ESA SPECIFICATION FOR TERABIT/S OPTICAL LINKS (ESTOL)

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CHANGE RECORD

Issue Number 1	Revision Number 0		
Reason for change	Date	Pages	Paragraph(s)
New document	19/07/2023	All	All
Issue Number 1	Revision Number 1		
Reason for change	Date	Pages	Paragraph(s)
Updated wavelength plan to include 1536,61 nm, for compatibility with existing developments: • ESTOL-PHY-110: updated wavelength plan. • New requirements added: ESTOL-PHY-120, ESTOL-PHY-130 and ESTOL-PHY-140. • ESTOL-PHY-160: updated formulation.	27/10/2023	16-18	
Updated control and management plane transport channel for 100Gbps+ to include dedicated wavelength and in data plane options. Improved formulations. • ESTOL-DLL-080: corrected OTU4 by ODU4. • ESTOL-DLL-100: updated formulation. • ESTOL-DLL-110: new requirement adding in-data plane CMP channel as an option. • ESTOL-DLL-120: new requirement adding a dedicated wavelength as an option.	27/10/2023	27-28	

Issue Number 2	Revision Number 0		
Reason for change	Date	Pages	Paragraph(s)
Include satellite-to-ground links. Updated introduction Added following requirements: • ESTOL-DLL-270 to ESTOL-DLL-390	17/01/2024	31-32	
Issue Number 2	Revision Number 1		
Reason for change	Date	Pages	Paragraph(s)
Updated irradiance sensitivity specification, affecting following requirements • ESTOL-PHY-300-340	22/03/2024	22-23	
Issue Number 2	Revision Number 2		
Reason for change	Date	Pages	Paragraph(s)
Updated introduction Added “Beacon” definition. Changed Quasi-error-free BER definition to 10^{-9} Updated PAT requirements including the tracking tone signal, affecting following requirements: • ESTOL-PHY-010 to ESTOL-PHY-160	26/07/2024	10-13 14 15 16-19 16-27	

• Updated numbering of PHY requirements Updated formulation ESTOL-PHY-270 Updated irradiance sensitivity values, affecting following requirements: • ESTOL-PHY-300 to ESTOL-PHY-350 Updated OSNR specification, affecting following requirements: • ESTOL-PHY-360 to ESTOL-PHY-410		23 23 24	
Issue Number 2	Revision Number	3	
Reason for change	Date	Pages	Paragraph(s)
Updates requirement labels	26/11/2024	16-end of document	
Added “Link Optimization and Telemetry (LOT)” definition. Updated CMP definition. Added LOT specification Update 10G OOK mode	11/04/2025		1.1 3.2.1 3.3.1 3.4.1
ESTOL-DLL-010 added a Note on user data rate specification ESTOL-DLL-080 changed ODU4 in OTU4	06/10/2025		
Issue Number 3	Revision Number	0	
Reason for change	Date	Pages	Paragraph(s)
Updated requirement labels and its definition	20/10/2025	All document	
Added Time diversity specification	21/10/2025	Section 3.6	
Added Annex A	21/10/2025	Annex A	
Added Annex B	21/10/2025	Annex B	
Added Annex C	21/10/2025	Annex C	
Added Annex D	21/10/2025	Annex D	
Issue Number 3	Revision Number	1	
Reason for change	Date	Pages	Paragraph(s)
Added Disclaimer and Waiver section	24/06/2026	p.23	
Updated numbering of ESTOL-OOK-2XXXX and ESTOL-OOK-LOT-2XXXX to ESTOL-OOK-4XXXX and ESTOL-OOK-LOT-4XXXX to follow the numbering convention	24/06/2026	p.45-51	
Updated ESTOL-HCO-LOT-00020 EtherType field set to mandatory to prevent undefined behaviour.	24/06/2026	p.38	
Updated ESTOL-HCO-LOT-00030 Added ESTOL-HCO-LOT-00035	24/06/2026	p.38	

Improved Ethernet encapsulation in LOT to ensure payload size is an integer number of octets.			
Updated Note-HCO-LOT-00060-1 Use of identifiers outside Table 5 is discouraged to avoid undefined behaviour.	24/06/2026	p.39	
Added Note-HCO-LOT-00070-1 Clarified the meaning of “on-request”	24/06/2026	p.39	
Updated Table 5 LOT codes and order changed to align them to corresponding SDA FCCH messages	24/06/2026	p.41	
Updated ESTOL-OOK-43020 and Figure 10 Clarified that payload, parity and CRC are 16320 bits	24/06/2026	p.47	
Added ESTOL-TDV-00075 Added ESTOL-TDV-00205 Clarified transmission order and serialization	24/06/2026	p.54, 55	
Removed content of section 3.6.2 Reserved for following issues	24/06/2026	p.54	
Updated Figure 17 1) Corrected ASM bytes (previous version incorrect). 2) Corrected bit/octet counter on the left.	24/06/2026	p.56	
Updated ESTOL-TDV-00230 Updated ESTOL-TDV-00240 Replaced invalid polynomial with a valid improved definition	24/06/2026	p.57	
Added Note-TDV-00360-2 New Ether type to avoid undefined behaviour	24/06/2026	p.64	
Updated ESTOL-TDV-00370 Updated Figure 28 Updated ESTOL-TDV-00390 Metadata is now placed at the end of the segment. Metadata is now optional.	24/06/2026	p.64-66	

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List of Contributors

The “ESA Specification for Terabit/s Optical Links (ESTOL)” is a specification document prepared by ESA in joint co-operation with multiple industrial contributors and researchers. The present issue of the document reflects the outcome and conclusions of the discussions among all parties that took place during the workshops organized by ESA since June 2022.

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- RNC (Directorate of Resilience, Navigation and Connectivity)
- OPS (Directorate of Operations)
- TEC (Directorate of Technology, Engineering & Quality)

Table of Acronyms

ASM	Attached Sync Marker
BEC	Binary Erasure Channels
BER	Bit Error Ratio
CCSDS	Consultative Committee for Space Data Systems
CER	Codeword Error Rate
CMP	Control and Management Plane
CRC	Cyclic Redundancy Check
DCO	Digital Coherent Optics
DP	Dual Polarization
DWDM	Dense Wavelength Division Multiplexing
EC	Erasure Code
ECDU	Erasure Code Data Unit
EDRS	European Data Relay System
ESA	European Space Agency
ESTOL	ESA Specification for Terabit/sec Optical Links
FEC	Forward Error Correction
GCC	General Communications Channel
GEO	Geostationary Orbit
HDR	Header
HydRON	High Throughput Optical Network
ID	Identification
IM/DD	Intensity Modulation Direct Detection
ITU	International Telecommunication Union
LDPC	Low Density Parity Check

LEO	Low Earth Orbit
LOT	Link Optimization and Telemetry
MEO	Medium Earth Orbit
ML	Maximum Likelihood
MSA	Multi-Source Agreement
NCG	Net Coding Gain
NR	New Radio
OCT	Optical Communications Terminal
oFEC	Open Forward Error Correction
OGS	Optical Ground Station
OGSL	Optical Ground to Space Link
OISL	Optical Inter Satellite Link
OOK	On-Off-Keying
OSI	Open Systems Interconnection
OTN	Optical Transport Network
PAT	Point Acquisition and Tracking
PDL	Polarization Dependent Loss
PMD	Polarization Mode Dispersion
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
ROADM	Reconfigurable Optical Add/Drop Multiplexer
RX	Receiver
SD	Soft Decision
SDA	Space Development Agency
SER	Symbol Error Rate

SOP	State Of Polarization
TX	Transmitter
UC	Uncertainty Cone
WDM	Wavelength Division Multiplexing

Summary of Figures

Summary of Tables

Reference documents

[RD 1]	ITU-T G.709/Y.1331, 06/2020	
[RD-2]	Space Development Agency (SDA), 9100-001-09 “Optical Communications Terminal (OCT),” Standard Version 4.0.0, 28/06/2024	Tranche 1 (T1) 9100-001-09 4.0.0
[RD-3]	Spectral grids for WDM applications DWDM frequency grid	ITU-T G.649.1 October 2020
[RD-4]	Flexible OTN long-reach interfaces	ITU-T G.709.3 December 2020
[RD-5]	OpenROADM MSA optical specifications (v9.0.0)	6th November 2025
[RD-6]	Optical high data rate (HDR) communication – 1064 nm	CCSDS 141.11-O-1
[RD-7]	Space Development Agency (SDA), SDA-9100-0001-03, Optical Intersatellite Link (OISL) Standard, Version 2.1.2, 3 January 2022.	Tranche 0 (T0), SDA-9100-0001-03
[RD-8]	3rd Generation Partnership Project (3GPP), TS 38.212 NR; Multiplexing and channel coding, 3GPP, version 16.5.0 Release 16, 2021.	
[RD-9]	TM Synchronization and Channel Coding. Issue 3. Recommendation for Space Data System Standards (Blue Book), CCSDS 131.0-B-3., Washington, D.C.: CCSDS, 2017.	
[RD-10]	Open ROADM MSA 5.0 W-Port Digital Specification (100G-400G)	1st July 2021
[RD-11]	CCSDS 131.5-O-1 Erasure Correcting Codes for use in Near-Earth and Deep-Space Communications, 2014.	November 2014
[RD-12]	OpenZR+ Specifications, v. 3.0	12th September 2023

1. INTRODUCTION

1.1. Background and objectives

The aim of future telecom satellites is to become part in terrestrial high-capacity networks in a seamless integrated manner, providing capabilities not available in purely terrestrial communication systems (e.g., large coverage, lower latency, cost advantage in sparsely populated regions, no geographical obstructions, etc.), rather than continuing the provision of services in an isolated way, or solely offering satellite bandwidth. Indeed, satellite communications play an important role in reaching areas that are not connected with fibre or wirelessly to mobile base stations, but satellite services are not yet an integral part of the terrestrial network architecture. Furthermore, satellites are also useful for distributing content from one source to multiple locations.

For that purpose, it is crucial to boost currently available capacity per satellite and network functionalities such as on-board switching capabilities, while considering satellite design constraints (i.e., mass, power consumption, volume, costs, operations complexity, etc.).

This entails the implementation of high data rate bidirectional space-space links (via high data rate optical inter-satellite links - OISLs), bidirectional space-ground links (via optical ground-to-satellite links OGSLs) and on-board processing capabilities (i.e., optical cross-connect, optical add & drop multiplexer) compatible with broadband switching operations. The interface transporting bidirectional traffic between the space segment and the terrestrial high-capacity network is realized via the optical ground segment. Such an implementation enables the space nodes to become just another type of network node and ultimately, both space and ground segments become an integral part of the overall terrestrial high-capacity transport network infrastructure.

The present document, ESTOL, is ESA's specification for high data rate (towards Terabit/s) optical links that allows European suppliers to become inter-operable when providing their equipment to broadband satellite constellations. ESTOL's first implementation and demonstration will be HydRON (High Throughput Optical Network), with the aim of fostering interoperability between network nodes (located in space or on ground) interconnected by means of high data rate optical links.

HydRON is the vision for a high throughput optical space network that will address and master the challenges of bringing connectivity to multiple users across different orbits and applications to showcase the capabilities of optical communication technology in end-to-end system implementations. The targeted capacity performance of HydRON is orders of magnitude greater compared to today's satcom systems (Tbit/s in contrast to Gbit/s), which has the potential to trigger a true revolution of applications, services and connectivity provided by satcom. In Figure 1, there is the representation of worldwide distributed ground nodes and space nodes in various Earth orbits (LEO, MEO, GEO) connected with OGSLs and optical inter-satellite links (OISLs).

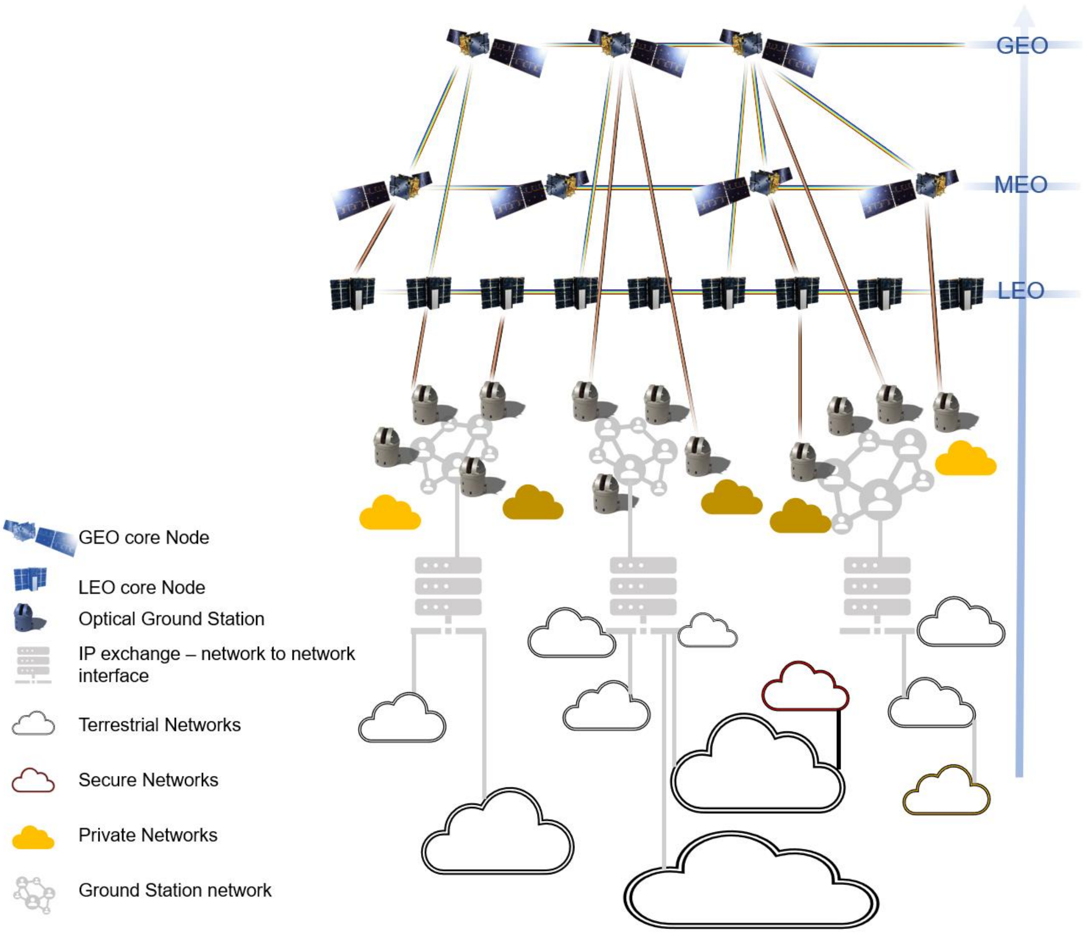

Figure 1. Vision of a high throughput optical space network bringing high data rate terrestrial connectivity to multiple space users across different orbits (e.g., LEO, MEO, GEO) and to ground users located in remote areas with no available broadband access.

