The Consultative Committee for Space Data Systems

Research and Development for
Space Data System Standards

DVB-S2 CODING & MODULATION STANDARD USE FOR HIGH DATA RATE TM LINKS

EXPERIMENTAL SPECIFICATION

CCSDS 131.3-O-1

June 2007

AUTHORITY

Issue:	Orange Book, Issue 1
Date:	June 2007
Location:	Washington, DC, USA

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CCSDS Secretariat
Office of Space Communication (Code M-3)
National Aeronautics and Space Administration
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PREFACE

This document is a CCSDS Experimental Specification. Its Experimental status indicates that it is part of a research or development effort based on prospective requirements, and as such it is not considered a Standards Track document. Experimental Specifications are intended to demonstrate technical feasibility in anticipation of a 'hard' requirement that has not yet emerged. Experimental work may be rapidly transferred onto the Standards Track should a hard requirement emerge in the future.

DOCUMENT CONTROL

Document	Title and Issue	Date	Status
CCSDS 131.2-O-0	DVB-S2 CODING & MODULATION STANDARD USE FOR HIGH DATA RATE TM LINKS	December 06	draft
CCSDS 131.3-O-1	DVB-S2 CODING & MODULATION STANDARD USE FOR HIGH DATA RATE TM LINKS	June 07	1st issue

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

The requirements of high resolution (less than one meter) and quite large field of view (around 20 km) and/or high revisit Earth observation missions (e.g. GMES and METEOSAT 3rd generation) with fast access to the new acquired data (less than two hours) combined with a limited number of possible ground stations are increasing towards Gbit-per-second information transfer rate for the Payload TM links speed.

The possible ITU allocated bands for near Earth Exploration Satellites Systems (EESS) remain the same with 8.025/8.4 GHz and 25.5/27 GHz. Since use of Ka band introduce some high dependency to ground facilities meteorological conditions especially at low elevations (under 10°), an efficient use of the X band, less affected by those phenomena, is becoming crucial. In parallel, new link margin management considerations are also needed for Ka band to avoid tremendous increase of power only for very low probability cases.

Then, new modulation and coding schemes with high spectral and energy efficiency are needed to better exploit the bandwidth and/or power limited satellite channel. Furthermore, the additional combined use of power margin evolution for Low Earth Orbits and variable effective rate with variable physical layer techniques (VCM = variable Coding and Modulations) brings further impressive average throughput boosts, but also more flexibility requirements to the modem.

The proposed use of the DVB-S2 ETSI standard (see ref /1/) fits with those evolutions as it offers both the effectiveness of variable rate (2/5 up to 8/9) Low Density Parity Check Codes combined with advanced shaping and Amplitude and Phase Shift Keying modulations (Square root Raised Cosine on QPSK, 8PSK and 16APSK).

1.2 NOMENCLATURE

The following conventions apply throughout this Specification:

a) the words ‘shall’ and ‘must’ imply a binding and verifiable specification;

b) the word ‘should’ implies an optional, but desirable, specification;

c) the word ‘may’ implies an optional specification;

d) the words ‘is’, ‘are’, and ‘will’ imply statements of fact.

1.3 CONVENTIONS

In this document, the following convention is used to identify each bit in an *N*-bit field. The first bit in the field to be transmitted (i.e., the most left justified when drawing a figure) is defined to be ‘Bit 0’, the following bit is defined to be ‘Bit 1’, and so on up to ‘Bit *N*-1’. When the field is used to express a binary value (such as a counter), the Most Significant Bit (MSB) shall be the first transmitted bit of the field, i.e., 'Bit 0' (see Figure 1).

Figure 1 : Bit Numbering Convention

In accordance with standard data-communications practice, data fields are often grouped into 8-bit 'words' which conform to the above convention. Throughout this Specification, such an 8-bit word is called a 'byte'.

The numbering for octets within a data structure starts with '0'.

1.4 REFERENCES

The following documents contain provisions which, through reference in this text, constitute provisions of this Experimental Specification. At the time of publication, the editions indicated were valid. All documents are subject to revision, and users of this Experimental Specification are encouraged to investigate the possibility of applying the most recent editions of the documents indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS documents.

[1] *Digital Video Broadcasting (DVB) - Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite application.* ETSI EN 302 307 v1.1.1 (2004-01) ETSI standards are available for free download at http://www.etsi.org

[2] *Space Packet Protocol.* Recommendation for Space Data System Standards, CCSDS 133.0-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, September 2003

[3] *TM Space Data Link Protocol.* Recommendation for Space Data Systems Standards, CCSDS 132.0-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, September 2003

[4] *TM Synchronization and Channel Coding.* Recommendation for Space Data Systems Standards, CCSDS 131.0-B-1. Blue Book. Issue 1. Washington, D.C.: CCSDS, September 2003

[5] *Information Technology – Open Systems Interconnection – Basic Reference Model: The Basic Model.* International Standard, ISO/IEC 7498-1 2nd ed. Geneva: ISO, 1994

[6] *Radio Frequency and Modulation Systems* – part 1 Earth Stations and Spacecraft, Recommendation for Space Data Systems Standards, CCSDS 401.0-B. Blue Book. Issue 15. Washington, D.C.: CCSDS, September 2005

[7] *Pseudo-random codes for High data rate telemetry : analysis and new proposal*, CCSDS working document SLS-RFM_06-10, June 2006

1.5 LIST OF ABBREVIATIONS

ACM	Adaptive Coding & Modulation
APSK	Amplitude & Phase Shift Keying
ASIC	Application Specific Integrated Circuit
ASM	Attached Synchronization Marker
BB	BaseBand
BBFRAME	BaseBand Frame
BCH	Bose-Chaudhuri-Hocquenghem binary block code
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
π/2-BPSK	Binary Phase Shift Keying with rotation of π/2 every constellation symbol
CADU	Channel Access Data Unit
CCM	Constant Coding & Modulation
CRC	Cyclic Redundancy Check
DFL	Data Field Length
DVB	Digital Video Broadcasting
EESS	Earth Exploration Satellites Systems
ETSI	European Telecommunications Standards Institute
FEC	Forward Error Correction
FECFRAME	Forward Error Correction Frame
FER	Frame Error Rate

FPGA	Field Programmable Gate Array
GMSK	Gaussian Minimum Shift Keying
GS	Generic Stream
HDRTM	High Data Rate TeleMetry
IP	Intellectual Property
IRA	Irregular Repeat Accumulate
ISSYI	Input Stream SYnchronisation Indicator
ITU	International Telecommunications Union
LDPC(C)	Low Density Parity Check (Code)
LEO	Low Earth Orbit (satellite)
LLR	Log Likelihood Ratio
MIS	Multiple Input Stream
MODCOD	Modulation & Coding identifier
MPEG	Motion Picture Experts Group
MSB	Most Significant Bit
NPD	Null Packet Deletion
OSI	Open Systems Interconnection
PL	Physical Layer
PLFRAME	Physical Layer Frame
PLHEADER	Physical Layer Header
PLS	Physical Layer Signaling
PRBS	Pseudo Random Bit Sequence
QEF	Quasi Error Free
QPSK	Quaternary Phase Shift Keying
(O)QPSK	(Offset) Quaternary Phase Shift Keying
RO	Roll-Off (for SRRC shaping)
SIS	Single Input Stream
SNR	Signal to Noise Ratio

SOF	Start Of Frame
S(R)RC	Square (Root) Raised Cosine shaping
SYNC	SYNChronisation byte
SYNCD	SYNChronisation byte distance
TC	TeleCommand
TF	(CCSDS) Transfer Frame
TM	TeleMetry
TS	Transport Stream
UP	User Packets
UPL	User Packets Length
VCM	Variable Coding & Modulation
XFECFRAME	compleX Forward Error Correction Frame
1PSK	1 Phase Shift Keying
8PSK	8-ary Phase Shift Keying
16APSK	16-ary Amplitude & Phase Shift Keying

2 OVERVIEW

DVB-S2 is the second-generation specification for satellite broadcasting – developed by the DVB (Digital Video Broadcasting) Project in 2004. It benefits from more recent developments in channel coding (LDPC codes) combined with a variety of phase and amplitude/phase shift keying modulation formats (QPSK, 8PSK, 16APSK and 32APSK). When used for interactive applications, it may implement Adaptive Coding & Modulation (ACM), thus optimizing the transmission parameters dependant on path conditions. When return channel is not available which corresponds to the High Data Rate TeleMetry case, it may implement Variable Coding & Modulation (VCM).

DVB-S2 is typically used for television/broadcasting by satellite or internet access but it can be used with practically any type of high data rate transmission. DVB-S2 can be used to transmit as well continuous bit-stream as packetised data (MPEG flux essentially).

The purpose of this book is to show the advantages and to describe a way to use DVB-S2 in TM space to earth transmissions. For that reason, we focus only on a subset of the complete ETSI standard (see ref [1]). We will then consider only the DVB-S2 standard in continuous Generic Stream mode with a short FECFRAME length (16200 coded bits). Generic Stream mode with a long FECFRAME length (64800 coded bits) could also be used at the expense of more hardware complexity.

The general aim is to be able to use generic Intellectual Property (IP) for the on-board development but also to deal at the ground side with a standard DVB-S2 receiver without custom precise modifications. For that reason, the global layering could seem to be quite overcharged but it corresponds to the price to pay for leaving it completely generic. But, when a very high frame efficiency is needed, we also proposed a new mode allowing to map directly CCSDS transfer frame on a DVB-S2 physical framing but at the expense of a non-standard DVB-S2 receiver. It should be noted , however, that only the Mode/stream adaptation is in fact non-standard in this case.

3 CONCEPT OF THE PACKETISED GENERIC STREAM TRANSMISSION IN DVB-S2 ETSI STANDARD

3.1 ARCHITECTURE

Figure 2 illustrates the relationship of the DVB-S2 ETSI standard to the Open Systems Interconnection (OSI) reference model (reference [5]). DVB-S2 ETSI standard corresponds to the two lowest OSI layers, i.e. the data link layer and the physical layer. In parallel, the CCSDS layers specific subdivision is also detailed.

