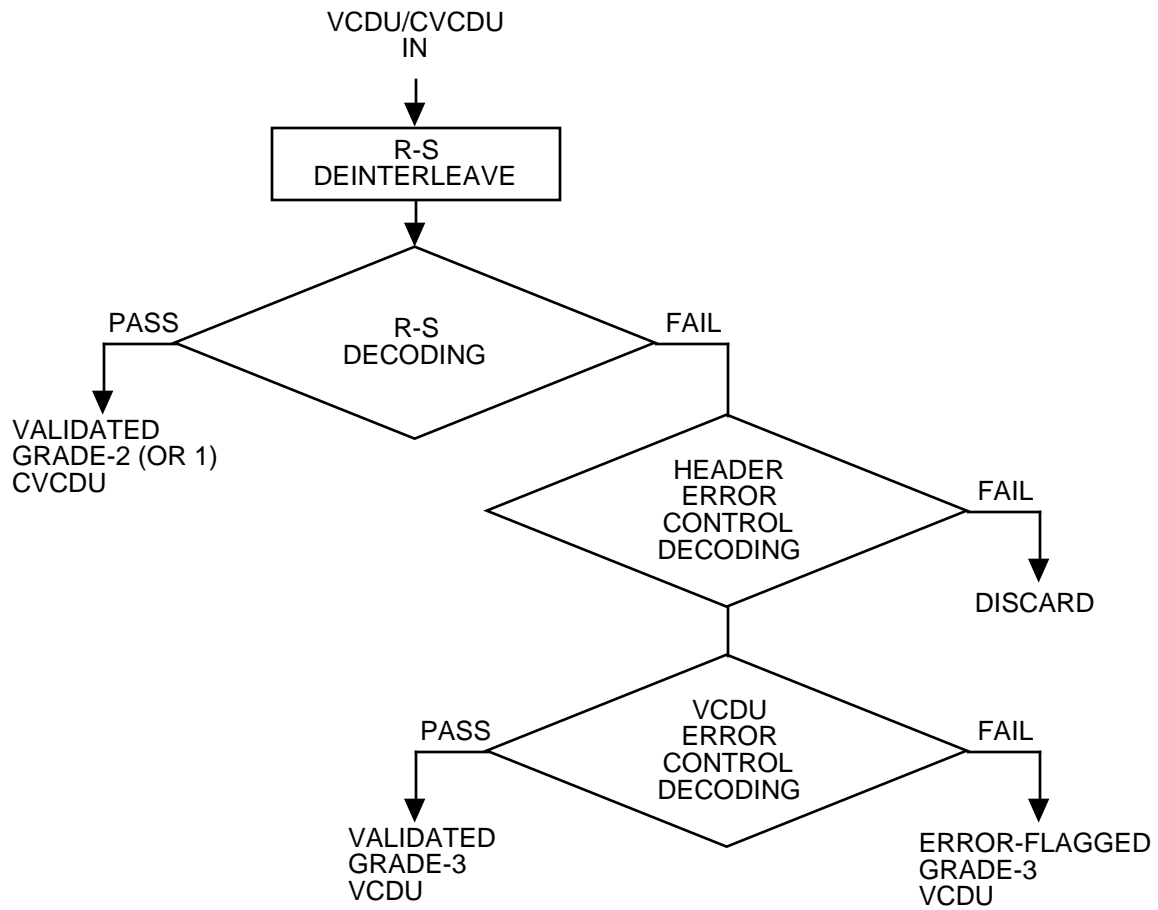
##### A.4.1 VCDU Primary Header Error Control Options

Two optional strategies exist for decoding the VCDU Primary Header control information:

- OPTION-A: The VCDU Header Error Control decoding is performed immediately after frame synchronization (see Figure A-5), and VCDU routing decisions are based on the decoded information.
- OPTION-B: All VCDU/CVCDUs are first passed through the Reed-Solomon (255,223) decoder (see Figure A-6). Those failing the Reed-Solomon (R-S) decoding process are tentatively assumed to be Grade-3 and are passed to the VCDU Header Error Control decoding procedure for confirmation that they are, in fact, "legal" Grade-3 VCDUs. Those passing the R-S decoding process are assumed to be valid CVCDUs.

Option-A has the advantage that the Grade-3 VCDUs are stripped out prior to R-S decoding, thereby potentially reducing the throughput rate requirements on the R-S decoder. On the other hand, Option-B reduces both the mean and the variance of the decoder delay for CVCDUs and also eliminates the need for a separate check to match the decoded VCDU-ID with a list of currently active "legal" (i.e., recognized by network management procedures) Grade-3 Virtual Channels. From an error control standpoint, the performance of both options is equivalent. This performance is described in the subsequent sections.

**Figure A-5: Option-A Error Control Decoding**



**Figure A-6: Option-B Error Control Decoding**

#### A.4.2 Error Correction Coding Description

It is assumed that, for both Option-A and Option-B, the following coding is performed on the VCDU/CVCDUs:

- (1) All CVCDUs are encoded using the R-S (255,223) code.
- (2) All VCDUs (Grade-3) are encoded using the optional VCDU Header Error Control Code (i.e., R-S [10,6] code) and with the optional VCDU Error Control code (i.e., CRC error detection code).
- (3) In addition to the above, an optional Rate 1/2 convolutional ( $K=7$ ) code may be used for some channels and, when used, will encode the entire transmitted bitstream (including the CADU Synchronization Marker). If this encoding is performed, then the corresponding decoding (Viterbi with  $Q=3$  soft bit quantization) will be performed prior to frame sync detection.
- (4) For Option-A only, there is a requirement to encode all CVCDUs with the optional VCDU Header Error Control Code when CVCDUs and VCDUs are intermixed on a single Physical Channel. This requirement equalizes the length of all VCDU Primary Headers on a given Physical Channel, but has no effect on the error control performance.

The details of the Error Control Decoding process depicted in Figure A-2 are shown on Figures A-5 and A-6 for Option-A and Option-B respectively. These figures illustrate a “Mixed-Mode” operation; the other cases in which only VCDUs or only CVCDUs are present on a single Physical Channel are simplifications of these Figures. Prior to entering this process, the (optional) Viterbi decoding and (mandatory) CADU frame synchronization will be performed and the Synchronization Marker will be removed.

Under the assumed noise environment (i.e., AWGN), the resulting channel bit error characteristic can be expected to be that of a Binary Memoryless Channel, where “memoryless” refers to the characteristic that errors are not clustered (i.e., the probability of a bit error at any location is a constant equal to the Bit Error Rate [BER]). The BER is a function of the signal-to-noise ratio ( $E_b/N_o$ ) as shown in the “Ideal PSK, no coding” case on Figure A-3.

Any error correction decoder changes the decoded error characteristics as well as the error rate. While a well-designed error correction subsystem should reduce the total number of decoded bit errors, no error correction subsystem is perfect, and, inevitably, the decoder will occasionally also introduce burst errors and/or deleted data blocks. The BER performance metric may suffice to completely specify the error characteristics of the uncoded channel, but no single parameter can adequately characterize the output errors or gaps from an error correction decoder.

Table A-3 summarizes the error control coding schemes used within the AOS Grade-2 and Grade-3 services, with a brief description of the resulting decoded error characteristics (when used alone).