Objectives of this air interface specification

The goal of this specification is to define a robust and versatile optical interface for optical inter-satellite links (OISLs) and optical ground to space links (OGSLs) between space nodes in various Earth orbits (LEO, MEO, GEO) and optical ground stations (OGSs) at very high data rates per individual wavelength and potentially exceeding 1 Tbit/s by means of multiple wavelengths (WDM) per link and direction.

***Scope** – Fostering multiple suppliers' availability and facilitating multi-vendor interoperability*

Scope of the document is to provide a technical specification of a Terabit/s air interface for OISLs to support interfaces standardization and then interoperability between elements provided by multiple manufacturers.

The specification targets:

- Physical layer requirements,
- Data Link layer requirements; including framing, synchronization and coding requirements.

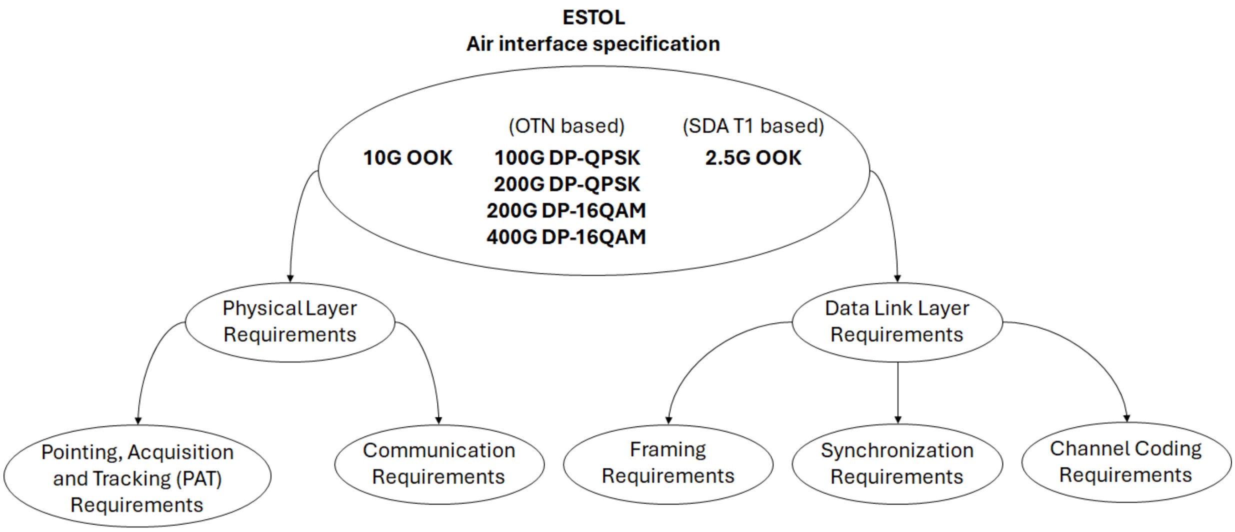

Figure 2. Air Interface specification contents

***Coherent roadmap** – Future upgradability*

This specification relies upon standards describing fibre-optic Digital Coherent Optics (DCO) transceivers and is intended to support currently available and future coherent modules. To support various baud rates a high granularity and flexibility in wavelength plan should be supported.

Backwards compatible – *With the baseline*

The specification allows for upgrading to next generations of coherent fibre-optic transceivers, as long as they are backwards compatible with the presented DP-QPSK 100Gbps baseline. Two terminals with *[400Gbps / λ]* capabilities can work at 400Gbps, but if one only supports 100Gbps, they will fall back to their highest commonly supported data rate, i.e., 100Gbps.

Business outlook – *Facilitating large networks of high data rate terminals*

High-capacity communications based on coherent technology is being employed in terrestrial fibre networks, where it became the common solution to reach Terabit/se communication links. The present air interface specification targets an extension of the terrestrial network toward space, by also exploiting fibre optical transceivers implementing terrestrial OTN standards (such as [RD-1] and [RD-5]). These units include the digital signal processing and the photonics in a single unit called Digital Coherent Optics (DCO) transceiver. Coherent technologies are also being standardized by CCSDS, and the space industry is investigating suitability of available components from terrestrial networks for space applications. First demonstrations have been already performed, and more are planned in the near future. Adoption of fibre-optics-based air interface guarantees interoperability for 100G+ future connections that allow to use technology developments of the fibre-communication market and paves the path to unprecedented high data rate satellite connections. Besides fibre-optics-based standards, the ESTOL specification includes also 10 Gbps solutions, as an intermediate step from EDRS data rates and 100+G data rates. This technology is tailored to medium data rates solutions for either low-cost or resource constraint missions. Thus, it targets supporting ongoing and future commercial activities on large-scale constellations, airborne terminals, high resolution Earth observation satellites and extensions of the optical backbone terrestrial network.

1.2. Definitions

Air Interface: Free space interface between satellite optical terminals or between satellite and ground optical terminals. The air interface specification should cover the elements as per Figure 1.

Beacon: Optical signal dedicated to acquisition purposes. It can be used by the optical ground station to reduce the acquisition time. The beacon provides an optical beam with a divergence large enough to cover the uncertainty cone.

Beacon-aided systems: Optical terminals using a dedicated laser for pointing, acquisition and tracking (PAT) purposes.

Beacon-less systems: Optical terminals using the communications signal for pointing, acquisition and tracking (PAT) purposes.

Control and management plane transport channel: A low data rate channel dedicated to providing any type of control and management plane data throughout the optical network (end-to-end).

Link optimization and telemetry channel (LOT): A low data rate channel dedicated to the exchange of link quality information between two direct-connected terminals, which could be used to optimize or characterize the performance of the optical link.

Isolation-band: Spectral separation between transmitter and receiver wavelength ranges to guarantee an isolation that minimizes crosstalk between them, to achieve bidirectional error-free communication.

openFEC (oFEC): a block-based encoder and iterative Soft Decision (SD) decoder. With 3 SD iterations the Net Coding Gain (NCG) is 11.1 dB for a BER @ 10^{-15} (DP-QPSK). The respective pre-FEC BER threshold corresponds to 2.0×10^{-2}.

Optical channel: Refers to a single wavelength employing one or two polarizations.

Optical ground-space links (OGSL): Optical ground-space links are links between optical terminals on ground and in space passing through the atmosphere.
Note: HAPs and UAVs are considered as ground terminals and hence they form an OGSL to the space nodes.

Optical inter-satellite links (OISL): Optical links between optical terminals located on different satellites passing only through vacuum.

Polarization dependent loss (PDL): the difference between the maximum and minimum values of the channel insertion loss (or gain), due to a variation of the State of Polarization (SOP) over all state of polarizations. Units: dB.

Mean polarization mode dispersion tolerance (mPMD): mean time difference tolerance between the fractions of an optical signal transmitted in the two principal states of polarization. The mPMD tolerance includes the maximum X-Y skew of the transmitter modem. Units: ps.

Quasi-error free: BER is assumed to be quasi-error free when it is below than 10^{-9}.

SOP changing rate: speed of rotation in Stokes space of the two polarizations of the optical signal. Units: krad/s.

1.3. Conventions

The following list describes the conventions followed by preparing the requirements in this specification:

- Firm requirements are specified by means of "*shall*".
- Optional (but desirable) requirements are specified by means of "*should*".
- Possibilities are specified by means of "*may*".
- All values defined in this document are specified end-of-life.
- Requirements can be normative text or enumerated requirements. Enumerated requirements are labelled according to the following descriptions:
    - PAT: Pointing, acquisition and tracking
    - WDM: wavelength plan and link characteristics
    - SIG: signal characteristics
    - HCO: "high" data rate coherent modes, including
        - 100G DP-QPSK, 200G DP-QPSK, 200G DP-16QAM, 400G DP-16QAM
    - OOK: on-off-keying modes
        - 2.5G OOK, 10G OOK
    - LOT: link optimization telemetry
    - TDV: time diversity coding for links crossing the atmosphere
- The requirement numbering is described in Table 1
    - Columns represent the different requirement categories, as defined previously:
    - Rows represent the different communication modes.
    - "Generic" means that the requirement is applicable to all cases.
        - For PAT, WDM, SIG it is applicable to all communications modes
        - For HCO and OOK it refers to all the modes that are defined respectively.
    - Adding a letter in front of the numbering, it indicates the applicability to space or ground:
        - SXXXX: requirement only applicable to the space terminal
        - GXXXX: requirement only applicable to the ground terminal
- Notes are written in Italic format and follow the numbering of the requirement, adding a hyphen, followed by a number.

Table 1. Relation between requirements numbering and communication modes

			PAT	WDM	SIG	HCO	HCO-LOT	OOK	OOK-LOT	TDV
Generic		00###	X	X	X	X	X			X
100G	DP-QPSK	31###			X	X				
200G	DP-QPSK	32###			X	X				
200G	DP-16QAM	33###			X	X				
400G	DP-16QAM	34###			X	X				
2.5G	OOK	41###			X			X	X	
10G	OOK	43###			X			X	X	

Examples:

- ESTOL-PAT-00XXX: requirement on the pointing, acquisition and tracking applicable to both ground and space terminal, for all air-interface modes.
- ESTOL-PAT-G00XXX: requirement on the pointing, acquisition and tracking applicable to the ground terminal, for all air-interface modes.

ESTOL-SIG-S31XXX: requirement on the signal characteristics, applicable to the space terminals, for the 100G DP-QPSK air interface mode.

1.4. Disclaimer and Waiver

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2. PHYSICAL LAYER REQUIREMENTS

2.1. Pointing, Acquisition, and Tracking (PAT)

Pointing, Acquisition and Tracking (PAT) has been defined in CCSDS Orange book 141.11-O-1 [RD-6] and demonstrated for inter-satellite links and satellite-to-ground links by TerraSar-X, NFIRE, Alphasat and EDRS. Moreover, PAT has been described in SDA standard "Optical Communications Terminal (OCT)" [RD-2] based on the definition proposed by [RD-6].

Two optical communication terminals require a 'spatial acquisition' sequence, to establish a communication link between them. This spatial acquisition process co-aligns the line-of-sight of both optical communication terminals.

The 'Uncertainty Cone' (UC) from one of the terminals is defined by the error in the knowledge of the pointing direction to the counter-terminal. This error is typically in the order of few milliradians. The definition of the parameters influencing the UC can be found in [RD-6]. The relationship between the beam divergence and the UC defines the approach in the spatial acquisition procedure.

- Open-loop pointing can be performed for beam divergence larger than the UC. This approach is usually implemented by beacon-aided systems.
- Spiral-scanning shall be performed for beam divergence smaller than the UC. This case is mainly performed by beacon-less systems, which use the communication beam also for the acquisition and tracking purposes.

In the rest of this subsection, the requirements for the PAT system are listed. They are based on the SDA standard [RD-2]. The requirements below amend, complement, or replace the ones defined in [RD-2].

ESTOL-PAT-00010 The pointing, acquisition and tracking (PAT) shall comply with the description provided by [RD-2] in section 2.1.3 and 2.1.4

Note-PAT-00010-1: The process from the SDA standard is selected as baseline, with the modifications defined by the following requirements.

ESTOL-PAT-00020 The acquisition scan shall be reconfigurable to guarantee that the illumination duration of the receiver acquisition sensor can be set between 80 μs and 150 μs, for each hit-event.

ESTOL-PAT-00030 The PAT acquisition time (defined as warm start in 2.1.6 of [RD-2]) shall be below 60 s, within the uncertainty cone.

ESTOL-PAT-00040 The PAT acquisition time (defined as warm start in 2.1.6 of [RD-2]) should be below 30 s, within the uncertainty cone.

ESTOL-PAT-00050 The PAT re-acquisition time shall be below 10s.
Note: the re-acquisition time is defined as the time from fine acquisition to tracking.

ESTOL-PAT-00060 In case of link loss prior to the commanded link end-time, automatic link re-acquisition shall be performed until the end of the scheduled link duration.

ESTOL-PAT-00070 The transmitter shall be capable of providing a sinusoidal amplitude modulated signal, defined as “tracking tone” for acquisition and tracking purposes.

ESTOL-PAT-00080 The tracking tone shall be either implemented in the L1/U1 channels or embedded with the communication signal(s) in case L1/U1 are not used.

ESTOL-PAT-00090 The tracking tone shall be settable for TX and RX at 40 and 50 kHz.

ESTOL-PAT-00100 Additionally, the tracking tone should be settable for TX and RX at 60 and 70 kHz.

ESTOL-PAT-00110 The deviation of the nominal tracking tone frequency from nominal shall be less than 1000 ppm.

ESTOL-PAT-00120 The modulation index of the sinusoidal tracking tone shall be settable at least between 0% (modulation off), 10%, 20% and 80%, taking as reference the optical transmitted power in the channel where the tracking tone is implemented.

Note-PAT-00120-1: the nominal tracking tone modulation index (MI) is defined as $MI = \frac{P_{max}-P_{min}}{P_{max}+P_{min}}$, *with* P_{max}, P_{min}, *defined as in Figure 3.*

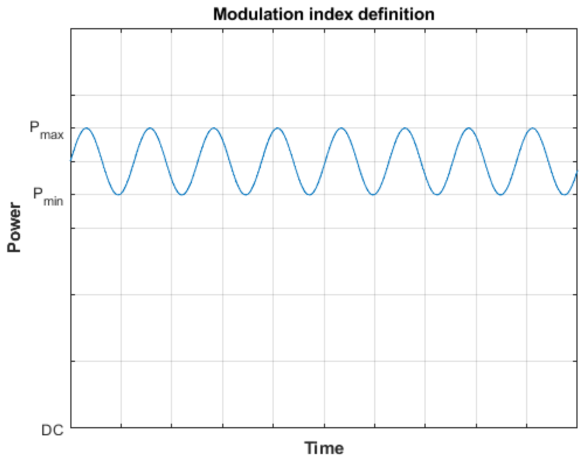


Figure 3. Modulation index definition

ESTOL-PAT-00130 The error in the modulation index shall be not greater than 20% of the setting value.

ESTOL-PAT-00140 The mean power of the modulated signal fraction (MMSF) into the receiver's aperture shall be at least -40 dBm.

Note-PAT-00140-1: This value includes already 3 dB margin.

Note-PAT-00140-2: The mean of the modulated signal fraction (MMSF) is defined as $MMSF = \frac{P_{max}-P_{min}}{2}$, *with* P_{max}, P_{min}, *defined as in Figure 3. The values shall be taken for the nominal frequency after passing through an ideal filter with a bandwidth of less than 1000 ppm of the nominal frequency, i.e. shall not include overtone(s) or signal distortions.*

ESTOL-PAT-G0150 In case a beacon signal is implemented for acquisition purposes, it shall be capable of providing a tracking tone as defined previously.