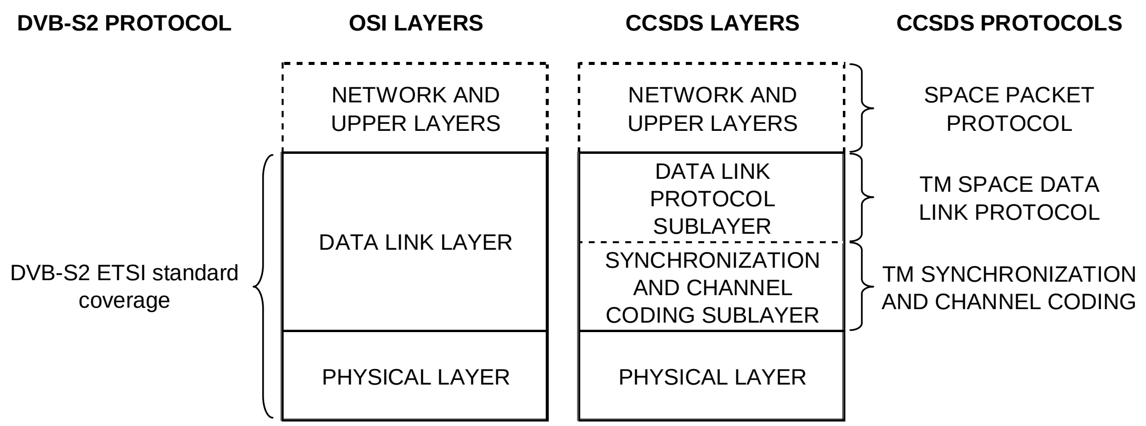


Figure 2 - Relationship with OSI Layers

The functional block diagram of the DVB-S2 standard for a packet stream transmission is given by Figure 3. We can divide this scheme in three main blocks:

- Mode and stream adaptation
- Forward Error Control Encoding
- Physical Layer Frame and Modulation

The mode and stream adaptation block provides buffering, signaling and scrambling functions for transferring data using the protocol data unit called the BaseBand Frame (BBFRAME). The signaling corresponds to a header insertion so as to delimit physical containers. The scrambling is for independence to the data contents ensuring sufficient transitions (‘0’ to ‘1’ and reverse) and bit equiprobability but also to avoid a too short periodicity. This block belongs to the data link layer of the OSI. Its function is equivalent to the CCSDS transfer framing with buffering preceded by the ASM concatenation and also the scrambling of the CCSDS actual “TM and synchronization channel coding” Blue Book (ref [4]) but is mapped to the specific DVB-S2 frame size. As far as DVB-S2 is rather concerned by MPEG packet stream transmission, it allows also a Generic Continuous Stream transmission which is the selected mode in this document. This option of the ETSI standard can work efficiently with CCSDS non coded Transfer Frame transmission. When very high frame efficiency is targeted, this mode and stream adaptation can be simplified through a CCSDS transfer frame splitting without using the BBFRAME.

The Forward Error Control encoding provides near Shannon limit error protection when associated with Belief propagation iterative decoding. The combined use of Irregular Repeat and Accumulate Low Density Parity Check Code (IRA-LDPCC) as inner code and Bose-Chaudhuri-Hocquenghem (BCH) bloc code as outer code is for compensation of short cycles in the Tanner graph of the LDPCC leading to small errors blocs and permits to avoid Error rate flattening. A wide range of coding rates is possible in the ETSI standard but we suggest to limit the number of possibilities. In DVB-S2 ETSI standard, two size of coded bits BBFRAME called “FECFRAME” are possible: 64800 bits (normal FECFRAME) or 16200 bits (short FECFRAME). For CCSDS use, only the short one (equivalent in size to the actual possible coded Transfer Frame size especially the one with CCSDS interleaver size I = 8) may be used. In fact, use of the short FECFRAME allows to limit the buffer size thus limiting the need of additional memory on board and permits more speed efficient parallel decoding at the receiver side. It should be noted that for very high rate data telemetry, due to this limited size of frame, specific attention should be paid when transmitting null contents frame, in order to comply with the ITU regulations (see ref [7]). This block belongs to the data link layer.

The Physical Layer Frame (PLFRAME) is obtained when mapping the coded bits of the FECFRAME with a specific header (PLHEADER) and optional pilot symbols distributed along the frame giving then a XFECFRAME. For robustness purpose, this PLHEADER and those pilot symbols are scrambled and modulated with a very robust scheme (BPSK for PLHeader and 1PSK for pilot symbols) so as to help the demodulator for low SNR. This physical scrambling is for energy dispersal and avoiding repetitive contents. Obtained by a set of Gold sequences, this scrambling lasts all the PLFRAME. The content of the PLHEADER allows to identify the Start of PLFRAME but also the chosen coding and modulation (defined at the frame level), the length of the frame (normal or short) and the use of pilot symbols or not. Due to its importance, this PLHEADER is strongly protected by a Reed-Muller derived bi-orthogonal (64,7) code. Finally, a bit interleaver (for modulations above QPSK) and a shaped (SRC) modulation transforms the message in order to be transmitted by the medium. Additionally, at this level, when no data are present at the interface, the equipment still operating can insert dummy frames so as to continue frame transmission. Those specific dummy frames can easily be suppressed at the receiver side without any ambiguity. All those processes belong to the physical layer.

It can be noticed that this orange draft book focuses only on a limited set of the DVB-S2 standard capacity but never proposes modifications on that standard so as to allow the use of standardized equipment. Especially at the physical layer, we have chosen to remove the 32APSK modulation among the possible options as its usage seems far more adapted to multiple carrier in a channel usage that is far from our high data rate telemetry focus.

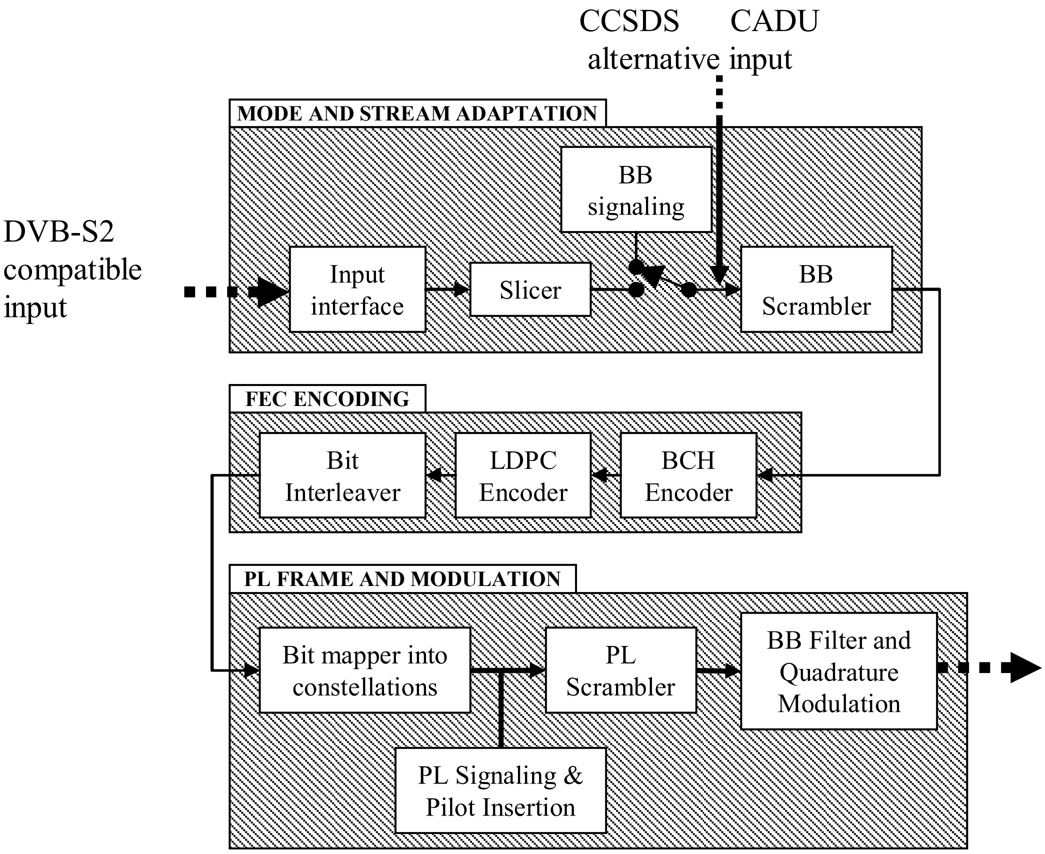


Figure 3 - Functional block diagram of the DVB-S2 System

3.2 MODE AND STREAM ADAPTATION

3.2.1 INPUT INTERFACE (DVB-S2 COMPATIBLE)

The input interface subsystem shall map the input electrical format into logical-bit format. The first received bit will be indicated as the Most Significant Bit (MSB) and will be transmitted first.

As said above, the DVB-S2 protocol allows the Generic Stream transmission mode as an option for professional services (see p15 in ref [1]). A Generic Stream is be characterized by a continuous bit-stream or a packetised stream of constant-length User Packets (UP), with length UPL bits (maximum UPL value 64 kbits). As the packetised mode suppose use of specific packet synchronization and CRC calculation, we prefer to focus on a continuous input generic stream mode.

3.2.2 SLICER (DVB-S2 COMPATIBLE)

According to the Figure 4, the Slicer input stream is organized to "slice" a generic continuous stream in successive frames. Thus, the Slicer shall read (i.e. slice) from its input (single input stream) a DATA FIELD, composed of DFL bits (Data Field Length), where:

$$k_{bch} - (10 \text{ bytes}) \geq DFL \geq 0$$ [1]

A DATA FIELD shall be composed of bits taken from a single input port and shall be transmitted in a homogeneous transmission mode (FEC code and modulation).

In our case, the Slicer shall allocate a number of input bits equal to the maximum DATAFIELD capacity (DFL= k_{bch} -80) in a buffer, thus breaking the continuous stream in subsequent DATAFIELDs.

When a DATA FIELD is not available at the slicer request on the input port, the physical Layer Framing subsystem shall generate and transmit a DUMMY PLFRAME. This process is of particular interest for CCSDS as it allows the TM transmitter to automatically fill so as to get full continuous transmission without being obliged to go at the CCSDS transfer frame level (problem of Virtual Channels and counters to increment).

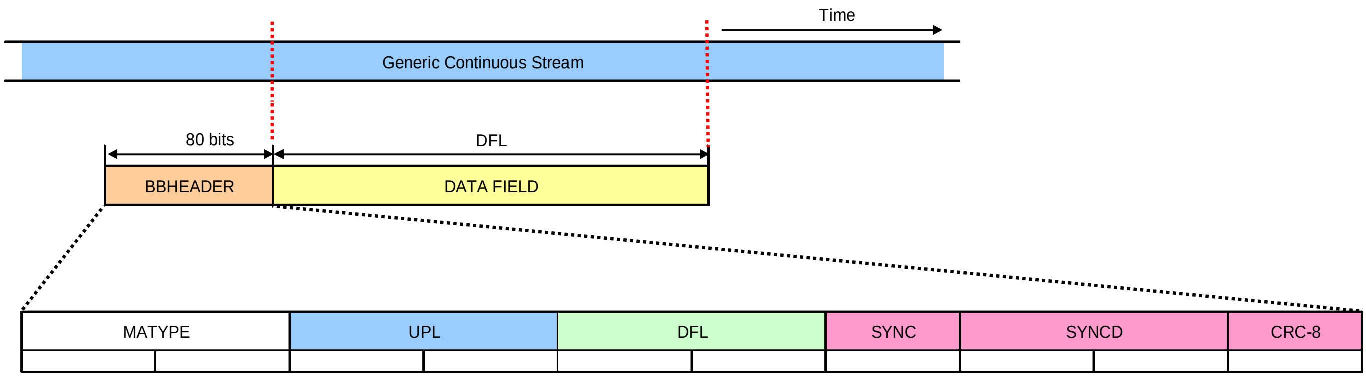


Figure 4 - Stream format at the output of the Mode Adapter (DVB-S2 compatible)

[1] k_{bch} as per [Table 1], 80 bits are dedicated to the BBHEADER, see clause 3.2.3

3.2.3 BASE-BAND HEADER INSERTION (DVB-S2 COMPATIBLE)

A fixed length base-band Header (BBHEADER) of 10 bytes shall be inserted in front of the DATA FIELD, describing its format. It's complete description is rather long and a lot of fields are not used in Generic continuous stream mode, for precise information, see ref [1] p16 to 20. For this byte signaling, the first transmitted bit corresponds to the MSB of the byte. Roughly, all the descriptors are the following :

First byte (MATYPE-1):

- TS/GS field (2 bits): Transport Stream Input or Generic Stream Input (packetised or continuous)
- SIS/MIS field (1 bit): Single Input Stream or Multiple Input Stream
- CCM/ACM field (1 bit): Constant Coding and Modulation or Adaptive Coding and Modulation (VCM is signaled as ACM)
- ISSYI (1 bit), (Input Stream Synchronization Indicator): Not active in our case.
- NPD (1 bit): Null-packet deletion active/not active. Always non active in our case.
- RO (2 bits): Transmission Roll-off factor (α). Three values are possible among 0.35, 0.25 and 0.2. As a compromise between crest factor and length of impulse response and also spectral sharpness, we propose to use a 0.25 roll-off factor value.