**Table A-3: Summary of AOS Error Control Codes**

<b>Coding Scheme</b>	<b>Anticipated Use</b>	<b>Decoder Error Characteristics</b>
Convolutional Code (K=7, R=.5) with Viterbi decoder	May be used for VCDU protection by itself (Grade 3), or as an inner code for Grade 1 or 2 service.	Decoder errors occur in bursts (see Table A-2 for typical burst length distribution). Decoder gives no reliable indication when its output is in error.
Reed-Solomon (10,6) code (symbol = 4 bits)	VCDU Header Error Control code, which is mandatory for Grade 3 and optional for Grades 1 & 2.	Can correct any two 4-bit symbols in protected area of VCDU header. May falsely correct if number of errored symbols >2 with no indicator that output is in error.
Cyclic Redundancy Code (n, n-16)	VCDU error detection only. Mandatory for Grade 3 and optional for Grades 1 & 2.	Decoder does not change bits, but (with very high probability) it will set a flag when it receives a VCDU containing error(s).
Reed-Solomon (255, 223) with I=5 interleaving (symbol = 8 bits).	For primary VCDU error correction of Grade 1 & 2 service; not used on Grade 3.	Can correct any combination of 16 symbol errors in a block. With interleaving (I=5), it can correct all bursts of length <634 bits. Provides excellent error detection when errors exceed correction capability.

#### **A.4.3 Error Detection Options**

The last three codes on Table A-3 possess moderate (VCDU Header error correcting code) or excellent (CRC error detecting and R-S [255,223] error correcting codes) error detection capability. The question arises as to what action should be taken when the decoder FAIL flag is set (i.e., an error is detected but cannot be corrected).

Basically there are two choices:

CHOICE-1: deliver the errored VCDU to the indicated destination along with an indicator that the VCDU contains error(s); or

CHOICE-2: delete the VCDU that contains the detected error(s), thereby causing a gap in the data stream.

There are two potential problems associated with the first choice:

- (a) the error(s) may be in the address field, thereby causing the VCDU to be delivered to the wrong destination; and



- (b) the mechanism has not yet been specified whereby the decoder error flag can be transmitted along with the errored VCDUs to alert the destination that the VCDU is unreliable.

If Choice-1 is selected there will be no gaps caused by deleted VCDUs (unless the error affected the address resulting in a misdelivery); however, there may be a significant number of errors in the delivered VCDUs. On the other hand, very few errors will occur in delivered VCDUs using Choice-2, but there may be a significant VCDU deletion rate.

## A.5 Required And Expected System Performance

Analysis to estimate the performance of the system is based on the assumption that the channel BER is  $1 \times 10^{-5}$ . Where no convolutional coding is included, the channel noise is assumed to be AWGN which gives rise to a memoryless channel. Where convolutional coding has been included, it is also assumed that the long-term BER is  $1 \times 10^{-5}$ ; however, the errors are assumed to occur in bursts given by the distribution in Table A-2 and the probability of a bit error within the interior of a given burst is assumed to be 50%. The combination of convolutional coding and lowered  $E_b/N_0$  results in the same average error rate, but it does change the error distribution.

The following are the set of performance metrics which will be used to estimate the SLS performance under the scenario conditions:

- BER-1: This is the BER if Choice-1 (see section A4.3) is selected. It represents the average BER from all received VCDUs, INCLUDING those decoded with detectable but uncorrectable error(s).
- BER-2: This is the BER if Choice-2 (see section A4.3) is selected. It represents the average BER from those VCDUs decoded without detecting an uncorrectable error.
- PDEL: Fraction of transmitted VCDUs which are deleted because an uncorrectable error was detected and Choice-2 was selected (Note: PDEL does not apply to Choice-1 since no VCDUs are deleted).

Table A-4 shows the required and expected performance of the system under the preceding condition and assumptions. In addition, the length of the VCDU or CVCDU is assumed to be 10,200 bits. In the case of Grade-1 or Grade-2 service, there is no substantive difference whether convolutional coding is employed or not; therefore, only a single expected performance figure is given. However, for Grade-3 service, there are significant differences in the expected performance depending upon whether or not convolutional coding was used. In this case the notations "With CC" and "Without CC" refer to the presence or absence of convolutional coding.

**Table A-4: Required and Expected Performance**

Grade of Service	BER-1		BER-2		VCDU Deletion Rate (PDEL)	
	Required	Expected	Required	Expected	Required	Expected
Grade-1	$1 \times 10^{-12}$	$< 1 \times 10^{-20}$	$1 \times 10^{-12}$	$< 1 \times 10^{-20}$	$1 \times 10^{-12}$	$< 1 \times 10^{-20}$
Grade-2	$1 \times 10^{-07}$	$< 1 \times 10^{-20}$	$1 \times 10^{-07}$	$< 1 \times 10^{-20}$	$1 \times 10^{-12}$	$< 1 \times 10^{-20}$
Grade-3	$1 \times 10^{-05}$		Unspecified		Unspecified	
With CC		$1 \times 10^{-05}$		$2.3 \times 10^{-11}$		$2.2 \times 10^{-05}$
W/O CC		$1 \times 10^{-05}$		$5.4 \times 10^{-14}$		$6.6 \times 10^{-12}$

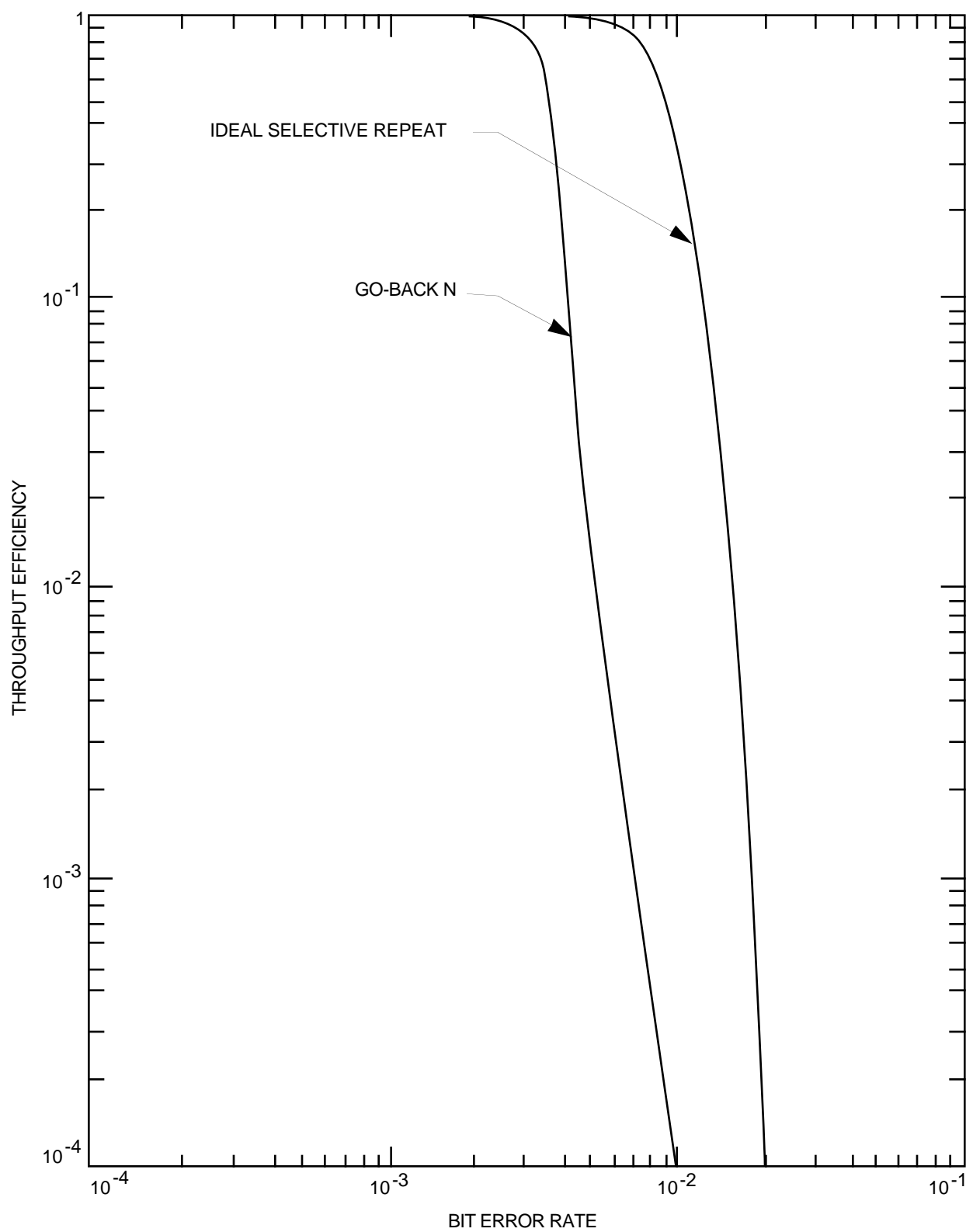
In Table A-4, when the error rate falls below  $1 \times 10^{-20}$ , the result is merely reported to be less than this threshold. It would seem from this Table that Grade-1 and Grade-2 are equivalent since all the error probabilities for both of these grades of service were lower than this threshold. This however is merely an artifact of the assumptions that were given in section A-3, namely that bit, node and frame synchronization had been established and the effective channel BER was  $1 \times 10^{-05}$ . Grade-1 service is far more robust under conditions where the above assumptions are violated.