ESTOL-PAT-G0160 In case a beacon signal is implemented for acquisition purposes, it shall be in-band and make use of L1/U1, or (one of) the same wavelength(s) used for communications purposes.

2.2. WDM requirements

Wavelength Division Multiplexing (WDM) is a technique developed in fibre-optic communications, to enable the use of multiple wavelengths over the same optical fibre. Multiple high-bit-rate data streams can be multiplexed together, for instance 2.5 Gbps up to 400 Gbps. This technique allows increasing the data throughput by making use of the whole available optical spectrum. The ITU-T G.649.1 [RD-3] defines the centre frequencies of the multiple optical channels for different channel spacing. WDM is considered also in free-space communications, to increase the data throughput in optical links. The definition of the centre frequencies in this specification follows [RD-3].

Table 2. Frequency channel grid.

Channel ID	ITU channel	Centre frequency (THz)	Wavelength (nm)	Channel ID	ITU channel	Centre frequency (THz)	Wavelength (nm)
U1	20	195.1	1536,61	**L1**	-1	193.0	1553.33
U2	19	195.0	1537,4	**L2**	-2	192.9	1554.13
U3	18	194.9	1538,19	**L3**	-3	192.8	1554,94
U4	17	194.8	1538,98	**L4**	-4	192.7	1555,75
U5	16	194.7	1539,77	**L5**	-5	192.6	1556.55
U6	15	194.6	1540,56	**L6**	-6	192.5	1557.36
U7	14	194.5	1541.35	**L7**	-7	192.4	1558.17
U8	13	194.4	1542.14	**L8**	-8	192.3	1558.98
U9	12	194.3	1542.94	**L9**	-9	192.2	1559.79
U10	11	194.2	1543.73	**L10**	-10	192.1	1560.61
U11	10	194.1	1544.53	**L11**	-11	192.0	1561.42
U12	9	194.0	1545.32	**L12**	-12	191.9	1562.23
U13	8	193.9	1546.12	**L13**	-13	191.8	1563.05
U14	7	193.8	1546.92	**L14**	-14	191.7	1563.86
U15	6	193.7	1547.72	**L15**	-15	191.6	1564.68
U16	5	193.6	1548.51	**L16**	-16	191.5	1565.50
U17	4	193.5	1549.32	**L17**	-17	191.4	1566.31
U18	3	193.4	1550.12	**L18**	-18	191.3	1567.13
U19	2	193.3	1550.92	**L19**	-19	191.2	1567.95
U20	1	193.2	1551.72	**L20**	-20	191.1	1568,77
U21	0	193.1	1552.52	**L21**	-21	191.0	1569,59

ESTOL-WDM-00170 Communications shall take place in the optical Super C-band.

ESTOL-WDM-00180: The frequency channel grid shall use nominal central frequencies for DWDM as defined in Table 2 and Figure 4.

Frequency	195,10	195,00	194,90	194,80	194,70	194,60	194,50	194,40	194,30	194,20	194,10	194,00	193,90	193,80	193,70	193,60	193,50	193,40	193,30	193,20	193,10
ITU channel #	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Wavelength	1536,61	1537,40	1538,19	1538,98	1539,77	1540,56	1541,35	1542,14	1542,94	1543,73	1544,53	1545,32	1546,12	1546,92	1547,72	1548,51	1549,32	1550,12	1550,92	1551,72	1552,52
ESTOL #	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	U18	U19	U20	U21

Frequency	193,00	192,90	192,80	192,70	192,60	192,50	192,40	192,30	192,20	192,10	192,00	191,90	191,80	191,70	191,60	191,50	191,40	191,30	191,20	191,10	191,00
ITU channel #	-1	-2	-3	-4	-5	-6	-7	-8	-9	-10	-11	-12	-13	-14	-15	-16	-17	-18	-19	-20	-21
Wavelength	1553,33	1554,13	1554,94	1555,75	1556,55	1557,36	1558,17	1558,98	1559,79	1560,61	1561,42	1562,23	1563,05	1563,86	1564,68	1565,50	1566,31	1567,13	1567,95	1568,77	1569,59
ESTOL #	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20	L21

Figure 4. ESTOL Wavelength plan

ESTOL-WDM-00190 Channels U1 and L1 (highlighted in Table 1 and Figure 4) shall be reserved for OOK IM/DD.

Note-WDM-00190-1: 2.5Gbps and 10Gbps OOK shall be allocated starting in U1/L1.

ESTOL-WDM-00200 Coherent modulation data channels shall be allocated into the channels U2-21 and L2-L21 starting in U2/L2.

Note-WDM-00200-1: 100Gbps-400Gbps shall be allocated starting in U2/L2.

Note-WDM-00200-2: in WDM systems, the typical channel bandwidth at -1dB is in the order of 40GHz.

ESTOL-WDM-00210 Multiple WDM channels shall be allocated in consecutive increasing ESTOL channel numbers.

Note-WDM-00210-1: as matter of example:

- *4 WDM channels at 100Gbps DP-QPSK will be allocated in channels U2, U3, U4, U5 and channels L2, L3, L4, L5*
- *3 WDM channels at 2.5Gbps OOK will be allocated in channels U1, U2, U3 and channels L1, L2, L3*
- *3 WDM channels, 1 channel at 2.5Gbps OOK and 2 channels at 100Gbps will be allocated as follows:*
    - *U1 and L1 will be assigned to 2.5Gbps*
    - *U2, U3 and L2, L3 will be assigned to 100Gbps channels.*

Note-WDM-00210-2: by assigning consecutive channels, compatibility between terminals can be guaranteed, even if they do not implement the same number of channels.

ESTOL-WDM-00220 Bidirectionality of optical links: All optical links shall be bidirectional (either symmetric or asymmetric in terms of user data rate).

Note-WDM-00220-1: the rationale is that this requirement shall ensure that parameters affecting the quality can be shared over the optical link, e.g., to adjust power level, tracking performance, wavelength offsets etc.

ESTOL-WDM-00230: The isolation between transmitted and received signals shall be based on spectral separation, assigning to each signal one of the bands (upper or lower) as defined in Table 2 and ESTOL-WDM-XXXXX requirements.

Note-WDM-00230-1: The band assignment shall be mirrored at the counter-terminal to allow for communication. E.g. TX1 (Upper-band) / RX1 (Lower-band) <<>>TX2 (Lower-band) / RX2 (Upper-band).

Note-WDM-00230-2: the isolation band between both beam directions will limit the maximum number of possible WDM channels that can be implemented. Typically, the isolation bandwidth can be in the order of 10nm.

2.3. Transmitted optical signal requirements

The transmitted optical signal requirements here below refer to the optical modulation schemes (modulation formats and symbol rates), the minimum power densities to enable acquisition, tracking and communication as well as Doppler shift and rate tolerances.

The considered modulations schemes are: Dual-Polarization Quadrature Phase Shift Keying (DP-QPSK), Dual-Polarization 16-ary Quadrature Amplitude Modulation (DP-16QAM), On-Off Keying (OOK). The former two modulation schemes, DP-QPSK and DP-16QAM, require coherent detection and make use of both orthogonal polarizations (i.e., polarization-multiplexed transmission) of the signal as symbol decisions are made using the in-phase (I) and quadrature (Q) signals encoded in the two orthogonally polarized fields. The latter, OOK modulation scheme, is based on a simple intensity modulation / direct-detection implementation.

2.3.1. Modulation scheme and transmitted signal properties

ESTOL-SIG-00240 The air interfaces shall employ one or more of the following modulation and detection schemes:

- DP-QPSK with coherent detection.
- DP-16QAM with coherent detection
- OOK with direct detection

ESTOL-SIG-00250 The symbol rates for each modulation shall be chosen among the ones included in the Table 3, below these lines.

Table 3. Symbol rates for each communication mode

Type of detection scheme	Type of modulation scheme	Symbol rate (per polarisation if applicable)
Coherent	DP-QPSK	31.5 Gbaud or 62 Gbaud [RD-5]
Coherent	DP-16QAM	31.5 Gbaud or 62 Gbaud [RD-5]
IM/DD	OOK	2.5Gbaud or 11.3 Gbaud

ESTOL-SIG-00260 The optical terminals shall accommodate any range effect (e.g. Doppler, clock frequency variation etc..) in the optical link.

Note-SIG-00260-1: Typical HCO receiver may tolerate up to 20 ppm [RD-5] of residual clock frequency variation.

2.3.2. Signal power

ESTOL-SIG-00270 The optical terminal shall provide tuneable optical transmit power. The optical power out of the terminal shall be either off or settable in steps of less than 3 dB with a minimum increment of 100 mW.

ESTOL-SIG-00280 The irradiance delivered to the receive aperture of the optical head unit should allow configuration at the source of the transmit signal during an active link for optimization of the link performance.

Note-SIG-00280-1: The irradiance delivered by a transmit aperture should be configurable by software operating the source transmit signal. This imposes the need for a "power meter" in the design and the definition of communication channels between the link parties accordingly.

ESTOL-SIG-00290 Output power tolerance: the actual output power should be within 20% tolerance of the set power value.

ESTOL-SIG-XXX340-XXX390 For each WDM channel, the minimum mean irradiance I_{RX} delivered at the entrance of the receiver aperture of the optical head unit shall be larger than the value specified by the following formula: $I_{RX} = 4\frac{P_{RX}}{\pi D_{RX}^2}$, where D_{RX} is the receiver aperture diameter and P_{RX} is the total collected power at the entrance of the optical system. P_{RX} is specified in Table 4 as follows:

Table 4. Total collected power at the entrance of the optical system.

	Space terminal		Ground terminal	
Modulation	**ID**	P_{RX}	**ID**	P_{RX}
DP-QPSK 100 Gbps	**ESTOL-SIG-S31340**	-31.7 dBm	**ESTOL-SIG-G31340**	-23.7 dBm
DP-QPSK 200 Gbps	**ESTOL-SIG-S32350**	-26.7 dBm	**ESTOL-SIG-G32350**	-18.7 dBm
DP-16QAM 200 Gbps	**ESTOL-SIG-S33360**	-23.2 dBm	**ESTOL-SIG-G33360**	-15.2 dBm
DP-16QAM 400 Gbps	**ESTOL-SIG-S34370**	-19.7 dBm	**ESTOL-SIG-G34370**	-11.7 dBm
IM/DD-OOK 2.5 Gbps	**ESTOL-SIG-S41380**	-36.4 dBm	**ESTOL-SIG-G41380**	-28.4 dBm
IM/DD-OOK 10 Gbps	**ESTOL-SIG-S43390**	-30.0 dBm	**ESTOL-SIG-G43390**	-22.0 dBm

Note-SIG-XXX340-XXX390-1: the P_{RX} values represent the total collected power by the terminal aperture and they are independent of the aperture diameter.

Note-SIG-XXX340-XXX390-2: the P_{RX} values specified in the table above include a system margin of 3 dB.

Note-SIG-XXX340-XXX390-3: the total collected power P_{RX} includes the required signal level for both communications, as well as acquisition and tracking system.

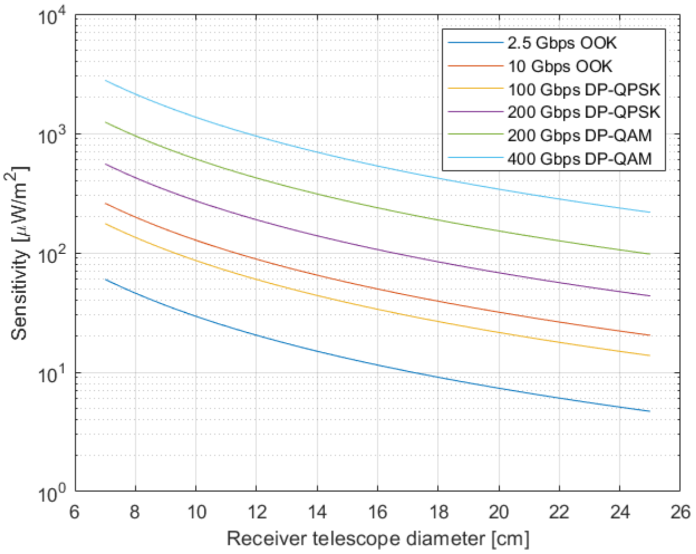
Note-SIG-XXX340-XXX390-4: the satellite terminal values are equivalent of a free-space link, i.e. no atmospheric effects have been included.

Note-SIG-XXX340-XXX390-5: the ground terminal values include additional 8 dB, which has been estimated reasonable for optical ground stations receivers at low elevation angles. This value considers additional optical and coupling losses, to account for (e.g.) reduced mean coupling efficiency. The link availability needs to be computed depending on the scenario and expected turbulence conditions.

Note-SIG-XXX340-XXX390-6: the sensitivity values assume a post-FEC quasi-error-free communication.

Note-SIG-XXX340-XXX390-7: following information shall be provided to guarantee a compatibility among terminals: maximum transmit power, transmit divergence and terminal aperture diameter(s).

Note-SIG-XXX340-XXX390-8: the left plot in Figure 5 shows the irradiance requirements at the receiver aperture, depending on the aperture diameter for each modulation. On the right, as example the table provides the sensitivity irradiance requirements for a 10 cm diameter receiver aperture, including the above-mentioned margin.



Modulation	Irradiance
DP-QPSK 100 Gbps	84 μW/m^2
DP-QPSK 200 Gbps	267 μW/m^2
DP-16QAM 200 Gbps	598 μW/m^2
DP-16QAM 400 Gbps	1340 μW/m^2
IM/DD-OOK 2.5 Gbps	30 μW/m^2
IM/DD-OOK 10 Gbps	125 μW/m^2

Figure 5. Left: Sensitivity at the receiver aperture depending on the receiver aperture diameter and the modulation data-rates. Right: exemplary irradiance values for a 10cm aperture diameter.

ESTOL-SIG-XX440-XX490 The minimum in-band optical signal-to-(noise + interference) ratio (i.e., optical S/(N+I)) at the receiver aperture of the optical head unit shall be larger than the values specified in the following tables for the corresponding modulation schemes.

Requirement	Modulation	Optical S/(N+I)
ESTOL-SIG-31440	DP-QPSK 100 Gbps	20 dB
ESTOL-SIG-32450	DP-QPSK 200 Gbps	25 dB
ESTOL-SIG-33460	DP-16QAM 200 Gbps	28.5 dB
ESTOL-SIG-34470	DP-16QAM 400 Gbps	32 dB
ESTOL-SIG-41480	IM/DD-OOK 2.5G	12 dB
ESTOL-SIG-43490	IM/DD-OOK 10G	15 dB

Note-SIG-XXX440-XXX490-1: the specification defines the minimum optical S/(N+I) to be guaranteed by the transmitter at the transmitter aperture, available for acquisition, tracking and communications.