Second byte (MATYPE-2):
If SIS/MIS= Multiple Input Stream, then second byte=Input Stream Identifier (ISI); else second byte reserved

UPL (2 bytes): User Packet Length in bits, in the range [0,65535].

DFL (2 bytes): Data Field Length in bits, in the range [0,58112]. There is a link between the Data Field Length and the chosen code rate. For example, use of the 2/5 code implies a DFL = 6312 (decimal) or 18A8 (hexadecimal).

SYNC (1 byte): copy of the User Packet Sync-byte, not used in generic continuous stream mode.

SYNCD (2 bytes): distance in bits from the beginning of the DATA FIELD and the first UserPacket from this frame (first bit of the CRC-8). SYNCD=65535 (decimal) means that no UserPacket starts in the DATA FIELD. Even if there remains some ambiguity, we suggest to use this value in the generic continuous stream mode.

CRC-8 (1 byte): not used for generic continuous stream.

The BBHEADER transmission order is byte by byte from the MSB of the TS/GS field.

So for the Generic continuous stream mode, this BBHEADER becomes (in hexadecimal, Most Significant Value first an X representing an undefined content and Y a specific variable content) :

61 XX 00 00 YY YY XX FF FF XX

The combination of the BBHEADER and the DFL DATAFIELD is called a BBFRAME.

3.2.4 INPUT & SLICING (CCSDS SPECIFIC)

When a very high frame efficiency is targeted, and due to the fact that a lot of the BBHEADER is not useful in the case of transmitting CCSDS transfer frame with ASM (CADU see ref 3 & 4 for details), the input can be derived from the standard place.

The input interface subsystem shall map the input electrical format into logical-bit format. The first received bit will be indicated as the Most Significant Bit (MSB) and will be transmitted first.

Then a simple slicing must be implemented in order to "slice" a continuous stream in successive frames.

In our case, the Slicer shall allocate a number of input bits equal to the maximum DATAFIELD2 capacity (DFL2= k_{bch}) in a buffer, thus breaking the continuous stream in subsequent DATAFIELDs further named also BBFRAMEs. The size DFL2 is in fact depending on the selected code rate as far as only n_{ldpc} is a constant.

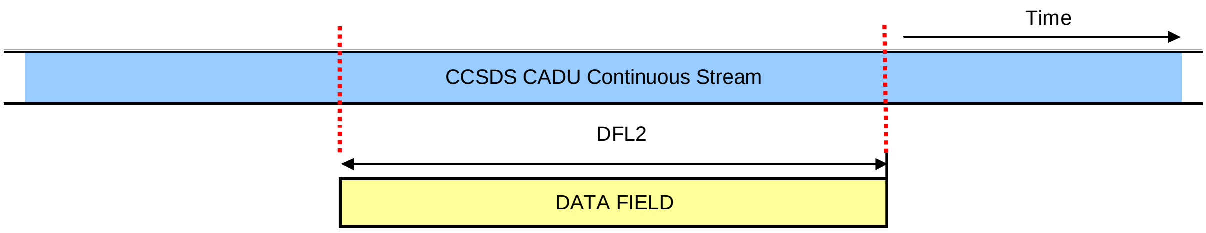


Figure 5 - Stream format at the output of the Mode Adapter (CCSDS specific)

When no data are available in the buffer for allowing a complete DFL2 transmission, zero bytes data are added at the end to fill the slice. Furthermore, when a DATA FIELD is not available at the slicer request on the input port, the physical Layer Framing subsystem shall generate and transmit a DUMMY PLFRAME. This process is of particular interest for CCSDS as it allows the TM transmitter to automatically fill so as to get full continuous transmission without being obliged to go at the CCSDS transfer frame level (problem of Virtual Channels and counters to increment).

3.2.5 BASE-BAND SCRAMBLING

The complete BBFRAME shall be randomized. The randomization sequence shall be synchronous with the BBFRAME, starting from the MSB and ending after k_{bch} bits.

The scrambling sequence shall be generated by the feed-back shift register of Figure 6. The polynomial for the Pseudo Random Binary Sequence (PRBS) generator shall be: $1 + X^{14} + X^{15}$

Loading of the sequence (100101010000000) into the PRBS register (DVB-S compatible), as indicated in figure 6, shall be initiated at the start of every BBFRAME (DVB-S2 compatible case) or every DFL2 length "slice" (CCSDS specific case).

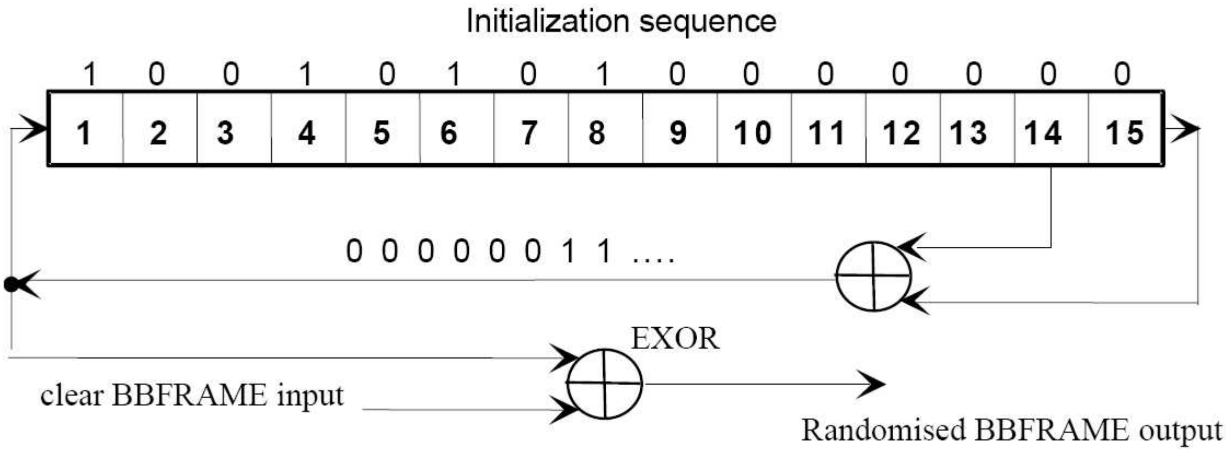


Figure 6 – Possible implementation of the PRBS encoder

3.3 FEC ENCODING

The FEC encoding shall perform Outer Coding (BCH), Inner Coding (LDPC) and Bit Interleaving for high efficiency modulations (8PSK and 16APSK). The input stream shall be composed of BBFRAMEs and the output stream of FECFRAMEs. Each BBFRAME (k_{bch} bits) shall be processed by the FEC coding subsystem, to generate a FECFRAME (n_{ldpc} bits).

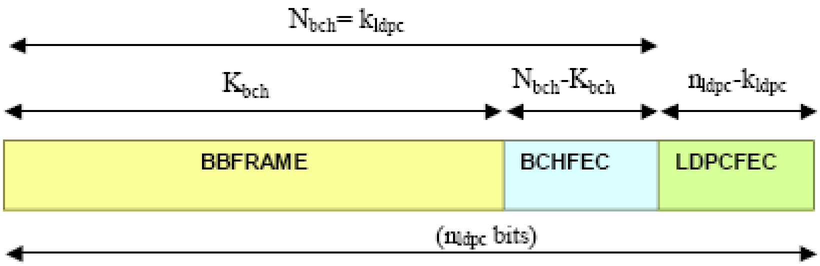


Figure 7 – Format of data before interleaving

Table 1 gives the FEC coding parameters for our selected code rates for the short FECFRAME (n_{ldpc}=16 200 bits). We have suppressed the rates 1/4 (which is rather a 1/5 for short frames), 1/3 and 1/2 as they offer quite limited performances in Eb/No compared to the 2/5 case. Furthermore, those code rates are only use for QPSK and as far as they correspond to very low efficiencies (near spread spectrum), we have considered their suppression as a potential hardware gain at the transmitter (on board) side.

For short frames, the BCH outer code is always working with a correcting capability t = 12.

All the precise information for BCH and LDPC check bits elaboration are described precisely in the standard ref [1] from p 23 to p 26. For that reason and as far as they are proprietary ETSI information we will not reproduce them in this document. We remind that the ETSI standards are available for free download at http://www.etsi.org.

The role of the bit interleaver is to allow to produce very easily bit metrics from the symbol's one obtained at the receiver for easy soft decoding. The principle is a very classic column-row interleaver with a bit serial written in column (size from 3 to 4 bits depending on modulation order) and a bit serial read in row (size 5400 or 4050 bits depending also on modulation order). For more details, see ref [1] p25 and 26.

3.4 PHYSICAL LAYER (PL) FRAMING

First, a bit mapping associates the bit interleaved FECFRAME to the set of modulations supported by the DVB-S2 ETSI standard (QPSK, 8PSK, 16APSK) with for each an absolute (not differential) and conventional Gray-coded mapping. Particularly, the QPSK mapping is fully compatible with the recent CCSDS definition (§2.4.10 of the ref [6]). As explained before, we will not detail the precise mapping including radius values for APSK modulations as far as they are fully defined in ref [1] from pages 26 to 29. We just emphasize the fact that radius for 16APSK constellations are a function of the code rate.

The PLFraming shall then generate a physical layer frame (named PLFRAME), this frame being defined at the constellation symbol level. It does a XFECFRAME slicing into an integer number S of constant length SLOTs (length: M=90 symbols each); S value shall be taken according to Table 2. All those S slots use the same modulation and coding.

So as to identify each PLFRAME beginning, a PLHEADER is added to the XFECFRAME but with a specific modulation, $\pi/2$-BPSK, and coding, bi-orthogonal (64,7), so as to be very robust to the worse possible receive conditions. This PLHEADER contains specific information for receiver configuration. PLHEADER shall occupy exactly one SLOT (length: M=90 Symbols).

To help receiver synchronization and tracking for low SNR with respect to modulation order, it is possible to insert Pilot Block every 16 SLOTS,. The Pilot Block shall be composed of P=36 pilot symbols of unmodulated carrier (1PSK with $I = 1/\sqrt{2}$, $Q = 1/\sqrt{2}$).