Figure A-7 compares throughput efficiency (i.e., the ratio of number of distinct frames transmitted to the total number of frames transmitted) for the “Ideal Selective Repeat” and the “Go-Back N” retransmission protocols. There is virtually no difference between the two protocols if the bit error rate is better than  $1 \times 10^{-03}$ ; the throughput efficiency for both is approximately 100% under those conditions. The SLAP is based on a “Go-Back N” protocol, since it is the easier of the two techniques to implement.

#### **A.6 Note Concerning Ambiguity Resolution of the Channel Access Data Units (CADUs) Using SQPSK Modulation**

This note provides some guidelines for phase and data channel resolution in a SQPSK system in which:

- (1) the I- and Q-channels together support a Bitstream generated by a single data source which shall be correctly reconstructed at the receiving end; and
- (2) the data mode is referred to as DG2 in the NASA Space Network Users' Guide and is used in the high-rate KSA channel.

**Figure A-7: Throughput of Grade-1 Service**

### **A.6.1 Phase Ambiguity Resolution**

In an SQPSK system, the phase detection process gives rise to a four-quadrant phase ambiguity that can be resolved in two ways:

- (a) using the CADU “frame synchronization” polarity; or
- (b) using differential encoding.

The second method is recommended both in the CCSDS Radio Frequency and Modulation Recommendations and the NASA Space Network Users’ Guide (Reference [3]). More precisely, D-NRZ format is recommended for both I- and Q-channels; i.e., the I- and Q-channels are separately differentially encoded.

### **A.6.2 Data Channel Ambiguity**

Phase ambiguity of 90 or 270 degrees gives rise to inversion of the I- or Q-channel in the demodulation. Generally speaking this data channel ambiguity can only be resolved if a “marker” is attached to either I- or Q-channel, i.e., power or data imbalance, different PN code modulation.

In the case being considered, a single data channel SQPSK-modulated does not give rise to data channel ambiguity. The staggering process always guarantees the correct reconstruction of the bitstream sequence.

## **APPENDIX B     IMPLEMENTATION OF ISOCHRONOUS SERVICES**

### **B.1     INTRODUCTION**

The primary multiplexing structure within the Space Link Subnetwork is the Virtual Channel. The traffic flowing across the space link can be either asynchronous (such as telemetry or computer data files), or isochronous (such as audio or teleoperations control). Isochronous traffic has minimum delay constraints associated with it.

Three concerns associated with the multiplexing and buffering of Virtual Channels are:

- (a)     the efficiency of link utilization, and buffering required, as a function of the type of traffic;
- (b)     the method used to support isochronous services;
- (c)     Doppler compensation requirements.

### **B.2     VIRTUAL CHANNEL MULTIPLEXING**

Three strategies exist for multiplexing Virtual Channels (VCs):

- (1)     Fully synchronous multiplexing.

In this case the sequence of VCs is fixed and repetitive, and each VC is transmitted in a designated time slot. This strategy is applicable when most traffic is isochronous and of fixed rate. Since a VC is transmitted whether data are available or not, this strategy is inefficient when handling bursty data.

- (2)     Fully asynchronous multiplexing.

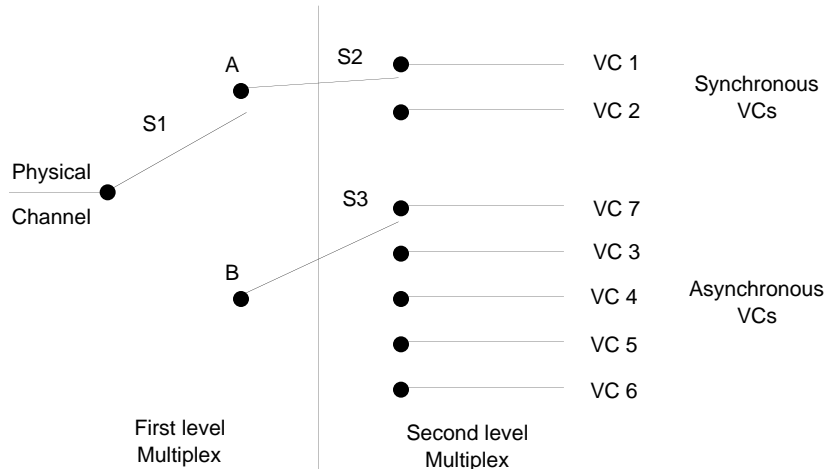
In this case a VC is transmitted when it is “complete,” i.e., filled with valid data. In the event that two or more VCs are ready at the same time, a release priority scheme is required. This has the effect of “backing up” the lower priority VCs, and hence some form of buffering is needed. If a round-robin priority scheme is used, then for “n” VCs each VC will be given priority once every “n” channel access time slots. This limits the amount of buffering bits “B” needed while queuing for link access to:

$$B = [n \times \text{time slot duration (secs)} \times \text{VC input data rate (b/s)}]$$

This data-driven strategy is efficient, even under varying loads, when the traffic is asynchronous. However since there is a queuing delay associated with channel access for all but the highest priority VC, this will lead to a jitter for isochronous traffic, which may not be acceptable in many cases.

## (3) Combination synchronous/asynchronous multiplexing.

In this case a two-level multiplexing strategy can be adopted. At the first level the channel is partitioned between synchronous and asynchronous VCs. At the second level the synchronous and asynchronous VCs are multiplexed as described in (1) and (2) above. This situation is shown in Figure B-1 for the case where there are two synchronous VCs of equal rate, and five asynchronous VCs. The ratio of the synchronous to asynchronous traffic is 1:3.



S1: switches to A every 4th VCDU time for 1 VCDU time

S2: alternates between VC1 and VC2 for each S1 A contact

S3: rotates round VCs 7-3-4-5-6-7 etc. according to a round-robin strategy

**Figure B-1: Example of a Combination VC Multiplexing Strategy**

This strategy handles both synchronous and asynchronous traffic and is thus free from the limitations of (1) and (2) above. However, since the VCs are “large” data units (often in the order of up to 10,000 bits) this can lead to inefficiencies when assigning VCs in a fixed manner for synchronous traffic. This is discussed in section B.3 below.

Inefficiency in any multiplexing strategy will occur if fill VCs have to be transmitted to satisfy timing constraints on release of data. In mixed synchronous/asynchronous multiplexing, fill VCDUs can be avoided by the following scheme. One in N slots can be given for guaranteed access to synchronous data. While synchronous VCDUs are available, asynchronous VCDUs are buffered. When a synchronous slot cannot be filled, rather than wastefully sending fill data, an asynchronous VCDU is sent.