Note-SIG-XXX440-XXX490-2: state-of-art COTS coherent transceivers for terrestrial communications provide output optical signals with an OSNR of 37 dB, as specified in the Open ROADM multi-source agreement [RD-5]. The OSNR values in the table above represent the minimum OSNR needed at the transmitter aperture, to guarantee communication at the

receiver, assuming that the main source of noise is provided by an optical pre-amplifier. From these values, the minimum required optical power values (ESTOL-SIG-XXX340 to ESTOL-SIG-XXX390) were calculated.
Note-SIG-XXX440-XXX490-3: the OSNR values are referenced to an optical noise bandwidth of 0.1 nm at 193.7 THz, or 12.5 GHz.

ESTOL-SIG-XX550-XX570 When the change in SOP is equal to or less than 1 rad/ms, the tolerance to peak PDL at the receiver aperture of the optical head unit for coherent systems shall be,

Requirement	Mode	Maximum peak PDL
ESTOL-SIG-31550	100G DP-QPSK	< 1.5 dB
ESTOL-SIG-32560	200G DP-QPSK	< 1.5 dB
ESTOL-SIG-33570	200G DP-16QAM	< 1.5 dB
ESTOL-SIG-34570	400G DP-16QAM	< 1.5 dB

Note-SIG-XX550-XX570-1: the specified tolerance to peak PDL at the receiving aperture allows an allocation of an additional 1.5 dB of peak PDL to cover imperfections in the receiver optical chain between the terminal aperture and the transceiver itself.

ESTOL-SIG-XX620-XX650 The maximum mPMD when the change in SOP is equal to or less than 1 rad/ms at the receiver aperture of the optical head unit shall be lower than,

Requirement	Mode	Maximum average PMD
ESTOL-SIG-31620	100G DP-QPSK	15 ps
ESTOL-SIG-32630	200G DP-QPSK	12.5 ps
ESTOL-SIG-33640	200G DP-16QAM	15 ps
ESTOL-SIG-34650	400G DP-16QAM	10 ps

Note-SIG-XX620-XX650-1: the mPMD tolerance includes the maximum X-Y skew or the transmitter modem.
Note-SIG-XX620-XX650-2: the specified mPMD tolerances at the receiving aperture allow an allocation of up to one time more mPMD (for each mode) to cover imperfections in the receiver optical chain between the terminal aperture and the transceiver itself.

ESTOL-SIG-XX700-XX730 The maximum changing rate in SOP over all PMD and PDL values at the receiver aperture of the optical head unit shall be less than,

Requirement	Mode	Maximum SOP change rate
ESTOL-SIG-31700	100G DP-QPSK	25 krad/s
ESTOL-SIG-32710	200G DP-QPSK	25 krad/s
ESTOL-SIG-33720	200G DP-16QAM	25 krad/s
ESTOL-SIG-34730	400G DP-16QAM	25 krad/s

Note-SIG-XX700-XX730-1: the specified maximum SOP change rates are understood as tolerance capabilities of the optical transceivers. During fade events in satellite-ground links the SOP change at the atmospheric turbulence timescale is expected to be much smaller.
Note-SIG-XX700-XX730-2: the specified maximum SOP change rates at the receiving aperture allow an allocation of an additional 25 krad/s SOP change rates to cover imperfections in the receiver optical chain between the terminal *aperture and the transceiver itself.*

3. DATA LINK LAYER REQUIREMENTS

The Data Link layer (i.e., Synchronization and Channel Coding layer), which corresponds to the "lower" part of the OSI Model's Layer 2, defines the tools necessary to permit error-corrected transmission (e.g., Forward Error Correction (FEC), scrambling, and line codes) as well as the structure of the data (e.g., framing). This layer will rely mostly on existing terrestrial standards (such as the OpenROADM v.5.1 specification [RD-5]) and other space-based standards (SDA T1 [RD-2], [RD-7]). In particular,

- the 100G, 200G and 400G coherent air interfaces rely on OpenROADM for both the framing structure and the FEC.
- the 2.5G IM/DD OOK air interface relies on the SDA Tranche 1 for both the framing structure and the FEC (5G NR FEC).
- the 10G IM/DD OOK air interface relies on the SDA Tranche 1 for the framing and partially on the SDA Tranche 0 for the FEC (Reed-Solomon).

3.1. (Reserved for following issues)

3.2. (Reserved for following issues)

3.3. High data-rate coherent modes: 100G, 200G and 400G

3.3.1. User data rates

ESTOL-HCO-3X010 The air interface shall offer the user data rates per wavelength at the respective symbol rate, as specified in the table below.

Requirement	User net data rate (upper bound)	Air interface	Symbol rate
ESTOL-HCO-31010	99.5328 Gbps	100G DP-QPSK	31.5 Gbaud
ESTOL-HCO-32010	2 x 99.5328 Gbps	200G DP-QPSK	62 Gbaud
ESTOL-HCO-33010	2 x 99.5328 Gbps	200G DP-16QAM	31.5 Gbaud
ESTOL-HCO-34010	4 x 99.5328 Gbps	400G DP-16QAM	62 Gbaud

3.3.2. Framing

ESTOL-HCO-30020 The high data-rate coherent modes air interfaces shall implement OpenROADM v.5.1 specification [RD-5].

Note-HCO-30020-1: The FlexO (100G) frame structure is defined in G.709.1 and copied in Figure 6 for reference. FlexO is a block format of 5140-bit columns × 128 rows and encapsulates client signals defined in ESTOL-HCO-3X03X. Alignment Markers (AM), Padding (PAD) and OverHead (OH) are inserted in the first row of each FlexO frame. FlexO frames are adapted into oFEC input blocks prior to oFEC encoding.

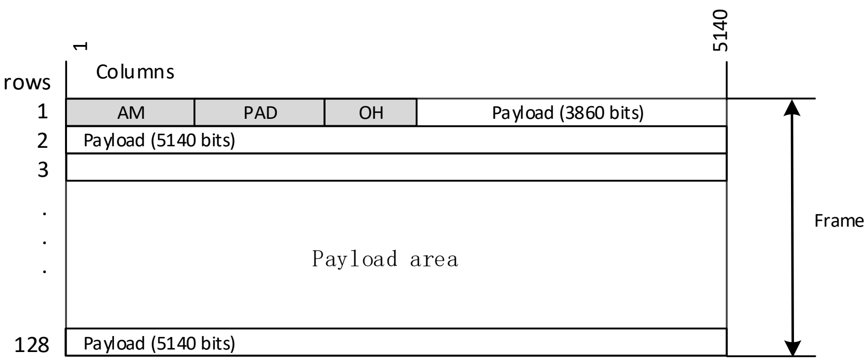


Figure 6. FlexO frame structure.

ESTOL-HCO-3X03X The air-interface shall support the client format signals specified in the following table:

Air-interface	REQ. ID	Client formats
100G DP-QPSK	**ESTOL-HCO-31030**	100GbE
100G DP-QPSK	**ESTOL-HCO-31031**	OTUC1
100G DP-QPSK	**ESTOL-HCO-31032**	OTU4
200G DP-QPSK	**ESTOL-HCO-32030**	200bE
200G DP-QPSK	**ESTOL-HCO-32031**	OTUC2
200G DP-16QAM	**ESTOL-HCO-33030**	200bE
200G DP-16QAM	**ESTOL-HCO-33031**	OTUC2
400G DP-16QAM	**ESTOL-HCO-34030**	400bE
400G DP-16QAM	**ESTOL-HCO-34031**	OTUC3

ESTOL-HCO-LOT-00010 The Link Optimization and Telemetry (LOT) logical channel shall be mapped into Ethernet frames compliant with IEEE 802.3 (10 MbE) and multiplexed over the GCC0 channel.
Note-HCO-LOT-00010-1: This enables the multiplexed transmission of other Ethernet/IP-based traffic (e.g., control and management plane data).

ESTOL-HCO-LOT-00020 Ethernet frames encapsulating LOT messages shall have a EtherType equal to 0x88B5.
Note-HCO-LOT-00020-1: LOT traffic is intended to be generated and consumed in the local communication between LCTs

ESTOL-HCO-LOT-00030 Payload of Ethernet frames encapsulating LOT messages shall start with an unsigned 64-bit long timestamp of the frame egress time.
Note-HCO-LOT-00030-1: The timestamp encodes Unix time with 1 microsecond per tic.

ESTOL-HCO-LOT-00035 *Multiple LOT messages may be encapsulated and transported over a single Ethernet payload, as depicted in Figure 7.*
Note-HCO-LOT-00035-1: When multiple (n) LOT messages are encapsulated within a single Ethernet payload, zero padding bits (zp) shall be added to ensure that the total LOT message length is an integer number of octets, i.e.: $(64 + n \cdot 22 + zp\ ) mod\ 8\ =\ 0$

Note-HCO-LOT-00035-2: The number of LOT messages (n) may be greater than or equal to 1. When multiple LOT messages are encapsulated within a single Ethernet payload, the number of messages (n) and the associated zero padding (zp) shall be selected such that the Ethernet MTU size does not exceed 1500 bytes.

64b	$n \times 22b$	zp_{bits}
TIMESTAMP	LOT MSGs	ZERO PADDING

$$zp_{bits} = \left(8 - (n \cdot 22\, mod\, 8)\right) mod\ 8$$

$$64 + n \times 22 + zp_{bits} \leq MTU_{bits}$$

Figure 7. Encapsulation of multiple LOT messages in a single Ethernet payload

ESTOL-HCO-LOT-00040 The LOT endpoints shall exchange LOT application messages through the LOT logical channel.

Note-HCO-LOT-00040-1: LOT endpoints are application-level clients and receiver applications transmitting and collecting the LOT messages.

ESTOL-HCO-LOT-00050 A LOT application message shall consist of a 6-bit long header (LOT Code) and a 16-bit long payload, as depicted in Figure 8.

Figure 8. LOT Message

ESTOL-HCO-LOT-00060 The LOT code shall uniquely identify the type of the LOT payload.
Note-HCO-LOT-00060-1: LOT code 6-bit identifiers are provided in Table 5. The use of custom LOT messages with identifiers outside Table 5 should be avoided.

ESTOL-HCO-LOT-00070: The LOT payload characteristics shall follow the definition provided in Table 5.

*Note-HCO-LOT-*00070-1: *LOT messages marked as "on request" are not transmitted regularly. In such cases, the LOT endpoint may explicitly request their transmission by issuing a SIGNL LOT message*.

ESTOL-HCO-LOT-00080: The LOT endpoints shall implement as minimum messages indicated as "mandatory" in Table 5.

ESTOL-HCO-LOT-00090: The LOT endpoints should implement additional LOT messages supporting link optimization and characterization.

Note-HCO-LOT-00090-1: Non-essential LOT messages are indicated as "optional" in the following Table 5*.*

ESTOL-HCO-LOT-00100: The LOT messages shall be transmitted at a rate [Hz] fixed by the transmitter and defined in Table 5.

ESTOL-HCO-LOT-00110: The LCT shall be designed to tolerate loss of any LOT messages.

ESTOL-HCO-00040 Control and management traffic may be implemented by:

- Using the GCC0 channel defined for OTU frames, multiplexed with LOT messages.
- Multiplexing the messages in the data-plane as packets
- Using the U1/L1 optical channels OOK IM/DD modulated, as defined in section 3.4 and section 3.5

Table 5. LOT Messages Characteristics

LOT Group	LOT Code		LOT payload			Tx Message Rate [Hz]	Implementation
	6b identifier	Tag	Description	Message Payload Size [bits]	Payload content and encoding		
	000000	PERF_UBLK	Counter of number of uncorrected blocks/frames Note: Follows SDA LAPC_BLER_REPORT definition	16	(U)INT16	1	Optional
	000001	RX_PW	Total optical input power at the transceiver/modem Averaged in 1 sec. Note: Follows SDA LAPC_RSSI_REPORT definition	16 (8+8)	8b, received power mean 8b, received power standard deviation. Step size = -0.25dBm, from 0 dBm to – 63.75 dBm (0x0000 to 0xFFFF)	1	**Mandatory**

Link quality report and optimization	000010	SYNC	RX synch report. Note: Follows SDA LAPC_SYNC_REPORT definition	16 (14+2)	14b, number of times frame sync lost (trailing 1 sec from 1 PPS). 2b, frame sync status (at 1 PPS sample time): - 00: not locked - 01: locked - 10: reserved - 11: reserved	1	**Mandatory**
	000011	RX_TSPW	Total optical input power at the tracking sensor. Averaged in 1 sec.	16 (8+8)	8b, received power mean 8b, received power standard deviation. Step size = -0.25dBm, from 0 dBm to – 63.75 dBm (0x0000 to 0xFFFF)	1	Optional
	000101	SYNC_FAST	[fast] RX synch report. Time window can span from 50 ms (20 Hz) to 1 ms (1 kHz)	16 (14+2)	14b, number of times frame sync lost 2b, frame sync status - 00: not locked - 01: locked - 10: reserved - 11: reserved	20 - 1000	Optional
	000110	PERF_FEC	pre-FEC BER (FER)	16	(U)INT16 BER(FER) = 10^(-5 + (x / 65535) * (log10(1e-1) - log10(1e-5))), with x being the integer in decimal format	1	Optional
	000111	PERF_PFEC	post-FEC BER (FER)	16	(U)INT16 BER(FER) = 10^(-9 + (x / 65535) * (log10(1e-2) - log10(1e-9))), with x being the integer in decimal format	1	Optional

	001000	RX_DPL_OFF	Represents an offset (relative to central frequency) ranging from - 12 GHz to 12 GHz. Averaged over a 1 s window	16	(U)INT16 Step size = +366 kHz, from -12 GHz to 11.986 GHz (0x0000 to 0xFFFF)	1	Optional
	001001	RX_OSNR	Received OSNR at transceiver input. Measurements are averaged over a time window. Time window can span from 1 s (1 Hz) to 10 ms (100 Hz)	16	Step size = 0.1 dB, from 0 dB	1-100	Optional
	001010	RX_TSPW_FAST	[fast] Total optical input power at the tracking sensor. Measurements are averaged over a time window. Time window can span from 0.1 ms (10 kHz) to 0.05 ms (20 kHz)	16	8b, received power mean 8b, received power standard deviation. Step size = -0.25dBm, from 0 dBm to – 63.75 dBm (0x0000 to 0xFFFF)	10000 - 20000	Optional
	001011	RX_OSNR_FAST	[fast] Received OSNR at transceiver input. Measurements are averaged over a time window. Time window can span from 0.1 ms (10 kHz) to 0.05 ms (20 kHz)	16	Step size = 0.1 dB, from 0 dB	10000 - 20000	Optional
Link configuration and future use	001100	VERSION	ESTOL spec version.	16 (8+8)	Version X.Y	On request	**Mandatory**
	001101	DIV_CONF	Bits reserved for communicating time diversity configuration parameters and metrics	16 (14+2)	14b, $r = \frac{nECDUCorrect}{nECDULost}$ encoded as $n = floor(r \cdot 2^{14} - 1)$ 2b, signalling: • 00, EC not active or not implemented • 01, EC decoder active • 10, EC encoder active • 11, EC decoder and encoder active	On request	Optional

	001110	SENSITIVITY	The receiver can transmit RX sensitivity (RX power lower limit) to calibrate TX power.	16	Step size = -0.25dBm, from 0 dBm to – 63.75 dBm (0x0000 to 0xFFFF)	On request	Optional
	001111	VEN_RESERVED	Vendor reserved	16	Vendor reserved	Vendor reserved	Vendor reserved
Request, Signalling, Error codes	010000	SIGNL	Request, Signalling, Error codes	16 (8+8)	8b, MSG Number 8b, MSG PYL - MSG0 : Generic error (no PYL) - MSG1: Request transmission of telemetry (PYL equal to the telemetry LOT code) - MSG2 : Requested telemetry not implemented (PYL equal to the telemetry LOT code) - MSG3: Stop transmission of telemetry (PYL equal to the telemetry LOT code) - MSG4: Telemetry overflow (PYL equal to the telemetry LOT code)	N/A	**Mandatory**

3.3.3. FEC

ESTOL-HCO-00050 Quasi-error free communication shall be achieved after FEC correction (post-FEC) for all high data-rate coherent (HCO) modes.