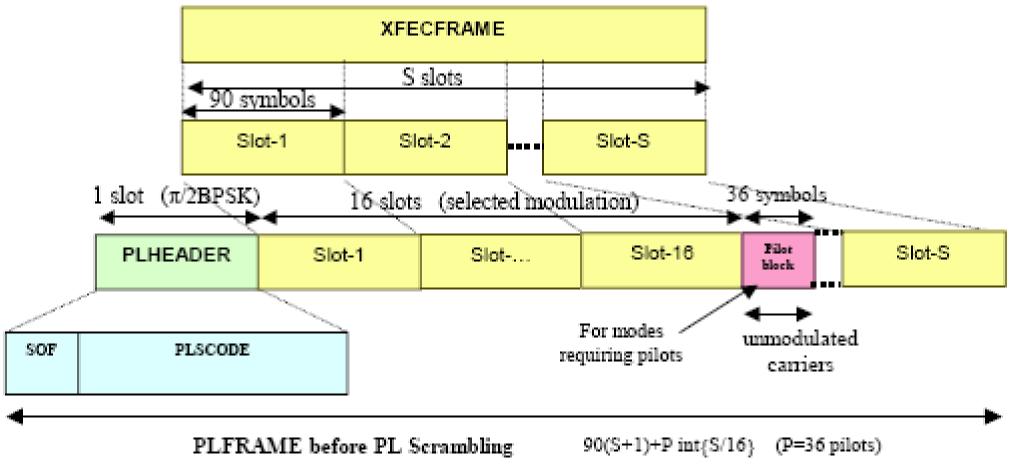


Figure 8 – Format of a "Physical Layer Frame" PLFRAME

3.4.1 PL SIGNALING

The PL signaling shall insert a PLHEADER before each XFECFRAME. PLHEADER is used at the receiver side for synchronization and physical layer signaling.

The PLHEADER shall be composed of the following fields:

SOF (26 symbols), identifying the Start of Frame shall correspond to the sequence 18D2E82 (in hexadecimal).

PLS (64 symbols), shall be a non-systematic binary code of length 64 and dimension 7. It transmits 7 bits for physical layer signaling purpose:

- MODCOD: (5 bits) identifying the XFECFRAME modulation and FEC rate.
- TYPE (2 bits), identifying length (normal or short FECFRAME) and the presence or not of pilots.

Possible values for these fields are given in ref [1] page 31 the PLFRAME constitution. The MODCOD field and the MSB of the TYPE fields are bi-orthogonally coded with a code (64,7) derived from a Reed-Muller (32,6) code. As described in Figure 9, LSB of the TYPE field determines if each odd bit in the code is either equal to the previous one or is always the opposite. This code allows to protect the PL signaling data down to -2 dB of channel SNR which leave good margin for QPSK modulation even with our ultimate 2/5 code rate.

The generator matrix of the linear block code is given in ref [1] page 32.

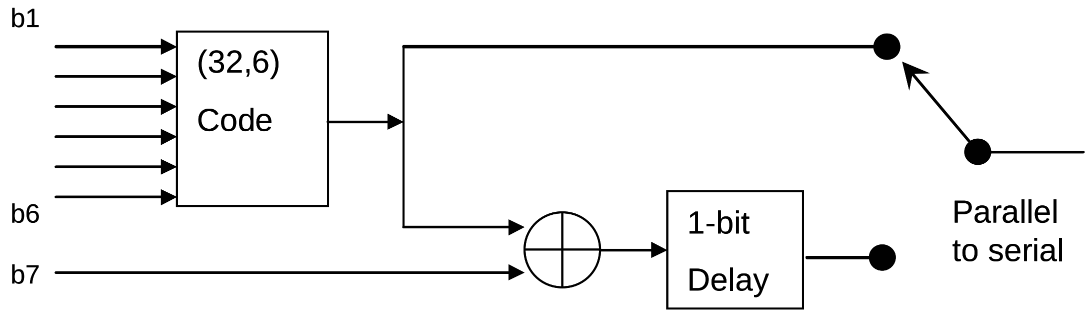


Figure 9 - PLS code

3.4.2 PHYSICAL LAYER SCRAMBLING

Before the modulation, each PLFRAME, excluding the PLHEADER, shall be randomized for energy dispersal. The scrambling code sequences is a complex sequence (C_I +jC_Q) constructed by combining two real m-sequences (generated by means of two polynomials of degree 18). The resulting sequence are segments of a set of Gold sequences (more detailed information about the generation of this sequences is given in ref [1] from pages 33 to 34).

The length of the sequence used has a period greater than the PLFRAME maximum required duration in order to avoid the spurious formation due to the sequence periodicity (see ref [7]). The sequence, will be then truncated to the current PLFRAME length and reinitialized at the end of each PLHEADER.

4 CODING EFFICIENCY AND MODULATION PERFORMANCES

4.1 CODING EFFICIENCY

DVB-S2 transmission efficiency is given by three coding phases, The BBFRAME forming, the FEC Encoding and the PL Framing.

The BBFRAME efficiency depends on the frame length (k_{bch}). The length chosen among the possible values for k_{bch} are given by the Table 1. The BBFRAME efficiency is then defined by:
$\eta_1 = (k_{bch}-80)/ k_{bch}$
When the CCSDS specific “slicer” is used, this efficiency η_1 is equal to 100%.

The subsequent FEC Encoding efficiency is also depending on the k_{bch} length. Table 2 shows the BBFRAME efficiency, FEC Encoding efficiency and the combination of both for all the possible values of k_{bch}. The FEC Encoding efficiency is $\eta_2 = k_{bch}/n_{ldpc}$.

LDPC Code Id.	BCH Uncoded Block k_{bch}	BCH Coded Block LDPC Uncoded Block k_{ldpc}	BCH t-error correction	Effective LDPC Rate	LDPC Coded Block n_{ldpc}	BBFRAME efficiency	FEC Encoding efficiency	BBFRAME + FEC Encoding efficiency
2/5	6312	6480	12	2/5	16200	98.73%	38.96%	**38.47%**
3/5	9552	9720	12	3/5	16200	99.16%	58.96%	**58.47%**
2/3	10632	10800	12	2/3	16200	99.25%	65.63%	**65.14%**
3/4	11712	11880	12	11/15	16200	99.32%	72.30%	**71.80%**
4/5	12432	12600	12	7/9	16200	99.36%	76.74%	**76.25%**
5/6	13152	13320	12	37/45	16200	99.39%	81.19%	**80.69%**
8/9	14232	14400	12	8/9	16200	99.44%	87.85%	**87.36%**

Table 1 – Coding parameters (for short FECFRAME n_{ldpc} = 16200)

The PL Frame efficiency depends on the modulation used. Values for both cases, with and without pilots, are given by Table 2.

ηmod	S	η pilot	η no-pilot
2	360	97.35%	99.72%
3	240	97.32%	99.59%
4	180	97.09%	99.45%

Table 2 – S=number of SLOTs (M=90 symbols) per XFECFRAME

The PLFRAME efficiency is η_3= 90S / [90(S+1)+ P int{(S-1)/16}], where P=36 and int{.} is the integer function.

Then the global efficiency can be obtained $\eta = \eta_1 \bullet \eta_2 \bullet \eta_3$

4.2 PERFORMANCE

Table 3 summarizes performance requirements at QEF over AWGN. Quasi Error Free can be assumed equivalent to a mean BER value of 10^{-10} after complete forward error correction (LDPC and BCH). It must be noticed that due to BCH protection, a lot of error patterns correspond to a 13 bits error in the frame when considering asymptotic performances (near and under the Ideal proposed value). The last columns allows to compare with Shannon bandlimited bound calculated from the overall efficiency Γ (in bits per constellation symbol) for no-pilots mode following the formula :

$$\frac{Eb}{No}_{Shannon} \text{(in dB)} = 10 * \log 10\left(\frac{2^{\Gamma}-1}{\Gamma}\right)$$

We give in annex 2 some results obtained in terms of Bit Error Rate but also Frame Error Rate when transmitting a CCSDS transfer frame of 16384 bits on a DVB-S2 physical frame by using the CCSDS specific framing capability.

Mode	Spectral efficiency Γ_{pilots}	Spectral efficiency $\Gamma_{no\text{-}pilots}$	Ideal Es/N0 (dB) for DECFRAME length=16200	ideal Eb/No (dB) pilots	ideal Eb/No (dB) no-pilots	Bandlimited Shannon Bound (no pilots) Eb/No (dB)
QPSK 2/5	0.744564	0.760928	-0.1	**1.18**	1.09	-0.40
QPSK 3/5	1.131661	1.156532	2.43	**1.89**	1.80	0.26
QPSK 2/3	1.260693	1.288400	3.3	2.29	**2.20**	0.49
QPSK 3/4	1.389725	1.420269	4.23	2.80	**2.71**	0.72
QPSK 4/5	1.475747	1.508181	4.88	3.19	**3.10**	0.87
QPSK 5/6	1.561768	1.596093	5.38	3.44	**3.35**	1.03
QPSK 8/9	1.690800	1.727961	6.4	4.12	**4.02**	1.27
8PSK 3/5	1.692033	1.725319	5.7	**3.42**	3.33	1.26
8PSK 2/3	1.884959	1.922040	6.82	**4.07**	3.98	1.62
8PSK 3/4	2.077885	2.118761	8.11	4.93	**4.85**	1.98
8PSK 5/6	2.335120	2.381056	9.55	5.87	**5.78**	2.47
8PSK 8/9	2.528046	2.577778	10.89	6.86	**6.78**	2.85
16APSK 2/3	2.505223	2.548792	9.17	**5.18**	5.11	2.80
16APSK 3/4	2.761633	2.809662	10.41	**6.00**	5.92	3.30
16APSK 4/5	2.932574	2.983575	11.23	6.56	**6.48**	3.65
16APSK 5/6	3.103514	3.157488	11.81	6.89	**6.82**	4.00
16APSK 8/9	3.359924	3.418357	13.09	7.83	**7.75**	4.53

Table 3 – E_s/N_0 performance at Quasi Error Free BER=10^{-10} (AWGN channel)

5 TELEMETRY SPACE DATA LINK PROTOCOL OVER DVB-S2

Since DVB-S2 allows a Continuous Generic Stream input, the transmission of Transfer Frames (reference [3]) over DVB-S2 is possible. Figure 10 illustrates the relationship of the Telemetry Space Data Link Protocol to the Open Systems Interconnection reference model (reference [5]).

TM Space Data link protocol corresponds to the data link layer in the OSI model. The CCSDS model has divided this layer in two sublayers, the data link protocol sublayer end the synchronization and channel coding sublayer. In this model the TM Space Data link protocol corresponds to the data link protocol sublayer.