The possibility of using this scheme depends on the relative rates of synchronous and asynchronous data, as there would be problems when there are many more asynchronous VCDUs generated than synchronous slots are freed. Also, this scheme could add a further level of complexity to S2 in the former example.

Selection of the most efficient strategy for a particular configuration is dependent on the data rate and volume of isochronous traffic relative to the overall data rate. A simulation developed by ESA/ESTEC, described in Reference [10], can be used to compare virtual channel multiplexing strategies for a particular system configuration. Input to the model provides a detailed description of each VC, including data type (audio, video, network data), data rate, priority, timing constraints associated with transmission of the data, and presence or absence of insert data. This information allows considerable flexibility in defining multiplexing strategies. Output from the model includes both overall channel efficiency and the amount of buffering required for each VC to queue data that is ready for transmission.

### B.3 ISOCHRONOUS DATA TRANSMISSION OPTIONS

The AOS Recommendations specify two methods for supporting synchronous (or isochronous) traffic:

- (1) using a dedicated VC (the case assumed in section B.2); or
- (2) using an "Insert Zone" in every transmitted VCDU.

The choice of which method to use is dependent on the VCDU transmission rate and the allowable link access delay for the isochronous traffic. The tradeoff is caused by the fact that to use a synchronous VC with an access delay of "T" secs automatically implies that a link transmission rate of

$$(L/T) \text{ b/s}$$

(where L = VCDU length in bits) has been assigned. If the data rate of the isochronous traffic is (much) less than this, inefficiency in the use of channel data transmission capacity results, because full VCDUs would have to be transmitted. Use of the Insert Zone potentially reduces this inefficiency by permitting a fractional allocation of a VCDU, based on the amount of synchronous traffic flowing.

In order to simplify the multiplexing implementation, the choice was made to allow Insert Zones either in all VCs or in none (i.e., VC-dependent allocation is not allowed). One effect of this is that use of the Insert Zone may be inefficient at high rates, since Insert space will be assigned even if not needed. Since the length of the Insert Zone must be at least 1 octet (8 bits), the fraction  $8/L$  represents the smallest possible ratio of bandwidth that can be reserved for the Insert Zones. Consequently, if

$$(\text{Channel Rate} \times 8/L) > S$$

(where S is the isochronous data rate), then use of the Insert Zone will introduce inefficiency. This is exactly the opposite to the efficiency/link rate dependency of the synchronous VC multiplexing strategy, where the percentage efficiency improves with increasing rate. This

can be seen by means of the following example (in which the VCDU lengths are chosen to be Reed-Solomon Code compatible).

(a) Conditions:

Isochronous channel: = 64 kb/s audio  
 Allowed multiplexing delay: < 10 % of link delay  
 < 30 ms  
 VCDU length: Case-1 = 8160 bits  
 Case-2 = 2040 bits

(b) CASE-1: Use of a dedicated VC.

The allowed delay implies the transmission of a VCDU every 30 milliseconds. This gives an allocated channel transmission rate of:

272 kb/s for 8160 bit VCDUs  
 68 kb/s for 2040 bit VCDUs

Although using the shorter VCDU length gives greater channel efficiency, this may not always be possible for reasons such as constraints coming from the asynchronous channels, the need for interleaving on the channel, etc. Thus, for completeness, Table B-1 shows the channel efficiency for the 8160 bit VCDU length case of the Insert Zone.

**Table B-1: “Worst Case” Efficiency for 1 Audio Channel (64 Kb/s)**

Total Link B/W	1 Mbps	2 Mbps	10 Mbps	20 Mbps
Link Inefficiency Due to Audio	20 %	10 %	2 %	1 %
(Audio delay = 30 millisecs)				

(c) CASE-2: Use of the Insert Zone.

In this case the Insert Zone may be of any length, in octet increments, from 1 octet to the length of the full Data Field of the VCDU. Thus the efficiency is 100 % (to within an octet) until the aggregate transmitted channel data rate “R” is such that:

$$(R \times 8/L) > \text{synchronous data rate } S$$

In the example here,  $S = 64 \text{ kb/s}$  and the above inequality occurs when:

$$\begin{aligned}
 R &> 65 \text{ Mb/s} \quad (L = 8160 \text{ bits}) \\
 R &> 16 \text{ Mb/s} \quad (L = 2040 \text{ bits})
 \end{aligned}$$

Comparing Case-1 and Case-2, it can be stated that, for this example:



- (a) For aggregate channel rates below 1-2 Mb/s, the Insert Zone approach (Case-2) should be used.
- (b) For high channel data rates ( $> 20$  Mb/s) the dedicated VC method (Case-1) should be used.
- (c) For intermediate channel data rates (2-20 Mb/s) the choice is implementation dependent.

#### B.4 DOPPLER COMPENSATION

The delays experienced by synchronous traffic depend not only on the multiplexing strategy, but also on the propagation path length variation between the orbiting vehicle and receiving ground station. This is dependent on path geometry, which for the AOS Recommendation will often include geostationary data relay satellites. In this case the path length variation can be up to 6900 km (i.e., a delay variation of 24 milliseconds) during one relay satellite pass for equatorial low earth orbits. This variation appears to the receiver as a slowly varying Doppler jitter. The magnitude of this jitter is such that it must be compensated for in those cases where it is necessary (a) to match fixed-rate ground data distribution networks and (b) to achieve constant delay for delay variation-sensitive signals. Two methods of compensation are possible, namely:

- (1) *Buffering to remove the path length Doppler variation.* The buffer capacity “B” required is given by:

$$B = 24 \times 10^{-3} \times \text{bit rate.}$$

For example, for a 10 Mb/s data rate, a buffer of 240 kb is needed.

- (2) *VC rate management by the use of “idle” VCDUs which can be discarded on reception.* In essence the channel is over-dimensioned to cope with the highest rate. Compared with (1), less buffering is required, but more inefficiency is accepted on the channel.

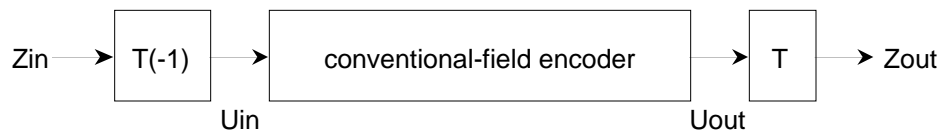
A third method which is sometimes used for Doppler compensation, i.e., to adjust the transmission clock, is not possible in this case because of the need to transfer from relay satellite to relay satellite with consequent jumps in the Doppler and hence in the clock.

## APPENDIX C PROCEDURES FOR VERIFYING CCSDS ENCODER IMPLEMENTATIONS

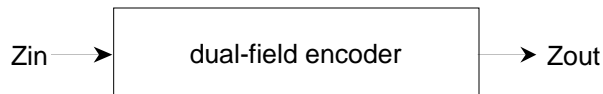
### C.1 INTRODUCTION

The objective of this appendix is to present test procedures for verifying software or hardware implementations of CCSDS error control encoders. The codes of interest are the CVCDU R-S outer code, the VCDU Header Error Control code, and the Cyclic Redundancy Code (CRC) polynomial used to generate the VCDU Error Control field.

Section C.2 describes the required input and corresponding outputs for verifying the encoder for CVCDU R-S outer code with the conventional-field encoder implementation shown below:



Section C.3 describes the required input and corresponding outputs for verifying the encoder for CVCDU R-S outer code with the dual-field encoder implementation shown below:



Section C.4 describes the required input and corresponding outputs for evaluating the R-S encoder for the VCDU Header Error Control field, using the conventional encoder implementation.

Section C.5 describes a method for evaluating the encoder for the CRC error detection polynomial used to generate the VCDU Error Control field.