ESTOL-HCO-00060 The FEC for the high data-rate coherent (HCO) modes shall implement oFEC as defined by [RD-10].

3.4. 2.5G OOK

3.4.1. User data rates

ESTOL-OOK-41010 The 2.5G OOK air interface shall offer the user data rates specified in the table below per wavelength.

Requirement	User net data rate (upper bound)	Air interface	Symbol rate
ESTOL-OOK-41010	1.174 Gbps - 2.221 Gbps*	2.5G IM/DD OOK	2.5 Gbaud

**The user-data depends on the selected code-rates as defined in the next sections*

3.4.2. Framing

ESTOL-OOK-41020 The 2.5G OOK air interface shall implement the frame structure described in Section 3.4.1 of [RD-2] that includes (see Figure 9Figure 9):

a) a preamble sequence (64 bits)
b) concatenated with a fixed-length header (960 bits)
c) followed by data bits (fixed size, plus Cyclic Redundancy Check (CRC)) (8416+32 bits)
d) then a variable number of parity bits.

Preamble (64 bits)	Header (960 bits)	Payload data (8416 bits)	CRC (32 bits)	Parity (variable)

Figure 9. 2.5G OOK frame structure.

ESTOL-OOK-41030 The data plane shall be mapped in DATA frames (FRAME_TYPE 01), as defined in [RD-2].

ESTOL-OOK-LOT-41010 The LOT shall make use of the FCCH channel and FCCH messages as defined in [RD-2]

ESTOL-OOK-41040 The CMP transport channel may be mapped in MGMT frames (FRAME_TYPE 10), as defined in [RD-2].

3.4.3. FEC

ESTOL-OOK-41050 The post-FEC BER of the 2.5G OOK air interface shall provide quasi-error free communication.

ESTOL-OOK-41060 The FEC for the 2.5G OOK air interface payload data shall be the 5G New Radio LDPC as described in 3GPP document [RD-8] with code-rate between 0.5 and 0.9.

ESTOL-OOK-41070 The 2.5G OOK air interface shall implement for the payload bits a FEC with the following properties:

- Systematic FEC (i.e., a copy of the payload data bits appears in the encoded payload codeword).
- Zero or more parity bits.
- The number of parity bits is a function of the codec and code rate selection. It can be as few as zero bits (uncoded) up to as many as 8448 bits (LDPC, code rate 1/2).
- The payload FEC is a quasi-cyclic low-density parity check (QC-LDPC) [RD-8].

ESTOL-OOK-41080 The payload bits of the 2.5G OOK air interface shall implement the following code rates: 1 (no FEC), 0.8462, 0.7586, 0.6667, 0.5000.

ESTOL-OOK-41090 The header of the 2.5G OOK air interface is encoded by a non-systematic constraint length 7, rate 1/6 convolutional code with generator polynomial described in Table 3-6 of [RD-2] and overall code description as in Section 3.4.5.2 of [RD-2].

3.4.4. Scrambling

ESTOL-OOK-41100 All portions of the 2.5G OOK frame, except for the Preamble Sequence, shall be scrambled prior to transmission as described in 3.4.4.2. of [RD-2].

3.5. 10G OOK

3.5.1. User data rates

ESTOL-OOK-43010 The 10G OOK air interface shall offer the user data rate specified in the table below per wavelength

Requirement	User net data rate (upper bound)	Air interface	Symbol rate
ESTOL-OOK-43010	10.0 Gbps	10G IM/DD OOK	11.3 Gbaud

3.5.2. Framing

ESTOL-OOK-43020 The 10G OOK air interface shall implement the following frame structure consisting of (see Figure 10):

a) a preamble sequence (64 bits)
b) concatenated with a fixed-length header (960 bits)
c) a fixed-length payload carrying 16320 information bits, including the payload data bits, the payload parity bits and the payload CRC.

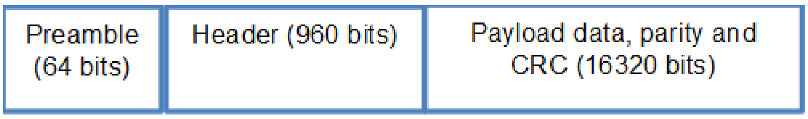


Figure 10. 10G OOK frame structure.

ESTOL-OOK-43030 10G OOK shall use particular implementations of FSO frames based on Section 3.4.8.1.3 of [RD2]. The FSO DATA frame depicted in Figure 3-7 of [RD2] is defined as the logical FSO frame.

ESTOL-OOK-43031 The FSO frame implementation shall follow Figure 11 and use a 64-bit internal data path for the FSO part of the to benefit from the processing parallelization of a logical FSO frame. In such an implementation:

- Each 32-bit FSO Payload Header and FSO Packet Header from the logical FSO frame is placed in bits [31:0] of a 64-bit word; bits [63:32] of the header words are hard-wired to zero.
- The FSO payload is arranged into the 10G OOK payload region using all 64 bits of each 64-bit word (lower and upper 32-bit halves both carry payload bits), until the Payload-Data field length defined in **ESTOL-OOK-43040** is filled.
- If the available payload bits from the logical FSO frame are insufficient to fill Payload-Data field length defined in **ESTOL-OOK-43040**, the remaining bits at the end of the payload region are set to zero (tail zero-padding). No additional zero-padding is introduced inside the payload region other than the header-word upper-32-bit zeros and this final tail filler.
- The payload CRC-32 defined in Section 3.4.5.1 of [RD2] is implemented with two parallel 32-bit CRC engines operating on the lower and upper 32-bit halves of each 64-bit word.

Note-OOK-43031-1: This mapping allows the hardware to process 64 bits per clock (including CRC and FEC pipelines).

ESTOL-OOK-43032 The FSO frame implementation *should* use a native 32-bit data-path, operating directly on the logical FSO frame as defined by Section 3.4.8.1.3 of [RD2] (excluding the CRC-32 Field).To guarantee compatibility with Figure 11, such a 32-bit implementation interfaces to a 64-bit framing block by applying the same mapping rules as in **ESTOL-OOK-43031**:

- For FSO Payload Header and FSO Packet Header words, the 32-bit header word is placed in bits [31:0] of the first 64-bit word, and bits [63:32] are set to zero, exactly matching the header-word representation assumed by existing 64-bit implementations.
- For payload bits, consecutive 32-bit words are concatenated into 64-bit words, filling both halves.

- Once all logical FSO payload bits have been mapped, if the total number of bits does not yet reach the fixed Payload-Data length defined in **ESTOL-OOK-43040**, the remaining bits at the tail of these fields are set to zero.
- The payload CRC-32 defined in Section 3.4.5.1 of [RD2] is implemented with two parallel 32-bit CRC engines operating on subsequent 32-bit data streams arranged to match the frame format depicted in Figure 11.

Note-OOK-43032-1: Following these rules, a 32-bit and a 64-bit implementation produce identical 64-bit words on the wire.

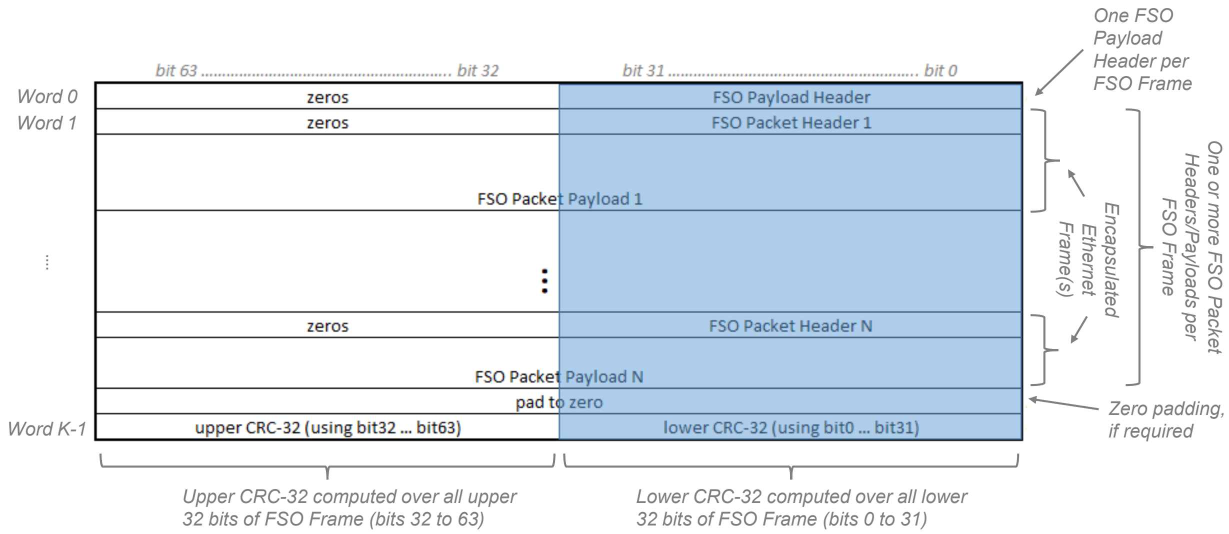


Figure 11 FSO Frame Format

ESTOL-OOK-43040 The 10G OOK frame structure preamble sequence shall be as in Section 3.4.2 of SDA 4.0 [RD-2] and shall take the value shown in Table 3-4 of [RD-2]. Compared to Table 3-4 of [RD-2], the 10G OOK payload fields shall have the following fixed lengths:

- Payload-Data: 15232 bits
- Payload-CRC: 32 bits (CRC-32 as defined in Section 3.4.5.1 [RD-2])
- Payload Parity: 1024 bits, corresponding to the 8×16 parity bytes of the RS (255,239) code defined in **ESTOL-OOK-43110**.

ESTOL-OOK-43041 The 64-bit implementation of the FSO frame in Figure 11 shall include the upper CRC-32 bits as the last 32 bits of the Payload Data Field, in line with **ESTOL-OOK-43031**.

ESTOL-OOK-43042 The 32-bit implementation of the FSO frame in Figure 11 as described in **ESTOL-OOK-43032** shall guarantee compatibility with the 64-bit implementation as described in **ESTOL-OOK-43031,** by applying the same mapping rules, therefore including the upper CRC-32 bits as the last 32 bits of the Payload Data Field.

ESTOL-OOK-43050 The 10G OOK frame structure header is as in Section 3.4.3 of SDA 4.0 [RD2]. The header fields shall follow Section 3.4.6.1 and Table 3-8 of [RD2].

ESTOL-OOK-43060 Two CRCs shall be used to generate the 10G OOK frame as described in Section 3.4.5.1 of SDA 4.0 [RD 2]:

- The 16-bit CRC 16 shall protect the modem header, with polynomial and initialization as defined in [RD 2].
- The 32-bit CRC 32 shall protect the payload information bits carried in the Payload Data field.

ESTOL-OOK-43061 In the 64-bit based implementation of the FSO frame in Figure 11, the 32-bit CRC 32 of **ESTOL-OOK-43060** shall be used as defined by requirements **ESTOL-OOK-43031** and **ESTOL-OOK-43041**.

ESTOL-OOK-43062 In the 32-bit based implementation of the FSO frame in Figure 11, the 32-bit CRC 32 of **ESTOL-OOK-43060** shall be used as defined by requirements **ESTOL-OOK-43032** and **ESTOL-OOK-43042**.

ESTOL-OOK-43070 The data plane shall be mapped in DATA frames (FRAME_TYPE 01), as defined in [RD-2].

ESTOL-OOK-43080 The FRAME_TYPE field of the frame shall signal the type of frame as described herein including IDLE (FRAME_TYPE 00) and MGMT frames (FRAME_TYPE 10).

ESTOL-OOK-LOT-43010 The LOT shall make use of the FCCH channel and FCCH messages as defined in [RD-2].

ESTOL-OOK-43090 The CMP transport channel may be mapped in MGMT frames (FRAME_TYPE 10), as defined in [RD-2].

3.5.3. FEC

ESTOL-OOK-43100 The post-FEC BER of the 10G OOK air interface shall provide quasi-error free communication.

ESTOL-OOK-43110 The FEC for the 10G OOK payload bits shall be encoded with fixed-rate Reed-Solomon code RS (255,239) described in Section 2.6.3.6.3 of [RD-7]).

ESTOL-OOK-43120 The 10G OOK header is encoded by a non-systematic constraint length 7, rate 1/6 convolutional code prior to transmission as described in Section 3.4.5.2 of [RD2]. Generator polynomials for this (7, 1/6) code are listed in Table 3-6 of [RD2].

3.5.4. Scrambling

ESTOL-OOK-43130 The whole 10G OOK frame except for the Preamble Sequence, shall be scrambled prior to transmission as described in Section 3.4.4.2 of the SDA 4.0 [RD2]. The generation of the scrambling sequence is presented in Fig. 3-3 of [RD2]. Figure 12 presents how the different portions of the frame are scrambled or not and the overall frame structure building.