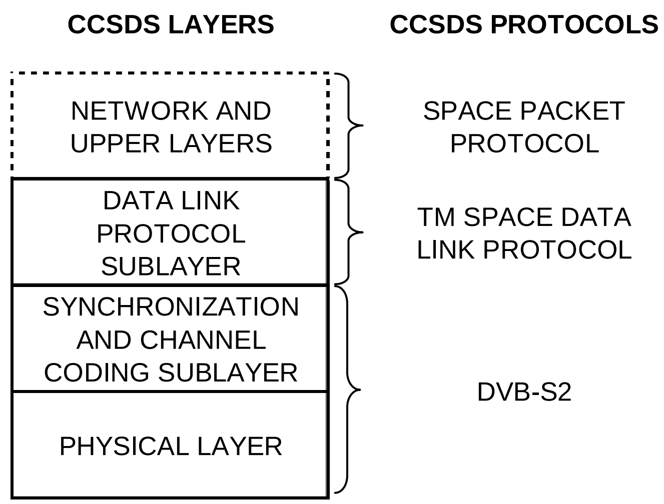


Figure 10 - Telemetry Space Data Link Protocol over DVB-S2

According to the CCSDS layers model, the transmission of Transfer Frames over the DVB-S2 standard is represented by Figure 11. Synchronization of the Transfer Frame is achieved by using a stream with fixed length Transfer Frames with an Attached Sync Marker (ASM) between them (the concatenation being called a CADU). The ASM will be inserted as described in reference [4] for an **uncoded** transfer frame (non Reed-Solomon coded or non turbo coded TF). The DVB-S2 standard will then allow to transmit the concatenation of Transfer Frame with a 6 byte header (Transfer Frame Header) with the ASM called a Channel Access Data Unit (CADU). We emphasize the fact that the use of the CCSDS optional Frame

Error Control Field of 2 bytes (CRC16) inside the CADU remains interesting, as the DVB-S2 BCH outer code is used with a limited to 12 bits error correction and detection capability on more than 6,3 kbits.

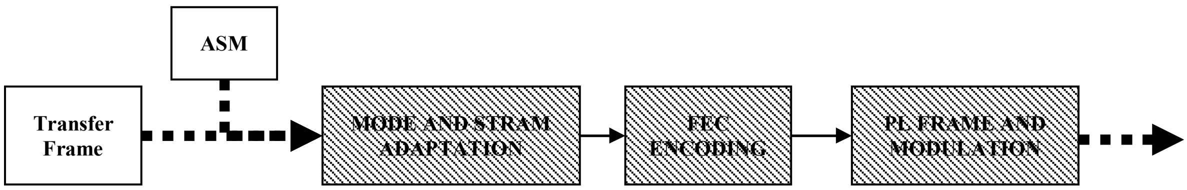


Figure 11 - Telemetry Transfer Frames encapsulation in DVB-S2

A ANNEX 1: ADVANTAGES OF THE VCM USE

We give in the figure below the typical evolution of the margin with respect to ground elevation for LEO Earth Observation satellites at around 700 km. It can be seen that only the low elevation case is predominant so all the margin at highest elevation can be used for a change in coding & modulation so as to increase the bit rate (without changing the Baud rate to keep the spectral occupation constant). This property is particularly evident in Ka band as far as those margin are calculated for a worst case with very few (around 1%) unavailability due to propagation (rain, clouds,…)

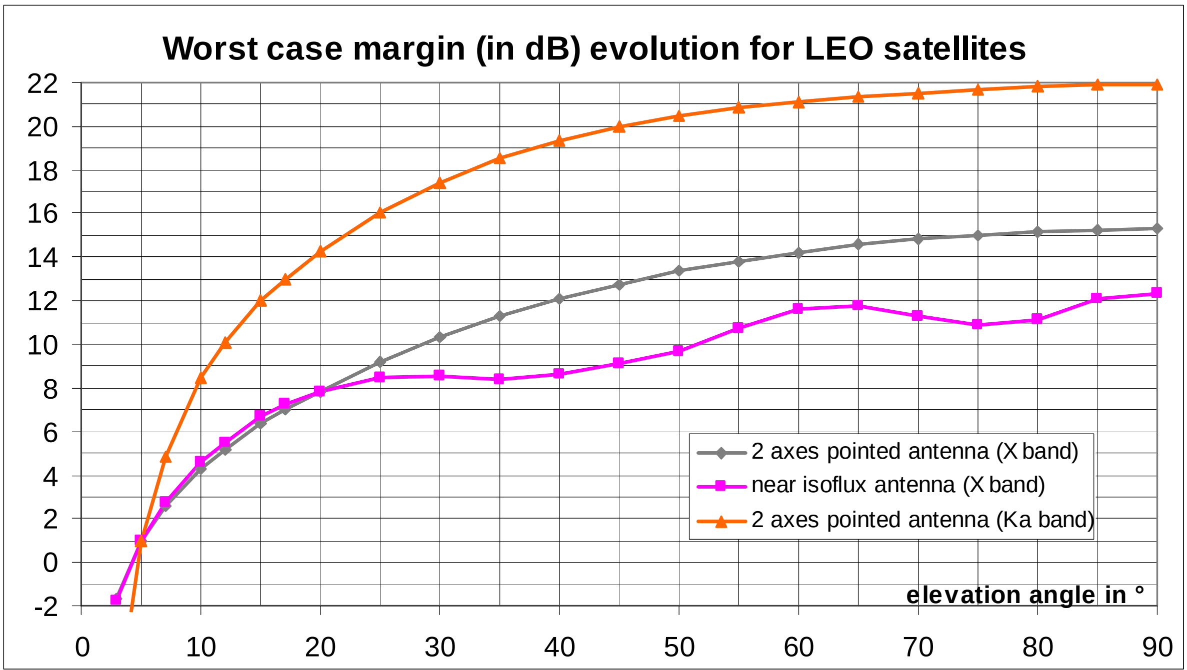


Figure 12 – Worst case margin evolution over elevation angle for LEO satellites

Taking into account that for LEO satellites between 600 and 850 km altitude and by averaging among several passes above mid-latitude (between 35 and 55 ° latitude) ground stations, it is possible to obtain durations and then a percentage of time of being under a given elevation angle. For higher latitude stations, this time distribution is a bit different but the same reasoning still applies. By considering the worst case margin evolution, and by using this percentage, it is then possible to show the benefits of a VCM strategy.

Let's assume a **100 MBauds HDRTM link** as far as it is an actual high value for having all digital Matched Filtering and emitting and receiving processing. By using VCM capabilities of DVB-S2, it is then possible to make some choice among the possible couples "coding/modulations" so as to keep a global worst case margin around 1 dB.

If we were using only **GMSK** with LDPC code of **rate 5/6** (CCM like), our margin will be ever growing far above 1 dB but the constant transmitted rate will be 100*5/6 = **83.5 Mb/s**. Over a mean **pass** of **420 seconds** duration, this CCM can then correspond to a **35 Gbits** transmitted data content.

If we consider a **DVB-S2 VCM** possible scheme, by using a combination of the modulation and coding rates presented in the following table, we could obtain a mean global transmitted rate of 15*1.654+12.5*1.98+20.3*2.228+14.2*2.478+25*2.966+13*3.3 = **247 Mb/s** for the **100 MBauds** HDRTM link. Over the same 420 s pass, this VCM corresponds to a **103.75 Gbits** transmitted data content so near three times the classical CCM value.

Some possible choices among the ones of the DVB-S2 standard selected for this orange book are synthesized in the following table (worst case for implementation value):

DVB-S2 coding/modulation	QPSK 5/6	8PSK 2/3	8PSK 3/4	8PSK 5/6	16APSK 3/4	16 APSK 5/6
efficiency (bit/channel_symbol)	1,654	1,98	2,228	2,478	2,966	3,3
Es/No for 10^-7 PER	5,2	6,7	8	9,4	10,3	11,7
implementation losses	1,5	1,9	2	2,1	2,5	2,7
overall Es/No	6,7	8,6	10	11,5	12,8	14,4
delta Es/No or Power	0,0	1,9	3,3	4,8	6,1	7,7
delta margin	0,0	1,9	3,3	4,9	6,1	7,4
percentage of being in this choice	15,0	12,5	20,3	14,2	25,0	13,0
elevation class	5 to 7,5°	7,5 to 10°	10 to 14°	14 to 17,5°	17,5°to 30°	30 to 90°

The global comparison can be summarized in the following figure :

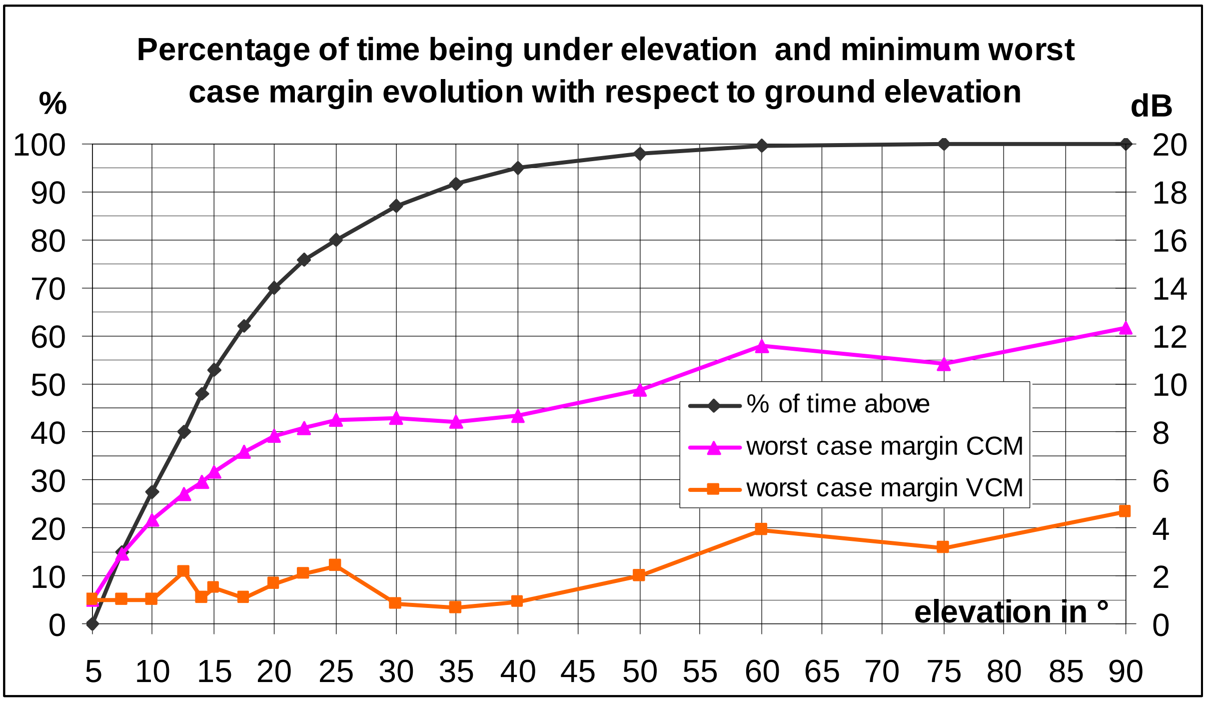


Figure 13 – Percentage of time and margin evolution over elevation angle when using VCM

This calculation shows that use of DVB-S2 VCM capabilities could offer a near 2.5 bit/channel_symbol efficiency instead of a less than 0.85 bit/channel_symbol allowed by classical CCM GMSK or (O)QPSK signaling.

This huge increase of efficiency is of great interest for sharing X and Ka band limited resources.