### C.2 TESTING A CONVENTIONAL R-S ENCODER

A Reed-Solomon outer code is used to generate check symbols that are appended to a VCDU to form a CVCDU. The particular R-S code that has been selected is described in Reference [4].

To test the R-S Generator Polynomial Matrix (or alternatively the table lookup) coefficients, it is necessary to apply at the input of the encoder eight 8-bit vectors (one at a time) consisting of one “1” and seven “0s” in the conventional field. Each of these input vectors tests one column of the generator matrix.

Thus, if  $U_0 \dots U_7 = 10000000$  (or  $U=1$ ), then each of the 32 parity bytes following this input will represent the first column of each of the 32 generator matrices (or the generator coefficients in case of lookup tables).

If  $U=2$  or  $01000000$ , then we obtain the second column of each of the matrices (or the generator coefficients multiplied by  $\alpha$ ).

Notice that putting the eight  $U$  vectors side by side results in the identity matrix.

The above is done in the conventional field,  $U$ . Since one may have access only to the input and output of the encoder (which are in the dual field,  $Z$ ), the  $U$  inputs and outputs have been translated to  $Z$ , the corresponding dual-field elements.

To check the individual columns of the Generator Polynomial Matrices, use the  $Z$ -field inputs indicated in the  $Z_{in}$  row of the table and compare the encoder output with the  $Z$ -field output shown in columns 1 through 32 of the tables. Any difference indicates one or more errors in the corresponding matrix column. If it is desired to find the exact location of the element(s) in error within a column of a Generator Polynomial Matrix, the erroneous  $Z$  value can be translated back to the  $U$  field. The table is constructed to check 32 matrices, even though many implementations of the Reed-Solomon Encoder will actually have only 16 different matrices, but will use each matrix twice. However, some VLSI chip designers have found it easier to put down all 32 matrices even though 16 are redundant, thus creating the possibility of an error in one or the other of a pair. This possibility means that a general-purpose test program such as this one must check all 32 matrices.

The following procedure, applied to the information presented below, can be used to test a conventional R-S encoder:

- a) Apply the symbol described by  $Z_{in}$  of the first column to the input of the encoder ( $Z_0$  being the first bit in); this limits the number of information bytes to one.
- b) Observe the 32 parity bytes at the encoder output; they should be identical to the bytes shown in step 1-32 of the first column.
- c) Repeat a and b for the remaining seven columns.

**U-VECTOR CHECK**

Remarks: Steps 1-32 are the Z-outputs 1-32;  
 first entry is the U corresponding to Z-input;  
 all Us and Zs in ascending order;  
 binary representation U0.U1,U2,..U7 OR Z0,Z1,Z2.....Z7.

Step	Zs							
Uin	10000000	01000000	00100000	00010000	00001000	00000100	00000010	00000001
Zin	01111011	10101111	10011001	11111010	10000110	11101100	11101111	10001101
1	01000111	11010001	10100000	00010010	11001110	10110110	01111011	10101111
2	00110010	11000100	10101011	00111110	00101101	11010010	11000010	01011111
3	01011111	00000010	01010011	11101011	00101010	00010111	01011000	11000111
4	10000110	11101100	11101111	10001101	11000000	00001100	11101001	01111001
5	01001010	00001001	01111111	00001000	01001110	10101110	10101000	01011100
6	00011000	11010011	11110011	11111001	11100100	10100001	00100011	01101000
7	10100000	00010010	11001110	10110110	01111011	10101111	10011001	11111010
8	01111000	11001101	11010100	00110110	01100011	01111100	01101010	00000011
9	10000011	01111010	10011110	00111111	00011100	01110100	00100100	10101101
10	11111010	10000110	11101100	11101111	10001101	11000000	00001100	11101001
11	10111001	11110000	10011011	10101001	01101101	11000110	11111000	11010101
12	01011100	01100000	00011110	00100111	11001111	10000111	11011101	01001001
13	01011111	00000010	01010011	11101011	00101010	00010111	01011000	11000111
14	01001111	10011111	00001110	10111010	10010010	11010110	01100101	10001000
15	11101100	11101111	10001101	11000000	00001100	11101001	01111001	11111100
16	11111110	00100001	00111011	10111011	10100011	01110000	10000011	01111010
17	11101100	11101111	10001101	11000000	00001100	11101001	01111001	11111100
18	01001111	10011111	00001110	10111010	10010010	11010110	01100101	10001000
19	01011111	00000010	01010011	11101011	00101010	00010111	01011000	11000111
20	01011100	01100000	00011110	00100111	11001111	10000111	11011101	01001001
21	10111001	11110000	10011011	10101001	01101101	11000110	11111000	11010101
22	11111010	10000110	11101100	11101111	10001101	11000000	00001100	11101001
23	10000011	01111010	10011110	00111111	00011100	01110100	00100100	10101101
24	01111000	11001101	11010100	00110110	01100011	01111100	01101010	00000011
25	10100000	00010010	11001110	10110110	01111011	10101111	10011001	11111010
26	00011000	11010011	11110011	11111001	11100100	10100001	00100011	01101000
27	01001010	00001001	01111111	00001000	01001110	10101110	10101000	01011100
28	10000110	11101100	11101111	10001101	11000000	00001100	11101001	01111001
29	01011111	00000010	01010011	11101011	00101010	00010111	01011000	11000111
30	00110010	11000100	10101011	00111110	00101101	11010010	11000010	01011111
31	01000111	11010001	10100000	00010010	11001110	10110110	01111011	10101111
32	01111011	10101111	10011001	11111010	10000110	11101100	11101111	10001101

# CCSDS REPORT CONCERNING ADVANCED ORBITING SYSTEMS

## HEX AND DECIMAL REPRESENTATION OF ABOVE (HEX,DEC,HEX,DEC. . . .)

Zin	7B	123	AF	175	99	153	FA	250	86	134	EC	236	EF	239	8D	141
1	47	71	D1	209	A0	160	12	18	CE	206	B6	182	7B	123	AF	175
2	32	50	C4	196	AB	171	3E	62	2D	45	D2	210	C2	194	5F	95
3	5F	95	2	2	53	83	EB	235	2A	42	17	23	58	88	C7	199
4	86	134	EC	236	EF	239	8D	141	C0	192	C	12	E9	233	79	121
5	4A	74	9	9	7F	127	8	8	4E	78	AE	174	A8	168	5C	92
6	18	24	D3	211	F3	243	F9	249	E4	228	A1	161	23	35	68	104
7	A0	160	12	18	CE	206	B6	182	7B	123	AF	175	99	153	FA	250
8	78	120	CD	205	D4	212	36	54	63	99	7C	124	6A	106	3	3
9	83	131	7A	122	9E	158	3F	63	1C	28	74	116	24	36	AD	173
10	FA	250	86	134	EC	236	EF	239	8D	141	C0	192	C	12	E9	233
11	B9	185	F0	240	9B	155	A9	169	6D	109	C6	198	F8	248	D5	213
12	5C	92	60	96	1E	30	27	39	CF	207	87	135	DD	221	49	73
13	5F	95	2	2	53	83	EB	235	2A	42	17	23	58	88	C7	199
14	4F	79	9F	159	E	14	BA	186	92	146	D6	214	65	101	88	136
15	EC	236	EF	239	8D	141	C0	192	C	12	E9	233	79	121	FC	252
16	FE	254	21	33	3B	59	BB	187	A3	163	70	112	83	131	7A	122
17	EC	236	EF	239	8D	141	C0	192	C	12	E9	233	79	121	FC	252
18	4F	79	9F	159	E	14	BA	186	92	146	D6	214	65	101	88	136
19	5F	95	2	2	53	83	EB	235	2A	42	17	23	58	88	C7	199
20	5C	92	60	96	1E	30	27	39	CF	207	87	135	DD	221	49	73
21	B9	185	F0	240	9B	155	A9	169	6D	109	C6	198	F8	248	D5	213
22	FA	250	86	134	EC	236	EF	239	8D	141	C0	192	C	12	E9	233
23	83	131	7A	122	9E	158	3F	63	1C	28	74	116	24	36	AD	173
24	78	120	CD	205	D4	212	36	54	63	99	7C	124	6A	106	3	3
25	A0	160	12	18	CE	206	B6	182	7B	123	AF	175	99	153	FA	250
26	18	24	D3	211	F3	243	F9	249	E4	228	A1	161	23	35	68	104
27	4A	74	9	9	7F	127	8	8	4E	78	AE	174	A8	168	5C	92
28	86	134	EC	236	EF	239	8D	141	C0	192	C	12	E9	233	79	121
29	5F	95	2	2	53	83	EB	235	2A	42	17	23	58	88	C7	199
30	32	50	C4	196	AB	171	3E	62	2D	45	D2	210	C2	194	5F	95
31	47	71	D1	209	A0	160	12	18	CE	206	B6	182	7B	123	AF	175
32	7B	123	AF	175	99	153	FA	250	86	134	EC	236	EF	239	8D	141