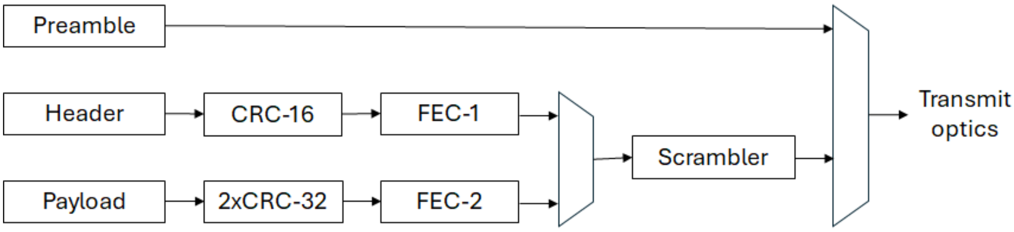


Figure 12. 10G OOK approach to scrambling and overall frame structure building. FEC-1 refers to Convolutional code (7, 1/6) and FEC-2 refers to RS(255, 239).

3.6. Time diversity for bidirectional satellite-ground links

Atmospheric turbulence in bidirectional OGSL introduces deleterious signal fluctuations (slow fading) in both uplink and downlink directions, requiring additional time diversity countermeasures, in addition to the FEC, to guarantee high link availability. This section specifies the use of erasure codes (ECs) as a time diversity technique to be implemented along with any of the air-interfaces specified in this document, for links crossing the atmosphere in any direction. The EC implementation is only mandatory if the system requirements are not met without applying the technique and it is only possible if both ends of the link are equipped with the necessary processing.

3.6.1. General Requirements

ESTOL-TDV-00010 When applied over optical space to ground links, all ESTOL air interfaces (2.5G, 10G, 100+G) shall be protected by a time diversity scheme based on an LDPC Erasure Code (EC) at data link layer to mitigate the effects of atmospheric turbulence.

Note-TDV-0010-1: In Figure 13*, there is a representation of the ESTOL stack with and without the use of Erasure Codes.*

Note-TDV-0010-2: Table 6 summarizes the allocated functions per EC protocol layer at encoder side (the decoder side is analogous).

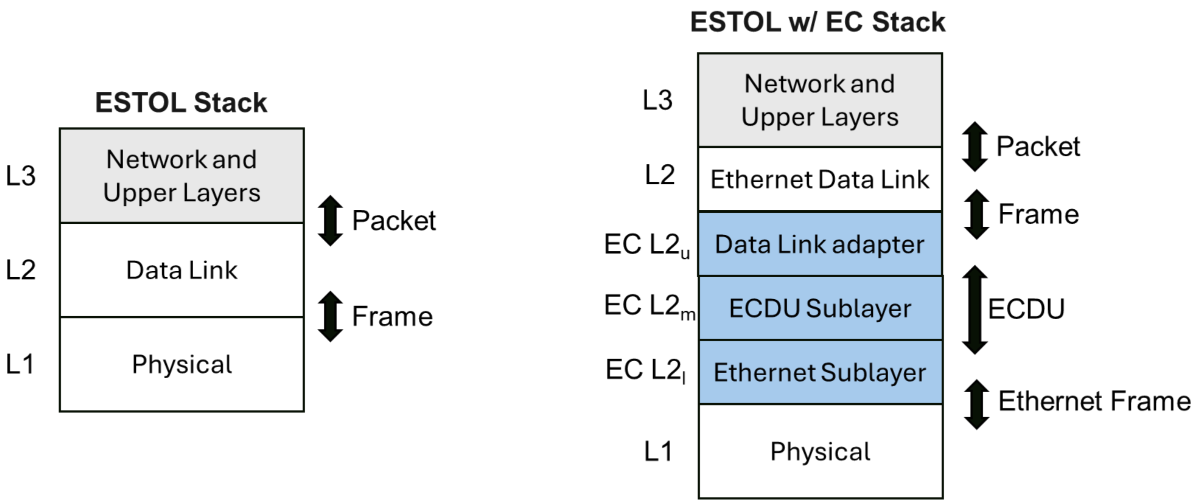


Figure 13. ESTOL Stack with and without use of Erasure Codes

Table 6. EC encoder: protocol layers and allocated functions

Layer	**Allocated Functions (encoder)**
EC L2$_u$ – Data link Adapter	Segmentation of ingress Ethernet frames into chunks to be mapped within ECDU (s) payload
EC L2$_m$– ECDU Sublayer	Generate info and redundant ECDUs
EC L2$_l$– Ethernet Sublayer	Segmentation of ECDUs into discrete segments for encapsulation within Ethernet frames, ensuring compliance with the MTU supported by the interfaced PHY, prior to transmission to the physical layer.

ESTOL-TDV-00020 The EC shall be implemented in the uplink, whereby the EC encoding takes place on ground and the EC decoding in space, with a configuration particular to the uplink channel.

ESTOL-TDV-00030 The EC shall be implemented in the downlink, whereby the EC encoding takes place in space and the EC decoding on ground, with a configuration particular to the downlink channel.

ESTOL-TDV-00040 It shall be possible to disable/bypass the EC encoding and decoding processes.

Note: This applies to the EC encoder and decoder rather than a packet-by-packet basis.

ESTOL-TDV-00050 The communication of additional EC parameters and metrics may be performed via LOT using the 1101-DIV_CONF message as defined in Table 5.

Note-TDV-00050-1: For configurations employing air interfaces where the FCCH is utilized, the 1101-DIV_CONF message shall be encapsulated within the 16-bit ACK_START_FN field of the frame header.

ESTOL-TDV-00060 At the transmitter, the EC encoding process shall be applied on the ingress Ethernet client signal.

Note-TDV-00060-1: The EC is not possible for the 100+G ODU client format.

ESTOL-TDV-00070 When EC is enabled, the encoder output (and decoder input, respectively) shall comply to the user data-rate requirements for all ESTOL air interfaces (2.5G, 10G, 100+G), defined in **ESTOL-HCO-3X010**, **ESTOL-OOK-41010** and **ESTOL-OOK-43010**.

Note-TDV-00070-1: Note: since the encoder creates overhead data, it may implement traffic shaping to reject or smooth-out (buffer) excessive input data spikes (depending on the selected code rate).

ESTOL-TDV-00075 Within the EC protocol stack, serialization shall use big-endian byte ordering (i.e. the most significant byte shall be transmitted first) and, within each byte, bits shall be transmitted most significant bit first.

3.6.2. EC L2$_u$ - Data Link Adapter (Reserved for following issues)

3.6.3. EC L2$_m$ - ECDU Sublayer

ESTOL-TDV-00190 For the purposes of the EC, the data bits shall be organized into EC Data Units (ECDU) consisting of the following fields:

a) Attached Sync Marker (ASM) of 2x32=64 bits
b) ECDU Header (HDR) of 5x32=160 bits
c) ECDU Header CRC 32 bits
d) ECDU Payload data, the size of which shall be flexible (PYL).
e) 8xCRC field each of 32 bits=256 bits

ESTOL-TDV-00200 The ECDU shall have the following structure of Figure 14.

Note-TDV-00200-1: To ease implementation of the Erasure Code into FPGAs, the size of the header, the payload and the ECDU CRC have been designed to be multiples of 256 bits.

Note-TDV-00200-2: The number of payload fields (PYL) in Figure 14 *is only one possible example implementation as payload data are flexible and hence the number of PYL can vary in different implementations.*

# Word	# Chunk of 32Bit								Description
	7	6	5	4	3	2	1	0	
0	ASM1	ASM0	HEADER4	HEADER3	HEADER2	HEADER1	HEADER0	HEADER CRC	64 Bit ASM + 160Bit Hdr + 32 Bit CRC
1	PYL7	PYL6	PYL5	PYL4	PYL3	PYL2	PYL1	PYL0	256 Bit Payload Word #0
2	PYL15	PYL14	PYL13	PYL12	PYL11	PYL10	PYL9	PYL8	256 Bit Payload Word #1
9750	PYL 77999	PYL 77998	PYL 77997	PYL 77996	PYL 77995	PYL 77994	PYL 77993	PYL 77992	256 Bit Payload Word #9749
9751	CRC7	CRC6	CRC5	CRC4	CRC3	CRC2	CRC1	CRC0	8 * 32 Bit

Figure 14. ECDU structure for an ECDU payload size of 2496 kbit

ESTOL-TDV-00205 The ECDU shall be serialized word-by-word in ascending word order. Within each word, transmission shall start from the most significant byte, and within each byte from the most significant bit (MSB-first).

ESTOL-TDV-00210: The ASM of the ECDU is a fixed 64-bit constant that shall be identical in every packet. Its value is 0x53 22 5B 1D 0D 73 DF 03 (hex).

Note-TDV-00210-1: Transmission is MSB-first: the most significant bit of 0x53 is sent first and the least significant bit of 0x03 is sent last, i.e., bits are sent from bit 63 down to bit 0. Accordingly, the eight bytes appear on the link in this order: 0x53, 0x22, 0x5B, 0x1D, 0x0D, 0x73, 0xDF, 0x03, with no additional byte swapping or bit reversal.

For reference, the transmitted nibbles are 5, 3, 2, 2, 5, B, 1, D, 0, D, 7, 3, D, F, 0, 3, and the corresponding binary stream begins 0101 0011 0010 0010 0101 1011 0001 1101 … and ends … 1111 0000 0011.

ESTOL-TDV-00220 The ECDU HDR contains the following fields in Figure 15 (numbering over the rows and columns refers to Bytes):

Octet	Bit	31–28 (Octet 3)	27–24 (Octet 3)	23–20 (Octet 2)	19–16 (Octet 2)	15–8 (Octet 1)	7–0 (Octet 0)	
0	0	ASM1 (0x5322 5B1D)						ASM
4	32	ASM0 (0x0d73 DF03)						ASM
8	64	Version	HdrLen	HdrCheck Type	PktCheck Type	PLCode Type		HDR
12	96	Codeword Number				ECDU Length		HDR
16	128	ECDU Length				ECDU Number		HDR
20	160	Reserved (Future Use)						HDR
24	192	Reserved (Future Use)						HDR
28	224	HDRCheck						HDR

Figure 15. ECDU HDR fields

Explanation of ECDU fields:

Version: currently, only Version = 0 is defined

HdrLen: in 4-Byte units, HdrLen = 6 (including CRC, exclusive ASM)

HDRcheck Type: currently only HDRcheck Type = 0,1 is defined

PKTcheck Type: currently only PKTcheck Type = 0,1 is defined

PLCode Type: up to 2^{16} code types can be defined, which refers to a specific parity check matrix.
Defined values:

- PLCode Type = 0: no coding
- PLCode Type = 1: code 94 (R = 0.94)
- PLCode Type = 2: code 80 (R = 0.8)
- PLCode Type = 3: code 61 (R = 0.61)
- PLCode Type = 4: code 44 (R = 0.44)
- PLCode Type = 5: code 20 (R = 0.2)

CodewordNumber: incremental counter for the codewords, after $2^{16} – 1$ the counter has to restart with value 0

ECDU Length: Payload size of the ECDU in Bytes

ECDU Number: Counter of the ECDU of the erasure code (0 ≤ PacketNumber ≤ n-1)

Note-TDV-00220-1: HDRcheck is a CRC just for the HDR. The HDR should be checked before the CRC check for the payload field. When the HDR CRC fails, the whole ECDU will be erased due to the missing packet number.

Note-TDV-00220-2: A Proposed procedure to analyse the HDR of an ECDU is as follows:

1. *Read and check "Version" (currently only Version = 0 is defined). Stop, if version is not defined and signal ECDU as "erased".*
2. *Read "HDRcheck Type": proceed, if HDRcheck Type is defined, otherwise stop and signal ECDU as "erased".*
3. *Read "PKTcheck Type": proceed, if PKTcheck Type is defined, otherwise stop and signal ECDU as "erased".*
4. *Do the HDRcheck: proceed, if HDRcheck is OK, otherwise stop and signal ECDU as "erased".*
5. *Read "PLCode Type": proceed, if PLCode Type is defined, otherwise drop ECDU and proceed with the next ECDU*
6. *Analyse ECDU Length and do the check (CRC) for the ECDU (payload): proceed, if check is OK. Drop ECDU and proceed with the next ECDU, if check is negative.*
7. *Analyse Codeword Number and ECDU number, save the ECDU, mark ECDU as present in the erasure vector belonging to the current Codeword Number.*
8. *Start decoding, if Codeword Number of the next ECDU has changed*

ESTOL-TDV-00230 In case of HDRcheck Type = 0, the 32 bits header CRC shall be specified by the 32-bit CRC generated by the following generator polynomial

32-bit CRC specified by Koopman $(x^{32} + x^{14} + x^{12} + x^{10} + x^9 + x^8 + x^4 + x^3 + x + 1)$

ESTOL-TDV-00240 In case of PKTcheck Type = 0, the 8x32 bits =256 bits ECDU CRC shall be specified by generating eight (8) times the 32-bit CRC employing the following generator polynomial

32-bit CRC specified by Koopman $(x^{32} + x^{14} + x^{12} + x^{10} + x^9 + x^8 + x^4 + x^3 + x + 1)$

ESTOL-TDV-00250 In case of PKTcheck Type = 0, the 8x32 bits =256 bits ECDU CRC shall be computed on the 32 bits column chunk of the ECDU.

ESTOL-TDV-00260 The length of the ECDU payload data field shall be fully configurable. Its size depends on the coherence time of the channel, the data rate, the code rate and the amount of support memory.

Note-TDV-00260-1: the ECDU payload length is configurable in a range from 0 to $2^{24} - 1$ Bytes (about 16.77 Mbyte). It can make sense for some implementations to restrict the ECDU payload length to multiples of 4 kBytes.

Note-TDV-00260-2: as an example, the ECDU for a ECDU Payload Size 2496 kbit is constituted by 9752 words, 256 bits each, which results is a total size of:

256 bits + 2 496 kbits + 256 bits = 2 496 512 bits

Thereby,

- *word #0 in Figure 14 will be ASM and header*
- *words #1 to 9750 will be ECDU payload, and*
- *word #9751 will be ECDU CRC.*

Note-TDV-00260-3: as an additional example, the ECDU for a ECDU Payload Size 832 kbit is constituted by 3252 words, 256 bits each, which results in a total size of:

256 bits + 832 kbits + 256 bits = 832 512 bits,

Thereby,

- *word #0 will be ASM and header,*
- *words #1 to 3250 will be ECDU payload, and*
- *word #3251 will be ECDU CRC.*

Note-TDV-00260-4: analyses of fading time series have shown that the ECDU payload length of about 2496 kbits for a channel data rate of 100 Gbit/s would be able to address typical fading events observed in measurements.

ESTOL-TDV-00270 The EC shall be a systematic Quasi-Cyclic Irregular Repeat Accumulate LDPC code based on a provided parity check matrix consisting of a Codeword of length N ECDU that are subdivided into a length K information ECDU and a length (N-K) parity of ECDU generated via the EC encoding process. The code rate is R=K/N. The EC is applied to the payload fields of the ECDU.