The VCM capability of the DVB-S2 standard allows to operate very easily for high data rate telemetry just asking the transmitter by the way of a limited set of TC bits to change the emitted scheme, those TC bits being elaborated from the On Board Computer (or a Payload Computer) from an operating plan, the orbit characteristics can be forecasted on a several day basis without being critical for the VCM change time. The internal data flux control allows also to regulate the change in effective data rate. It should be noted that this proposed practice represent an evolution for operations. Firstly, it should be emphasized that the VCM scheme has just to be prepared during working plan elaboration by looking at the mission simulator (implementing a simplified version of the link budget). At the Transmitter side all is then fully automatic due to DVB-S2 capabilities. Secondly, for the induced links to a Telecommand in efficiency of the Transmitter, it must be considered that the use of a pointing antenna (quasi imposed by link budget in Ka band) corresponds to far more complex commands and usage….

ANNEX 2: BER AND FER PERFORMANCES

For comparison with other proposed coding schemes, we give hereunder some Bit Error Rate and Frame Error Rate (size = 16384 bits) when using the DVB-S2 standard transmission. For QPSK 8/9 we have also computed the FER for 8192 bits frames. It can be seen that the difference is negligible.
The abscissa is either the Es/No , constellation symbol energy Es and Noise power spectral density No ratio or the Eb/No, bit energy and Noise power spectral density No ratio both in dBs. The first ratio Es/No is proportional to the necessary transmit power for a same spectral occupation and it can be seen that a progression of around 0.8 up to 2.5 dB (QPSK) and 0.5 up to 1.5 dB (8PSK & 16APSK) is offered by the different code rates. Naturally, the power gain for low rates and low order modulation (QPSK) is at the expense of the overall spectral efficiency (power/normalized occupied bandwidth dilemma).
The second ratio (Eb/No) is a more classical normalized performance metric that allows to compare for the same useful bit rate. For each simulation, as far as neither carrier phase neither symbol rate recovery have been simulated, only the “no pilots” case has been considered for Eb/No computation. The use of pilot symbols only penalized the Eb/No by adding the value $10*\log10(\eta_{no\text{-}pilots/}\ \eta_{pilots})$ (see §4.1) to the no-pilots given value.

The decoder used for those performances is using a 6 bits quantized bit (derived from received symbol) Log Likelihood Ratio (LLR) at input with a “belief propagation” iterative algorithm with a maximum of 50 iterations. The propagation is done with the Mansour/Shandbhag immediate flooding algorithm with 360 parallel node processors using the following ψ non linear function implemented with Look Up Table (6 bits quantized) :

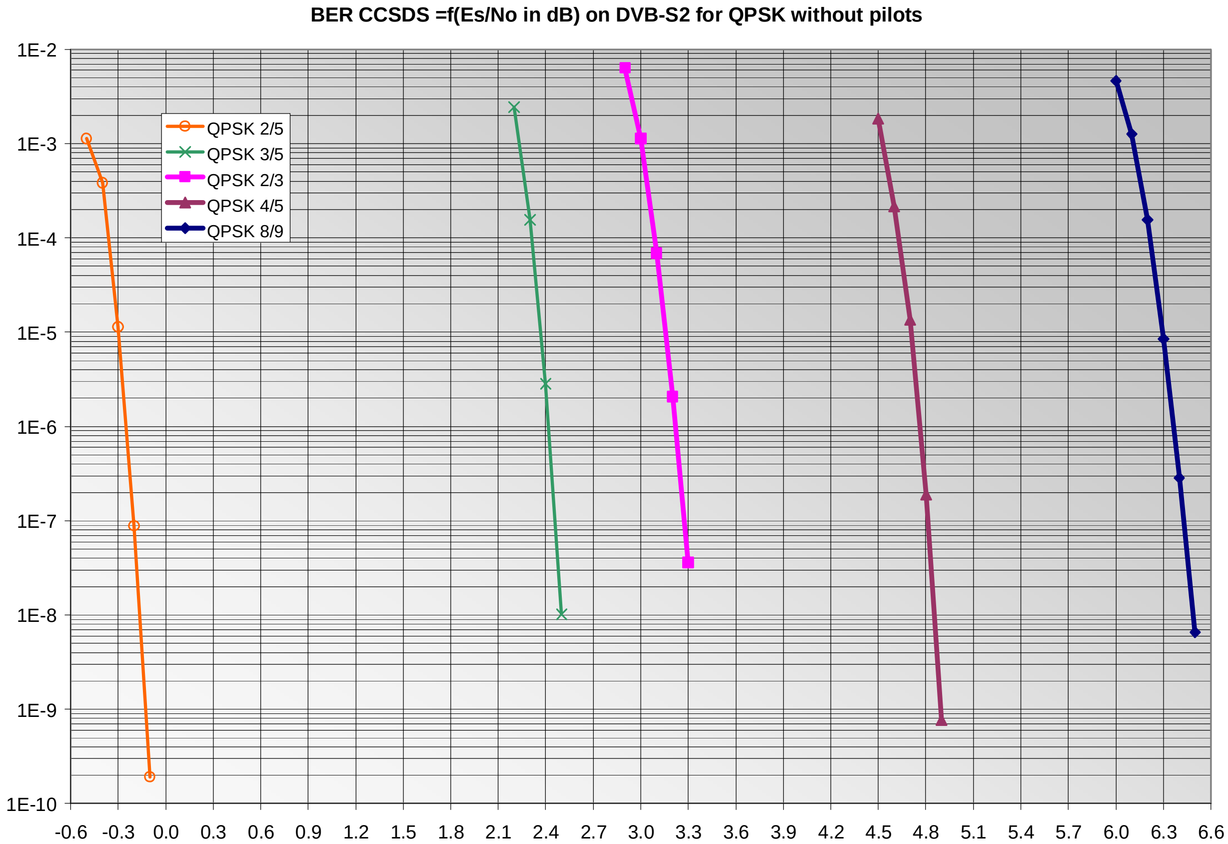
$\psi(x) = [\mathrm{sign}(x),-\log\{(\tanh(|x|/2)\}]$

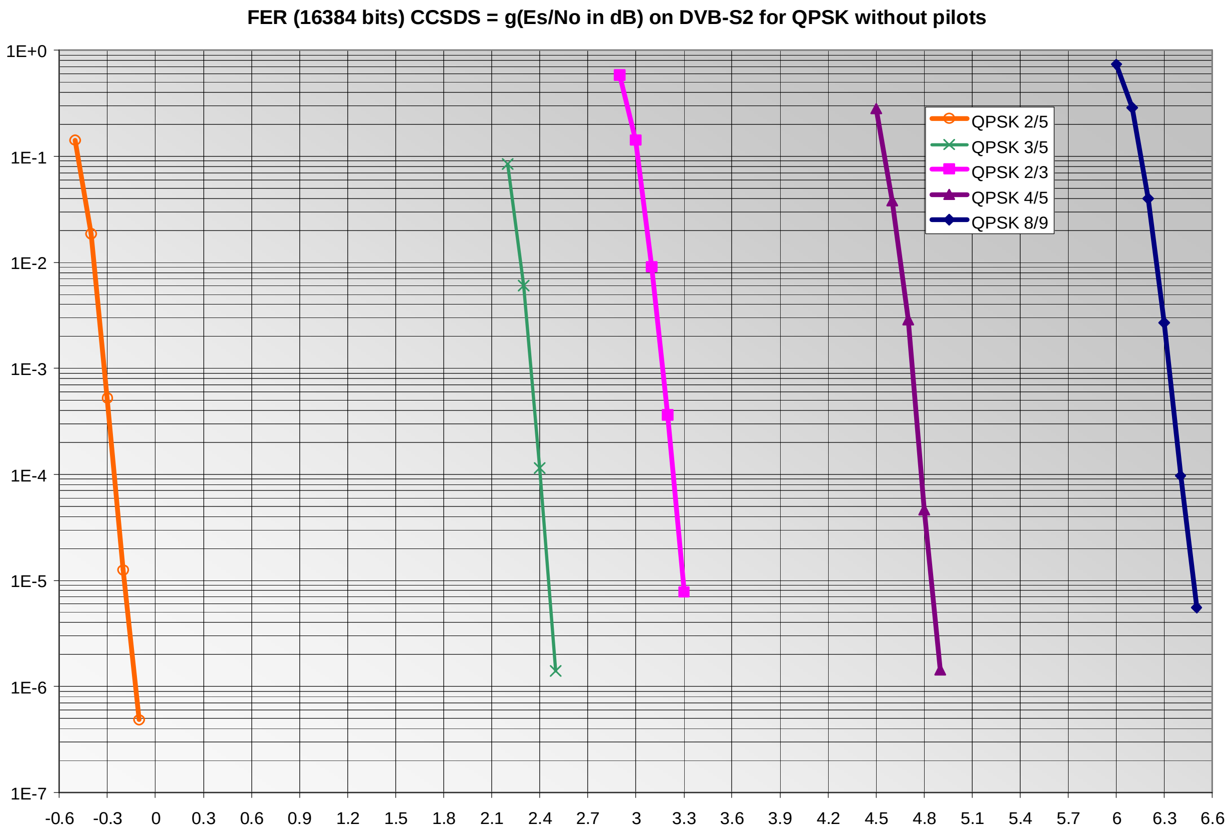
with $\psi(x) +\psi(y)= [\mathrm{sign}(xy),-\log\{(\tanh(|x|/2)\}-\log\{(\tanh(|y|/2)\}]$

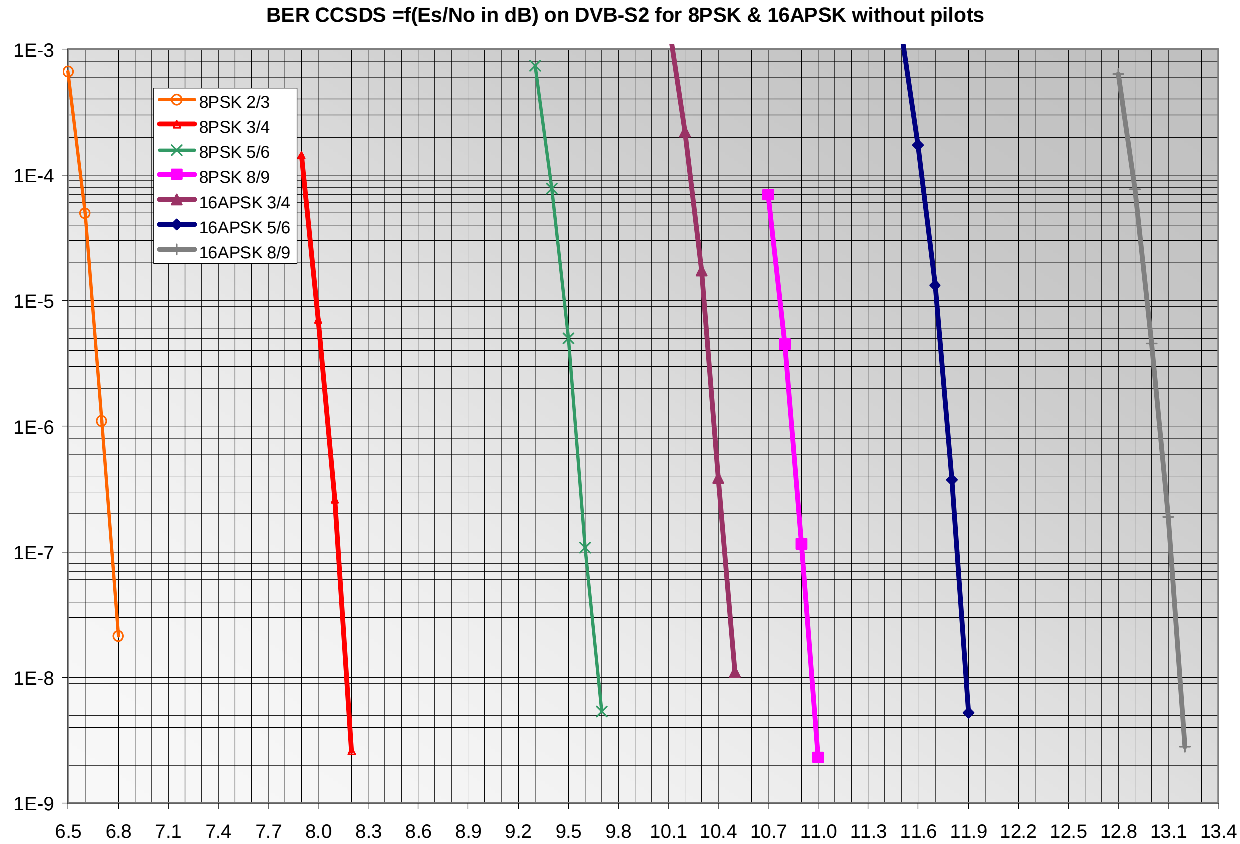
and $\psi^{-1}(b,x) =-b.\ \log\{(\tanh(|x|/2)\}$