**U IMPULSE RESPONSE**

Remarks: Zin is the Z-INPUT (ZO transmitted first) followed by  
 222 octets of value=0 (i.e., Z2=Z3=,...,Z223=00000000);  
 steps 1-32 are the Z-outputs 1-32;  
 U,Z in ascending order;  
 binary representation U0.U1,U2,..U7 OR Z0,Z1,Z2.....Z7

Uin	10000000	01000000	00100000	00010000	00001000	00000100	00000010	00000001
Zin	01111011	10101111	10011001	11111010	10000110	11101100	11101111	10001101
1	01111011	10101111	10011001	11111010	10000110	11101100	11101111	10001101
2	01000111	11010001	10100000	00010010	11001110	10110110	01111011	10101111
3	00110010	11000100	10101011	00111110	00101101	11010010	11000010	01011111
4	01011111	00000010	01010011	11101011	00101010	00010111	01011000	11000111
5	10000110	11101100	11101111	10001101	11000000	00001100	11101001	01111001
6	01001010	00001001	01111111	00001000	01001110	10101110	10101000	01011100
7	00011000	11010011	11110011	11111001	11100100	10100001	00100011	01101000
8	10100000	00010010	11001110	10110110	01111011	10101111	10011001	11111010
9	01111000	11001101	11010100	00110110	01100011	01111100	01101010	00000011
10	10000011	01111010	10011110	00111111	00011100	01110100	00100100	10101101
11	11111010	10000110	11101100	11101111	10001101	11000000	00001100	11101001
12	10111001	11110000	10011011	10101001	01101101	11000110	11111000	11010101
13	01011100	01100000	00011110	00100111	11001111	10000111	11011101	01001001
14	01011111	00000010	01010011	11101011	00101010	00010111	01011000	11000111
15	01001111	10011111	00001110	10111010	10010010	11010110	01100101	10001000
16	11101100	11101111	10001101	11000000	00001100	11101001	01111001	11111100
17	11111110	00100001	00111011	10111011	10100011	01110000	10000011	01111010
18	11101100	11101111	10001101	11000000	00001100	11101001	01111001	11111100
19	01001111	10011111	00001110	10111010	10010010	11010110	01100101	10001000
20	01011111	00000010	01010011	11101011	00101010	00010111	01011000	11000111
21	01011100	01100000	00011110	00100111	11001111	10000111	11011101	01001001
22	10111001	11110000	10011011	10101001	01101101	11000110	11111000	11010101
23	11111010	10000110	11101100	11101111	10001101	11000000	00001100	11101001
24	10000011	01111010	10011110	00111111	00011100	01110100	00100100	10101101
25	01111000	11001101	11010100	00110110	01100011	01111100	01101010	00000011
26	10100000	00010010	11001110	10110110	01111011	10101111	10011001	11111010
27	00011000	11010011	11110011	11111001	11100100	10100001	00100011	01101000
28	01001010	00001001	01111111	00001000	01001110	10101110	10101000	01011100
29	10000110	11101100	11101111	10001101	11000000	00001100	11101001	01111001
30	01011111	00000010	01010011	11101011	00101010	00010111	01011000	11000111
31	00110010	11000100	10101011	00111110	00101101	11010010	11000010	01011111
32	01000111	11010001	10100000	00010010	11001110	10110110	01111011	10101111

# CCSDS REPORT CONCERNING ADVANCED ORBITING SYSTEMS

## HEX AND DECIMAL REPRESENTATION OF ABOVE (HEX,DEC,HEX,DEC. . .)

Zin	7B	123	AF	175	99	153	FA	250	86	134	EC	236	EF	239	8D	141
1	7B	123	AF	175	99	153	FA	250	86	134	EC	236	EF	239	8D	141
2	47	71	D1	209	A0	160	12	18	CE	206	B6	182	7B	123	AF	175
3	32	50	C4	196	AB	171	3E	62	2D	45	D2	210	C2	194	5F	95
4	5F	95	2	2	53	83	EB	235	2A	42	17	23	58	88	C7	199
5	86	134	EC	236	EF	239	8D	141	C0	192	C	12	E9	233	79	121
6	4A	74	9	9	7F	127	8	8	4E	78	AE	174	A8	168	5C	92
7	18	24	D3	211	F3	243	F9	249	E4	228	A1	161	23	35	68	104
8	A0	160	12	18	CE	206	B6	182	7B	123	AF	175	99	153	FA	250
9	78	120	CD	205	D4	212	36	54	63	99	7C	124	6A	106	3	3
10	83	131	7A	122	9E	158	3F	63	1C	28	74	116	24	36	AD	173
11	FA	250	86	134	EC	236	EF	239	8D	141	C0	192	C	12	E9	233
12	B9	185	F0	240	9B	155	A9	169	6D	109	C6	198	F8	248	D5	213
13	5C	92	60	96	1E	30	27	39	CF	207	87	135	DD	221	49	73
14	5F	95	2	2	53	83	EB	235	2A	42	17	23	58	88	C7	199
15	4F	79	9F	159	E	14	BA	186	92	146	D6	214	65	101	88	136
16	EC	236	EF	239	8D	141	C0	192	C	12	E9	233	79	121	FC	252
17	FE	254	21	33	3B	59	BB	187	A3	163	70	112	83	131	7A	122
18	EC	236	EF	239	8D	141	C0	192	C	12	E9	233	79	121	FC	252
19	4F	79	9F	159	E	14	BA	186	92	146	D6	214	65	101	88	136
20	5F	95	2	2	53	83	EB	235	2A	42	17	23	58	88	C7	199
21	5C	92	60	96	1E	30	27	39	CF	207	87	135	DD	221	49	73
22	B9	185	F0	240	9B	155	A9	169	6D	109	C6	198	F8	248	D5	213
23	FA	250	86	134	EC	236	EF	239	8D	141	C0	192	C	12	E9	233
24	83	131	7A	122	9E	158	3F	63	1C	28	74	116	24	36	AD	173
25	78	120	CD	205	D4	212	36	54	63	99	7C	124	6A	106	3	3
26	A0	160	12	18	CE	206	B6	182	7B	123	AF	175	99	153	FA	250
27	18	24	D3	211	F3	243	F9	249	E4	228	A1	161	23	35	68	104
28	4A	74	9	9	7F	127	8	8	4E	78	AE	174	A8	168	5C	92
29	86	134	EC	236	EF	239	8D	141	C0	192	C	12	E9	233	79	121
30	5F	95	2	2	53	83	EB	235	2A	42	17	23	58	88	C7	199
31	32	50	C4	196	AB	171	3E	62	2D	45	D2	210	C2	194	5F	95
32	47	71	D1	209	A0	160	12	18	CE	206	B6	182	7B	123	AF	175

### C.3 TESTING THE DUAL-FIELD R-S ENCODER

The procedure for testing a dual-field R-S encoder is the same as the procedure for testing a conventional R-S encoder. However, in this case, the inputs are the Z vectors, rather than the U vectors.