Note-TDV-00270-1: as a matter of example, one possible implementation of the EC encoder can perform the following functions in sequence:

0. *collect and packetize user data to K ECDU*
1. *generate an instruction list specifying which ECDU must be XORed in the payload fields and at which positions the result must be stored. This list can be generated offline and stored in a vector. The list is always the same for a given EC (parity check matrix), i.e. it does not depend on the K ECDU.*
2. *calculate (XOR) and store N-K redundancy ECDU by following the instruction list*
3. *store N ECDU as complete codeword*
4. *pass on the Codeword to the next stage transceivers. Split into fixed sized Ethernet frames.*

ESTOL-TDV-00280 The EC Codeword shall include a total number of 3600 ECDU (N=3600).

ESTOL-TDV-00290 The EC shall support the following code rates R:

a) R=0.94 (K=3400)
b) R= 0.8 (K=2880)
c) R=0.61 (K=2200)
d) R=0.44 (K=1600)
e) R=0.2 (K=720)

Note-TDV-00290-1: The Table 7, below these lines, presents examples of how the EC codeword can be flexibly dimensioned for the three air interfaces and different EC code rates in order to mitigate different channel coherence times.

Table 7. Examples of EC codeword dimensioning, to achieve different channel coherence times

Air Interface [Gbit/s]	EC Code Rate	D	K ECDU Packets	N ECDU Packets	ECDU Payload size [kbits]	ECDU packet size [bits]	EC codeword size [Gbit]	EC codeword duration [ms]	Cumulative durations of erasures that can be corrected per codeword [ms]
100	0.94	1	3400	3600	832	832512	3.00	26.07	1.56
100	0.61	1	2200	3600	832	832512	3.00	26.07	10.17
100	0.94	1	3400	3600	2496	2496512	8.99	78.19	4.69
100	0.61	1	2200	3600	2496	2496512	8.99	78.19	30.49
10	0.94	1	3400	3600	83.2	83712	0.30	26.64	1.60
10	0.61	1	2200	3600	83.2	83712	0.30	26.64	10.39
10	0.94	1	3400	3600	249.6	250112	0.90	79.60	4.78
10	0.61	1	2200	3600	249.6	250112	0.90	79.60	31.04
2.5	0.94	1	3400	3600	20.8	21312	0.08	30.69	1.84
2.5	0.61	1	2200	3600	20.8	21312	0.08	30.69	11.97
2.5	0.94	1	3400	3600	62.4	62912	0.23	90.59	5.44
2.5	0.61	1	2200	3600	62.4	62912	0.23	90.59	35.33

Note-TDV-00290-2: Although it is possible to vary the code rate on a codeword per codeword basis, a more realistic use case is to keep the same code rate fixed during a pass of the satellite over the ground station or possibly pre-program different code rates at different ranges of elevation angles.

ESTOL-TDV-00300 The EC code shall be based on the following H matrix for code rate R=0.94 shown in QC form (see Figure 16) and IRA form (see Figure 17):

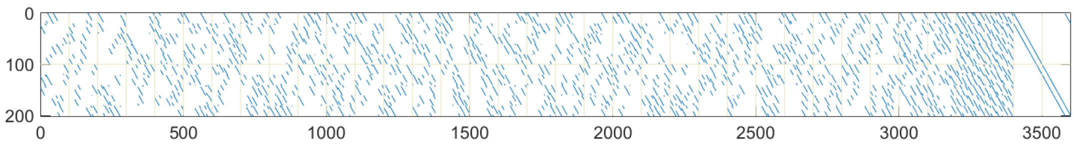


Figure 16. H matrix (QC form) of code (n=3600, k=3400, rate 0.94)

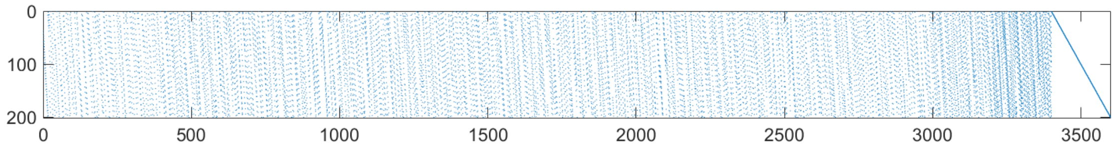


Figure 17. H matrix (IRA form) of code (n=3600, k=3400, rate 0.94)

Note-TDV-00300-1: The parity-check matrix H of a (3600,3400) (R=0.94) LDPC based EC is provided as ASCII file in Annex A.

ESTOL-TDV-00310 The EC code shall be based on the following H matrix for code rate R=0.8 shown in QC form (see Figure 18) and IRA form (see Figure 19):

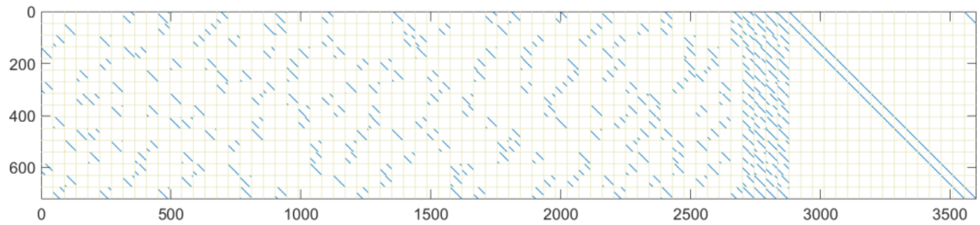


Figure 18. H matrix (QC form) of code (n=3600, k=2880, rate 0.8)

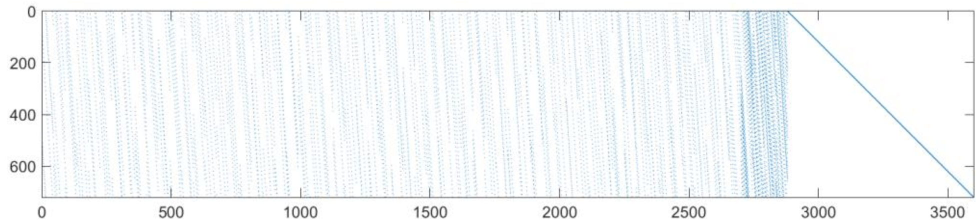


Figure 19. H matrix (IRA form) of code (n=3600, k=2880, rate 0.8)

Note-TDV-00310-1: The parity-check matrix H of a (3600,2880) (R=0.8) LDPC based EC is provided as ASCII file as an Annex to ESTOL.

ESTOL-TDV-00320 The EC code shall be based on the following H matrix for code rate R=0.61 shown in QC form (see Figure 20) and IRA form (see Figure 21):

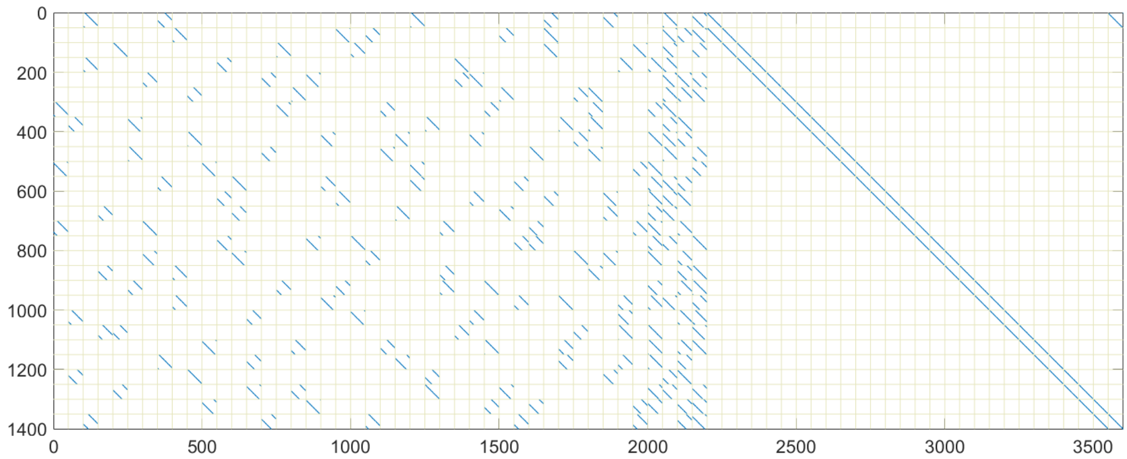


Figure 20. H matrix (QC form) of code (n=3600, k=2200, rate 0.61)

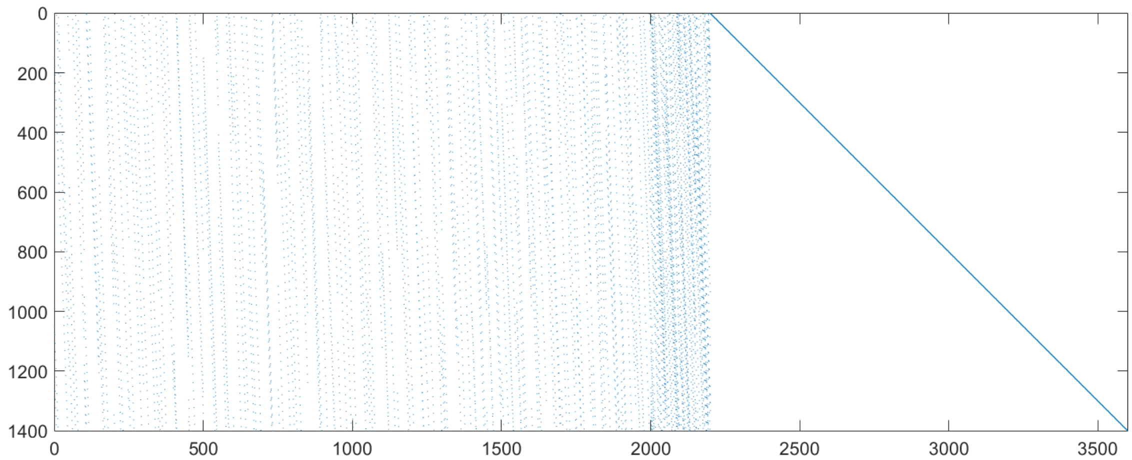


Figure 21. H matrix (IRA form) of code (n=3600, k=2200, rate 0.61)

Note-TDV-00320-1: The parity-check matrix H of a (3600, 2200) (R=0.61) LDPC based EC is provided as ASCII file in Annex A.

ESTOL-TDV-00330 The EC code shall be based on the following H matrix for code rate R=0.44 shown in QC form (see Figure 22) and IRA form (see Figure 23):

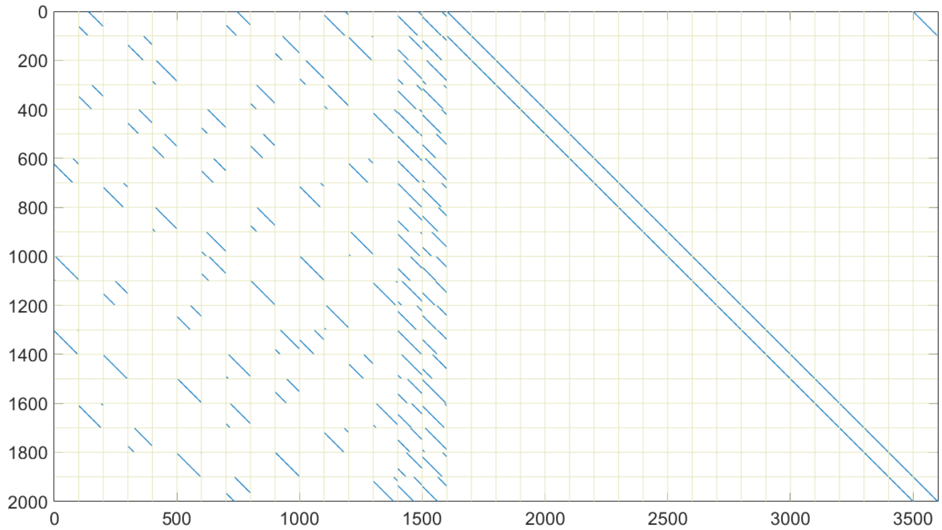


Figure 22. H matrix (QC form) of code (n=3600, k=1600, rate 0.44)

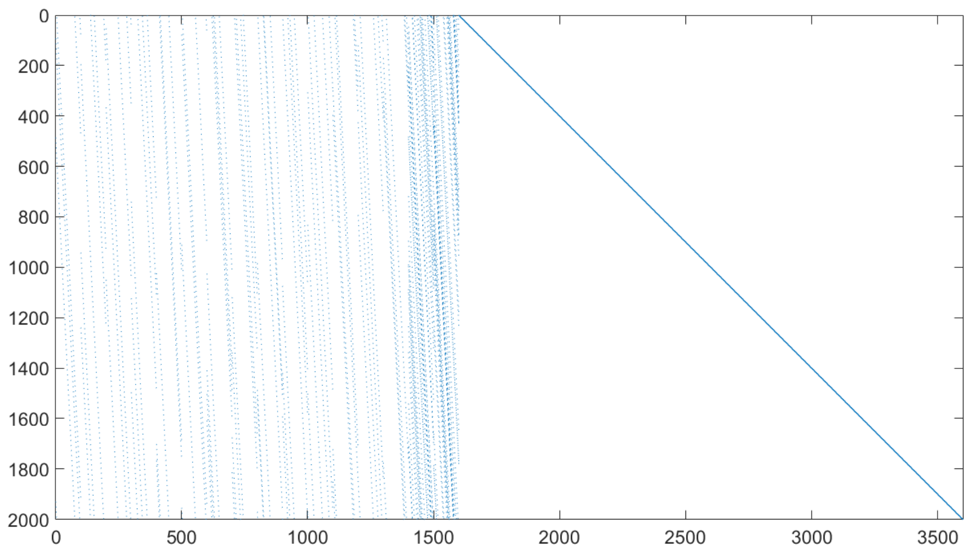


Figure 23. H matrix (IRA form) of code (n=3600, k=1600, rate 0.44)

Note-TDV-00330-1: The parity-check matrix H of a (3600,2200) (R=0.44) LDPC based EC is provided as ASCII file in Annex A.