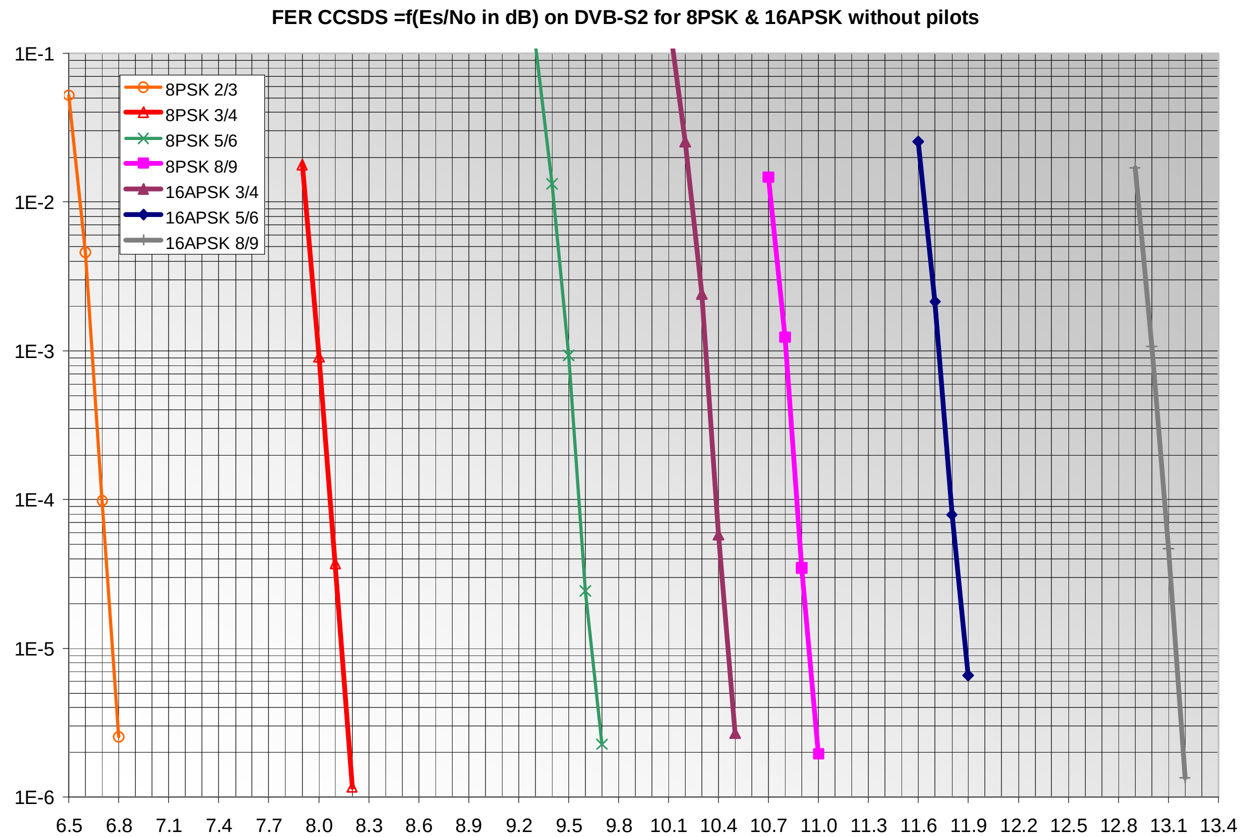
For the rate 8/9 code rate, we give some elements about the sensivity to the number of parallel processors (180 instead of 360) and with a simplification of the recursive computations. Those variations can allow some important gates gain for FPGA or ASIC implementations.

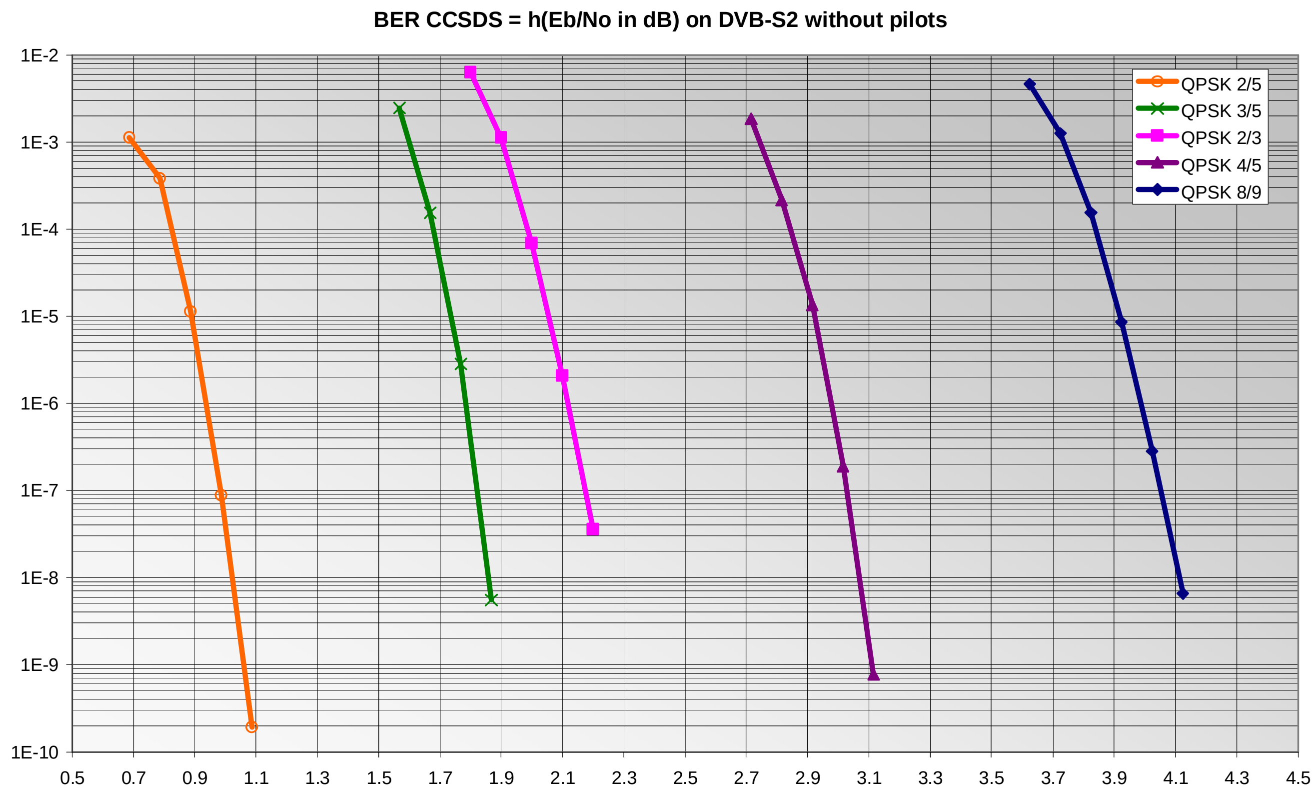
It should be also noticed that for BER less than 10^{-8}, the average number of iterations is always less than 6 to 10 (depending on code rate with an exception for rate 2/5 with around 16) and using only a maximum of 20 iterations doesn’t lead to a noticeable degradation of performance for around QEF transmissions.

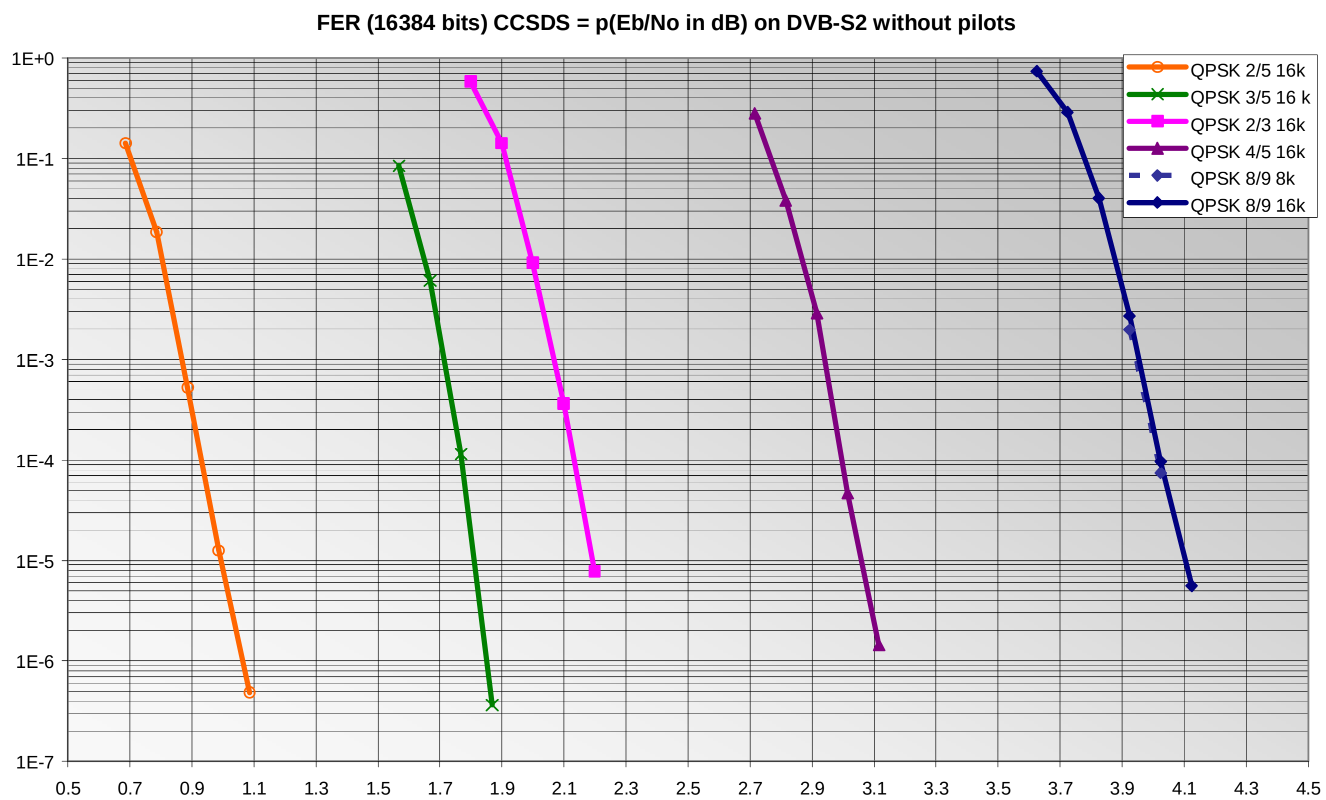

BER CCSDS =f(Es/No in dB) on DVB-S2 for QPSK without pilots
QPSK 2/5
QPSK 3/5
QPSK 2/3
QPSK 4/5
QPSK 8/9
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
-0.6 -0.3 0.0 0.3 0.6 0.9 1.2 1.5 1.8 2.1 2.4 2.7 3.0 3.3 3.6 3.9 4.2 4.5 4.8 5.1 5.4 5.7 6.0 6.3 6.6