The following table of information should be used:

#### Z-VECTOR CHECK

Remarks: Step 0 is Z-input;  
steps 1-32 are the Z-outputs 1-32.

Step	Zs							
U	10100011	01000010	01110100	10111111	00001111	10011110	00110101	00110011
Zin	10000000	01000000	00100000	00010000	00001000	00000100	00000010	00000001
1	00110011	10101010	11010101	01011001	10101100	01010110	10101011	01100110
2	00000100	00000110	10000011	11000101	01100010	00110001	00011000	00001000
3	10010011	01011010	10101101	01000101	10100010	11010001	01101000	00100111
4	11111001	00000101	10000010	10111000	01011100	00101110	00010111	11110010
5	11000001	10100001	11010000	00101001	00010100	00001010	10000101	10000011
6	10100000	11110000	01111000	00011100	00001110	10000111	11000011	01000001
7	00001101	10001011	11000101	01101111	10110111	01011011	00101101	00011011
8	11000101	10100111	01010011	11101100	01110110	00111011	10011101	10001011
9	10010100	01011110	10101111	11000011	11100001	11110000	01111000	00101000
10	11110011	10001010	01000101	01010001	10101000	01010100	00101010	11100110
11	00001111	00001000	00000100	00001101	10000110	01000011	00100001	00011111
12	11010110	10111101	11011110	10111001	11011100	11101110	11110111	10101101
13	10010011	01011010	10101101	01000101	10100010	11010001	01101000	00100111
14	10101100	11111010	11111101	01010010	10101001	11010100	11101010	01011001
15	11100100	10010110	01001011	11000001	01100000	10110000	01011000	11001000
16	00111100	10100010	11010001	01010100	00101010	00010101	10001010	01111001
17	11100100	10010110	01001011	11000001	01100000	10110000	01011000	11001000
18	10101100	11111010	11111101	01010010	10101001	11010100	11101010	01011001
19	10010011	01011010	10101101	01000101	10100010	11010001	01101000	00100111
20	11010110	10111101	11011110	10111001	11011100	11101110	11110111	10101101
21	00001111	00001000	00000100	00001101	10000110	01000011	00100001	00011111
22	11110011	10001010	01000101	01010001	10101000	01010100	00101010	11100110
23	10010100	01011110	10101111	11000011	11100001	11110000	01111000	00101000
24	11000101	10100111	01010011	11101100	01110110	00111011	10011101	10001011
25	00001101	10001011	11000101	01101111	10110111	01011011	00101101	00011011
26	10100000	11110000	01111000	00011100	00001110	10000111	11000011	01000001
27	11000001	10100001	11010000	00101001	00010100	00001010	10000101	10000011
28	11111001	00000101	10000010	10111000	01011100	00101110	00010111	11110010
29	10010011	01011010	10101101	01000101	10100010	11010001	01101000	00100111
30	00000100	00000110	10000011	11000101	01100010	00110001	00011000	00001000
31	00110011	10101010	11010101	01011001	10101100	01010110	10101011	01100110
32	10000000	01000000	00100000	00010000	00001000	00000100	00000010	00000001



# CCSDS REPORT CONCERNING ADVANCED ORBITING SYSTEMS

## HEX AND DECIMAL REPRESENTATION OF ABOVE (HEX,DEC,HEX,DEC. . . .)

Zin	80	128	40	64	20	32	10	16	8	8	4	4	2	2	1	1
1	33	51	AA	170	D5	213	59	89	AC	172	56	86	AB	171	66	102
2	4	4	6	6	83	131	C5	197	62	98	31	49	18	24	8	8
3	93	147	5A	90	AD	173	45	69	A2	162	D1	209	68	104	27	39
4	F9	249	5	5	82	130	B8	184	5C	92	2E	46	17	23	F2	242
5	C1	193	A1	161	D0	208	29	41	14	20	A	10	85	133	83	131
6	A0	160	F0	240	78	120	1C	28	E	14	87	135	C3	195	41	65
7	D	13	8B	139	C5	197	6F	111	B7	183	5B	91	2D	45	1B	27
8	C5	197	A7	167	53	83	EC	236	76	118	3B	59	9D	157	8B	139
9	94	148	5E	94	AF	175	C3	195	E1	225	F0	240	78	120	28	40
10	F3	243	8A	138	45	69	51	81	A8	168	54	84	2A	42	E6	230
11	F	15	8	8	4	4	D	13	86	134	43	67	21	33	1F	31
12	D6	214	BD	189	DE	222	B9	185	DC	220	EE	238	F7	247	AD	173
13	93	147	5A	90	AD	173	45	69	A2	162	D1	209	68	104	27	39
14	AC	172	FA	250	FD	253	52	82	A9	169	D4	212	EA	234	59	89
15	E4	228	96	150	4B	75	C1	193	60	96	B0	176	58	88	C8	200
16	3C	60	A2	162	D1	209	54	84	2A	42	15	21	8A	138	79	121
17	E4	228	96	150	4B	75	C1	193	60	96	B0	176	58	88	C8	200
18	AC	172	FA	250	FD	253	52	82	A9	169	D4	212	EA	234	59	89
19	93	147	5A	90	AD	173	45	69	A2	162	D1	209	68	104	27	39
20	D6	214	BD	189	DE	222	B9	185	DC	220	EE	238	F7	247	AD	173
21	F	15	8	8	4	4	D	13	86	134	43	67	21	33	1F	31
22	F3	243	8A	138	45	69	51	81	A8	168	54	84	2A	42	E6	230
23	94	148	5E	94	AF	175	C3	195	E1	225	F0	240	78	120	28	40
24	C5	197	A7	167	53	83	EC	236	76	118	3B	59	9D	157	8B	139
25	D	13	8B	139	C5	197	6F	111	B7	183	5B	91	2D	45	1B	27
26	A0	160	F0	240	78	120	1C	28	E	14	87	135	C3	195	41	65
27	C1	193	A1	161	D0	208	29	41	14	20	A	10	85	133	83	131
28	F9	249	5	5	82	130	B8	184	5C	92	2E	46	17	23	F2	242
29	93	147	5A	90	AD	173	45	69	A2	162	D1	209	68	104	27	39
30	4	4	6	6	83	131	C5	197	62	98	31	49	18	24	8	8
31	33	51	AA	170	D5	213	59	89	AC	172	56	86	AB	171	66	102
32	80	128	40	64	20	32	10	16	8	8	4	4	2	2	1	1

**Z IMPULSE RESPONSE**

Remarks: Zin is the Z-INPUT (ZO transmitted first) followed by  
 222 octets of value=0 (i.e., Z2=Z3=,...,Z223=00000000);  
 steps 1-32 are the Z-parities corresponding to Zin.