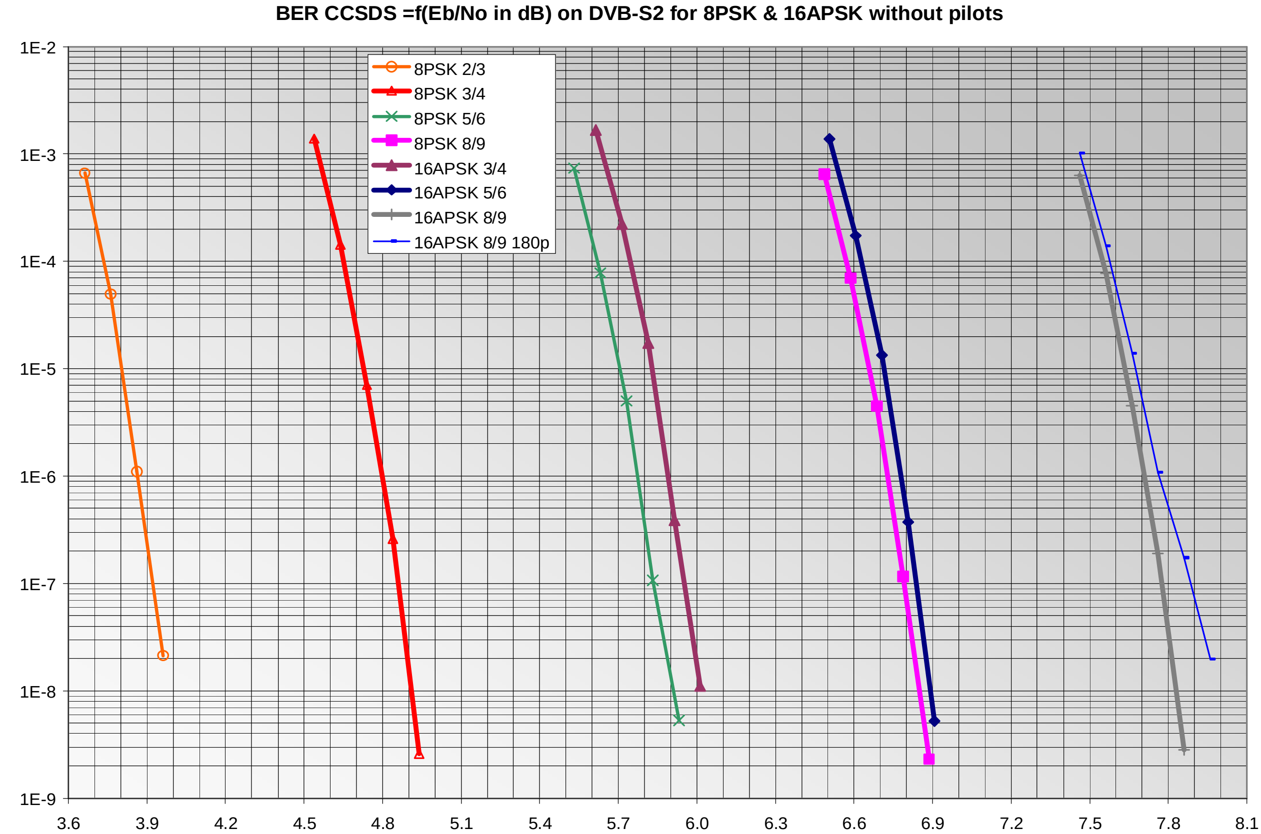

FER (16384 bits) CCSDS = g(Es/No in dB) on DVB-S2 for QPSK without pilots
QPSK 2/5
QPSK 3/5
QPSK 2/3
QPSK 4/5
QPSK 8/9
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
-0.6 -0.3 0 0.3 0.6 0.9 1.2 1.5 1.8 2.1 2.4 2.7 3 3.3 3.6 3.9 4.2 4.5 4.8 5.1 5.4 5.7 6 6.3 6.6


BER CCSDS =f(Es/No in dB) on DVB-S2 for 8PSK & 16APSK without pilots
8PSK 2/3
8PSK 3/4
8PSK 5/6
8PSK 8/9
16APSK 3/4
16APSK 5/6
16APSK 8/9
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
6.5 6.8 7.1 7.4 7.7 8.0 8.3 8.6 8.9 9.2 9.5 9.8 10.1 10.4 10.7 11.0 11.3 11.6 11.9 12.2 12.5 12.8 13.1 13.4


FER CCSDS =f(Es/No in dB) on DVB-S2 for 8PSK & 16APSK without pilots
8PSK 2/3
8PSK 3/4
8PSK 5/6
8PSK 8/9
16APSK 3/4
16APSK 5/6
16APSK 8/9
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
6.5 6.8 7.1 7.4 7.7 8.0 8.3 8.6 8.9 9.2 9.5 9.8 10.1 10.4 10.7 11.0 11.3 11.6 11.9 12.2 12.5 12.8 13.1 13.4


BER CCSDS = h(Eb/No in dB) on DVB-S2 without pilots
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
3.5
3.7
3.9
4.1
4.3
4.5
QPSK 2/5
QPSK 3/5
QPSK 2/3
QPSK 4/5
QPSK 8/9


FER (16384 bits) CCSDS = p(Eb/No in dB) on DVB-S2 without pilots
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
3.5
3.7
3.9
4.1
4.3
4.5
QPSK 2/5 16k
QPSK 3/5 16 k
QPSK 2/3 16k
QPSK 4/5 16k
QPSK 8/9 8k
QPSK 8/9 16k


BER CCSDS =f(Eb/No in dB) on DVB-S2 for 8PSK & 16APSK without pilots
8PSK 2/3
8PSK 3/4
8PSK 5/6
8PSK 8/9
16APSK 3/4
16APSK 5/6
16APSK 8/9
16APSK 8/9 180p
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
3.6
3.9
4.2
4.5
4.8
5.1
5.4
5.7
6.0
6.3
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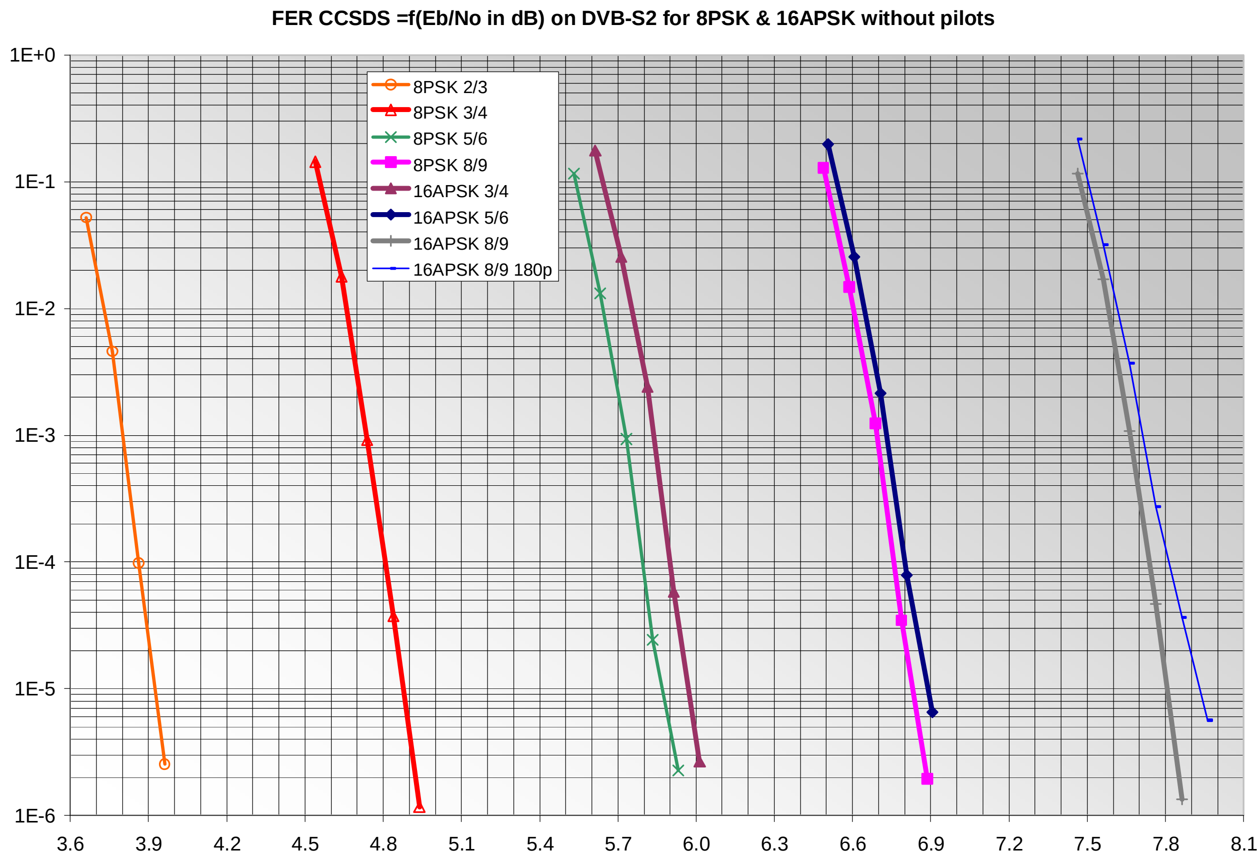
6.9
7.2
7.5
7.8
8.1


FER CCSDS =f(Eb/No in dB) on DVB-S2 for 8PSK & 16APSK without pilots
8PSK 2/3
8PSK 3/4
8PSK 5/6
8PSK 8/9
16APSK 3/4
16APSK 5/6
16APSK 8/9
16APSK 8/9 180p
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
3.6
3.9
4.2
4.5
4.8
5.1
5.4
5.7
6.0
6.3
6.6
6.9
7.2
7.5
7.8
8.1