Uin	10100011	01000010	01110100	10111111	00001111	10011110	00110101	00110011
Zin	10000000	01000000	00100000	00010000	00001000	00000100	00000010	00000001
1	10000000	01000000	00100000	00010000	00001000	00000100	00000010	00000001
2	00110011	10101010	11010101	01011001	10101100	01010110	10101011	01100110
3	00000100	00000110	10000011	11000101	01100010	00110001	00011000	00001000
4	10010011	01011010	10101101	01000101	10100010	11010001	01101000	00100111
5	11111001	00000101	10000010	10111000	01011100	00101110	00010111	11110010
6	11000001	10100001	11010000	00101001	00010100	00001010	10000101	10000011
7	10100000	11110000	01111000	00011100	00001110	10000111	11000011	01000001
8	00001101	10001011	11000101	01101111	10110111	01011011	00101101	00011011
9	11000101	10100111	01010011	11101100	01110110	00111011	10011101	10001011
10	10010100	01011110	10101111	11000011	11100001	11110000	01111000	00101000
11	11110011	10001010	01000101	01010001	10101000	01010100	00101010	11100110
12	00001111	00001000	00000100	00001101	10000110	01000011	00100001	00011111
13	11010110	10111101	11011110	10111001	11011100	11101110	11110111	10101101
14	10010011	01011010	10101101	01000101	10100010	11010001	01101000	00100111
15	10101100	11111010	11111101	01010010	10101001	11010100	11101010	01011001
16	11100100	10010110	01001011	11000001	01100000	10110000	01011000	11001000
17	00111100	10100010	11010001	01010100	00101010	00010101	10001010	01111001
18	11100100	10010110	01001011	11000001	01100000	10110000	01011000	11001000
19	10101100	11111010	11111101	01010010	10101001	11010100	11101010	01011001
20	10010011	01011010	10101101	01000101	10100010	11010001	01101000	00100111
21	11010110	10111101	11011110	10111001	11011100	11101110	11110111	10101101
22	00001111	00001000	00000100	00001101	10000110	01000011	00100001	00011111
23	11110011	10001010	01000101	01010001	10101000	01010100	00101010	11100110
24	10010100	01011110	10101111	11000011	11100001	11110000	01111000	00101000
25	11000101	10100111	01010011	11101100	01110110	00111011	10011101	10001011
26	00001101	10001011	11000101	01101111	10110111	01011011	00101101	00011011
27	10100000	11110000	01111000	00011100	00001110	10000111	11000011	01000001
28	11000001	10100001	11010000	00101001	00010100	00001010	10000101	10000011
29	11111001	00000101	10000010	10111000	01011100	00101110	00010111	11110010
30	10010011	01011010	10101101	01000101	10100010	11010001	01101000	00100111
31	00000100	00000110	10000011	11000101	01100010	00110001	00011000	00001000
32	00110011	10101010	11010101	01011001	10101100	01010110	10101011	01100110

# CCSDS REPORT CONCERNING ADVANCED ORBITING SYSTEMS

## HEX AND DECIMAL REPRESENTATION OF ABOVE (HEX,DEC,HEX,DEC. . . .)

Zin	80	128	40	64	20	32	10	16	8	8	4	4	2	2	1	1
1	80	128	40	64	20	32	10	16	8	8	4	4	2	2	1	1
2	33	51	AA	170	D5	213	59	89	AC	172	56	86	AB	171	66	102
3	4	4	6	6	83	131	C5	197	62	98	31	49	18	24	8	8
4	93	147	5A	90	AD	173	45	69	A2	162	D1	209	68	104	27	39
5	F9	249	5	5	82	130	B8	184	5C	92	2E	46	17	23	F2	242
6	C1	193	A1	161	D0	208	29	41	14	20	A	10	85	133	83	131
7	A0	160	F0	240	78	120	1C	28	E	14	87	135	C3	195	41	65
8	D	13	8B	139	C5	197	6F	111	B7	183	5B	91	2D	45	1B	27
9	C5	197	A7	167	53	83	EC	236	76	118	3B	59	9D	157	8B	139
10	94	148	5E	94	AF	175	C3	195	E1	225	F0	240	78	120	28	40
11	F3	243	8A	138	45	69	51	81	A8	168	54	84	2A	42	E6	230
12	F	15	8	8	4	4	D	13	86	134	43	67	21	33	1F	31
13	D6	214	BD	189	DE	222	B9	185	DC	220	EE	238	F7	247	AD	173
14	93	147	5A	90	AD	173	45	69	A2	162	D1	209	68	104	27	39
15	AC	172	FA	250	FD	253	52	82	A9	169	D4	212	EA	234	59	89
16	E4	228	96	150	4B	75	C1	193	60	96	B0	176	58	88	C8	200
17	3C	60	A2	162	D1	209	54	84	2A	42	15	21	8A	138	79	121
18	E4	228	96	150	4B	75	C1	193	60	96	B0	176	58	88	C8	200
19	AC	172	FA	250	FD	253	52	82	A9	169	D4	212	EA	234	59	89
20	93	147	5A	90	AD	173	45	69	A2	162	D1	209	68	104	27	39
21	D6	214	BD	189	DE	222	B9	185	DC	220	EE	238	F7	247	AD	173
22	F	15	8	8	4	4	D	13	86	134	43	67	21	33	1F	31
23	F3	243	8A	138	45	69	51	81	A8	168	54	84	2A	42	E6	230
24	94	148	5E	94	AF	175	C3	195	E1	225	F0	240	78	120	28	40
25	C5	197	A7	167	53	83	EC	236	76	118	3B	59	9D	157	8B	139
26	D	13	8B	139	C5	197	6F	111	B7	183	5B	91	2D	45	1B	27
27	A0	160	F0	240	78	120	1C	28	E	14	87	135	C3	195	41	65
28	C1	193	A1	161	D0	208	29	41	14	20	A	10	85	133	83	131
29	F9	249	5	5	82	130	B8	184	5C	92	2E	46	17	23	F2	242
30	93	147	5A	90	AD	173	45	69	A2	162	D1	209	68	104	27	39
31	4	4	6	6	83	131	C5	197	62	98	31	49	18	24	8	8
32	33	51	AA	170	D5	213	59	89	AC	172	56	86	AB	171	66	102

## C.4 TESTING THE ENCODER FOR VCDU HEADER ERROR CONTROL

A shortened Reed-Solomon (10,6) code with parameters as specified in reference [1] is used to generate the optional VCDU Header Error Control field. The following information can be used to test the encoder:

U <sub>in</sub> = 1      U <sub>3..U0</sub> =0001					U <sub>in</sub> = 4      U <sub>3..U0</sub> =0100				
← U OUT →					← U OUT →				
STEP	U	HEX	POWER	U <sub>3....U0</sub>	STEP	U	HEX	POWER	U <sub>3....U0</sub>
2	8	8	3	1000	2	6	6	5	0110
3	2	2	1	0010	3	8	8	3	1000
4	8	8	3	1000	4	6	6	5	0110
5	1	1	0	0001	5	4	4	2	0100

U <sub>in</sub> = 2      U <sub>3..U0</sub> =0010					U <sub>in</sub> = 8      U <sub>3..U0</sub> =1000				
← U OUT →					← U OUT →				
STEP	U	HEX	POWER	U <sub>3....U0</sub>	STEP	U	HEX	POWER	U <sub>3....U0</sub>
2	3	3	4	0011	2	12	C	6	1100
3	4	4	2	0100	3	3	3	4	0011
4	3	3	4	0011	4	12	C	6	1100
5	2	2	1	0010	5	8	8	3	1000

## C.5 TESTING THE CRC POLYNOMIAL

A CRC code is used to generate the optional 16-bit VCDU Error Control Field. This field is mandatory only within Virtual Channels that are not Reed-Solomon encoded. The particular CRC code that has been selected is given in the AOS Blue Book, Reference [1].

Figure C-1 presents a shift-register arrangement for this CRC encoding. To encode, the storage stages are set to “ones”, gates A and B are enabled (closed), gate C is inhibited (open), and (n-16) message bits are clocked into the input. They will appear simultaneously at the output. After the bits have been entered, the output of gate A is clamped to “zero”, gate B is inhibited, gate C is enabled, and the register is clocked a further 16 counts. During these counts the required check bits will appear in succession at the output. The encoder illustrated in this figure can be tested as follows:

Starting with all 1s in the encoder, and inputting a 1, followed by ten 0s, the 16 outputs should be 11101111101111. The bit to the left is the most significant bit (or the first bit transmitted).