ESTOL-TDV-0340 The EC code shall be based on the following H matrix for code rate R=0.2 shown in QC form (see Figure 24) and IRA form (see Figure 25):

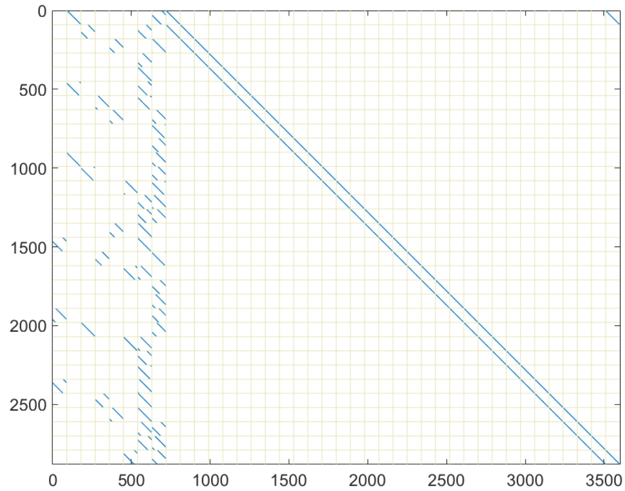


Figure 24. H matrix (QC form) of code (n=3600, k=720, rate 0.2)

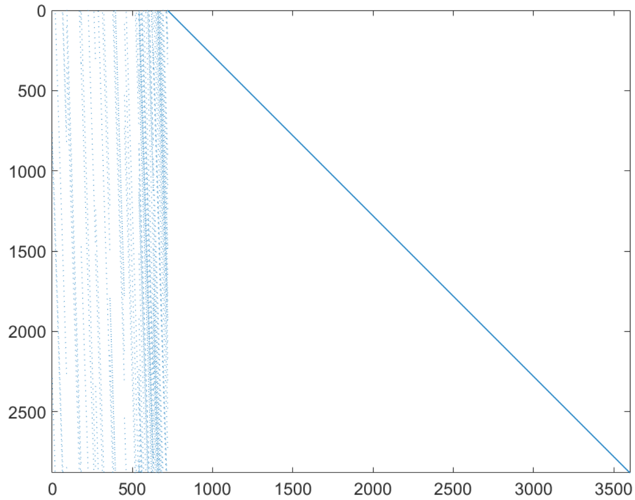


Figure 25. H matrix (IRA form) of code (n=3600, k=720, rate 0.2)

Note-TDV-00340-1: The parity-check matrix H of a (3600,72 0) (R=0.2) LDPC based EC is provided as ASCII file in Annex A.

ESTOL-TDV-00350 The EC encoder may be performed by applying a decoding process and assuming an erasure vector with erasures at the positions of the parity symbols/packets to be generated.

Note-TDV-00350-1: as matter of example, one possible implementation of the EC decoder can perform the following functions in sequence:

1. *collect and store all correct ECDU with the codeword number of the actual codeword*
2. *analyse the packet numbers of these correct ECDU and generate the erasure vector of this actual codeword. This erasure vector is a list with N entries indicating the correct and lost/corrupt ECDU within the actual codeword. Entries can be "ECDU correct" or "ECDU erased".*
3. *Solve the equations defined by the H-matrix, the erasure vector, and the correct codeword symbols (correct ECDU). The addition operation for the codeword symbols (payload of the ECDU packets) is a parallel XORing of the bits of the payload of the ECDU.*
4. *forward the user-data of the corrected codeword. If the codeword could not be corrected, the user data of the correct ECDUs can nevertheless be forwarded.*

Note-TDV-00350-2: The H-matrix resolution strategy may be based on a pure iterative decoder which iteratively solves all parity check equations with one unknown (one erasure), or a combined iterative/maximum likelihood decoder to achieve a good erasure correction performance (recommended).

3.6.4. EC $L2_I$ – Ethernet Sublayer

ESTOL-TDV-00360 At transmitter side, the EC encoder shall split and encapsulate ECDU in multiple segments to be encapsulated in Ethernet frame.

Note-TDV-00360-1: Ethernet frames are specified to be able to interface the 2.5G/10G/100G transceivers

Note-TDV-00360-2: Ethernet frames encapsulating ECDUs should have EtherType 0x88B6.

ESTOL-TDV-00370 The ECDU segmentation process shall be implemented in accordance with the following provisions:

1. A sequence of n words belonging to the same ECDU shall be grouped in order, forming a segment whose size shall not exceed the MTU defined in **ESTOL-TDV-00380**.
2. Each segment should include optionally a metadata header of 3 bytes, positioned at the end of the segment.
3. The segment shall be conveyed to the Layer 2 data link as the payload of an Ethernet frame for transmsission over the optical line.

Note-TDV-00370-1: Segments shall only contain words from a single ECDU. No zero-padding shall be applied if the MTU is not fully utilized.

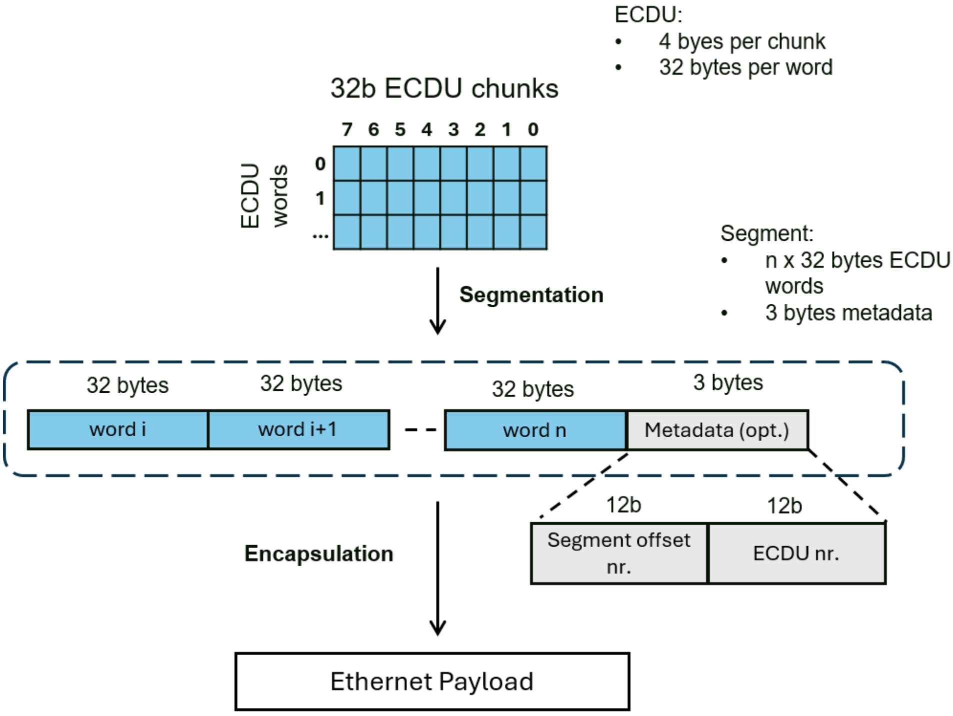


Figure 26 L2I segmentation process

ESTOL-TDV-00380 The number of ECDU words per segment/ethernet frame shall not exceed the value specified in Table 8 given a MTU size.

Table 8 Number of ECDU words per ethernet frame

Air Interface	L2 MTU (bytes)	Number of ECDU words per ethernet frame	Implementation
10G and lower	1475	46	Mandatory
100G and higher	1475	46	Mandatory
100G and higher	8995	281	Mandatory
100G and higher	>9000	>281	Optional

Note-TDV-00380-1 Implementation of Layer 2 MTU values greater than 9000 bytes is not mandatory.

Note-TDV-00380-2 The Layer 2 MTU, and consequently the L2I encapsulation of the ECDU, shall be negotiated and configured during the link opportunity definition phase, prior to link establishment.

Note-TDV-00380-3: The following Table 9 *presents an example of how ECDU of different size are encapsulated into Ethernet frames for the 100G air interface.*

Table 9. Example - Encapsulation of ECDU into Ethernet frames for the 100G air interface

ECDU payload	***ECDU size***	***MTU size***	***Ethernet Frames***
832 kbit	*852480 bits*	*71960 bits (8995 bytes)*	*~ 12*
2496 kbit	*2556416 bits*	*71960 bits (8995 bytes)*	*~ 36*

ESTOL-TDV-00390 The segment metadata should comprise the following fields:

- A 12-bit segment offset number, indicating the sequential position of the segment within the current ECDU to which the current Ethernet frame refers.
- A 12-bit ECDU identifier, specifying the ECDU number within the same codeword.

ESTOL-TDV-00400 At the receiver side, the EC decoder shall reconstruct ECDUs by:

- Identifying and parsing information contained in the segment metadata and ECDU's headers.
- Applying the procedure defined in **ESTOL-TDV-00370** in reverse order.

ANNEX A. ERASURE CODE LDPC DESIGN & PARITY CHECK MATRICES

A.1 Parity Check matrices

Attached to this document are the LDPC parity-check matrices, for of the Erasure Code (EC) defined in Section 3.6, one for each code rate.

Note-TDV-00210-1 *The parity-check matrix H of a (3600,3400) (R=0.94) LDPC based EC is provided as ASCII file*

Hcode94.txt

Note-TDV-00220-1 *The parity-check matrix H of a (3600,2880) (R=0.8) LDPC based EC is provided as ASCII file*

Hcode80.txt

Note-TDV-00230-1 *The parity-check matrix H of a (3600, 2200) (R=0.61) LDPC based EC is provided as ASCII file*

Hcode61.txt

Note-TDV-00240-1 *The parity-check matrix H of a (3600,2200) (R=0.44) LDPC based EC is provided as ASCII file*

Hcode44.txt

Note-TDV-00250-1 *The parity-check matrix H of a (3600,720) (R=0.2) LDPC based EC is provided as ASCII file*

Hcode20.txt

A.2 IRA LDPC code parameters

These IRA LDPC codes are based on circulant permutation matrices with different code rates and block lengths. The code parameters (*N,K,M,R,q,a*) for the IRA codes (94, 80, 61, 44, 20) are summarized in the Table 10, where *M* is the number of parity bits, *q* is the circulant size and $a = M/q$.

Table 10. Parameters for the IRA codes

	N	*K*	*M*	*R*	*q*	*a*
Code 94	3600	3400	200	0.94	20	10
Code 80	3600	2880	720	0.8	45	16
Code 61	3600	2200	1400	0.61	50	28
Code 44	3600	1600	2000	0.44	100	20
Code 20	3600	720	2880	0.20	90	32

A.3 Description of the encoding process for erasure codes

The EC encoding for each code rate can be performed making use of either the parity check matrices in ***Note-TDV-00210-1** to **Note-TDV-00250-1*** , or, alternatively, the accumulator indices in the tables between Table 11 to Table 15. The encoding process based on the accumulator indices is as follows:

a) The encoder maps the information word $\boldsymbol{u} = [u_0, u_1, ..., u_{K-1}]$ of size *K* onto a codeword $\boldsymbol{c} = [c_0, c_1, ..., c_{N-1}]$ of size *N*, where the code is systematic; i.e., $\boldsymbol{c}$ is made up of the information symbols $\boldsymbol{u}$ and the parity symbols $\boldsymbol{p} = [p_0, p_1, ..., p_{(M-1)}]$ as $\boldsymbol{c} = [\boldsymbol{u}|\boldsymbol{p}]$.
b) Vector $\boldsymbol{p}$ can be calculated in an IRA-like fashion, by obtaining $\boldsymbol{p}$ from $\boldsymbol{u}$ as follows:
   1. $\boldsymbol{p}$ is initialized as $\boldsymbol{p} = [p_0, p_1, ..., p_{M-1}] = [0, 0, ...,0]$.
   2. Accumulate the first information bit, u_0, at parity bit addresses specified in the first row of the tables between Table 11 to Table 15.
   3. Accumulate the next *q-1* information bits (with q being the IRA code parameter in Table 10) at parity bit addresses $g_X = mod(y + mod(x,q) \cdot a, m)$, where *y* denotes the address of the parity bit of the accumulator corresponding rows of the tables between Table 11 to Table 15. Parameter *a* has been defined previously in Table 10.
   4. In general, for the information bit in position $[(z-1)q]$, , the addresses of the parity bit accumulators are given in the row z of the following tables (Table 11 to Table 15). The addresses $g_X \; with \; x \in \{(z-1)q+1, \dots, zq-1\}$ of the parity bit accumulators for the following $(q-1)$ information bits are obtained using the formula $g_X = mod(y + mod(x,q) \cdot a, M)$.
   5. After all information bits have been processed, the additions $p_x = p_{x-1} \oplus p_x$ are performed, where $x \in \{1, ..., M-1\}$.

Table 11. Accumulator indices for Code 94. The matrix has been split in 3 parts, being the most left part the upper one, followed by the other ones in consecutive manner.

36	41	57							
6	74	150							
53	68	150							
33	118	139							
82	106	185							
71	84	152							
88	97	115							
94	103	142							
49	71	140							
125	169	197							
87	161	180							
37	159	198							
39	93	128							
26	29	102							
40	81	192							
33	124	182							
3	75	86							
37	94	168							
66	104	165							
60	155	181							
50	58	101	112						
22	83	115	134						
16	68	82	164						
35	72	117	148						
89	100	106	147						
65	123	180	184						
84	91	113	156						
59	105	121	196						
0	37	79	83						
71	138	157	169						
45	52	91	139						
107	143	155	188						
12	65	96	190						
73	81	84	182						
25	74	92	173						
96	114	163	180						
31	39	150	178						
27	38	46	179						
67	71	114	156						
67	89	110	168						
3	19	31	66						
39	100	148	177						
7	148	176	199						
19	43	135	174						
83	117	151	172						
5	8	162	184						
50	61	102	114						
14	16	27	30						
32	45	140	161						
113	126	135	188						
84	109	146	180						
71	97	175	188						
19	57	106	118						
42	53	101	165						
148	160	172	189						
12	106	170	197						
3	24	118	150						
35	53	106	164						
2	141	185	193						
77	84	161	189						
49	78	84	157						
3	9	138	155						
7	30	74	175						
27	146	162	191						
11	15	100	132						
29	93	172	186						
66	103	168	170						
4	45	131	163						
37	78	136	149						
2	14	71	120						
52	95	151	180						
93	124	141	160						
36	77	145	188						
6	137	159	198						
22	63	98	169						
50	52	113	154						
13	101	144	170						
36	54	57	85						
6	51	59	108						
22	27	95	189						
52	86	89	105						
33	52	91	176						
23	37	118	199						
84	150	153	188						
60	67	105	114						
14	42	176	180						
51	70	92	133						
76	89	161	195						
15	98	141	187						
144	148	157	189						
3	61	80	199						
90	156	187	189						
21	54	93	100						
116	169	182	197						
47	83	98	175						
54	75	82	133						
38	51	162	167						
22	86	141	164						
79	165	168	190						
54	56	118	155						
60	65	77	156						
24	30	69	162						
17	20	63	125						
64	133	141	152						
102	105	113	121						
51	78	86	184						
68	83	122	139						
8	47	86	169						
28	149	160	164						
77	156	161	175						
9	71	98	145						
109	130	168	187						
59	65	108	161						
0	51	147	192						
0	119	143	158						
63	96	117	164						
94	146	153	182						
55	76	117	181						
40	63	94	162						
24	92	126	195						
18	36	59	143						
68	114	155	171						
21	30	72	187						
52	60	74	133						
40	51	125	152						
122	141	154	197						
15	19	38	47						
36	57	105	159						
23	66	149	158						
100	104	143	196						
0	21	144	163						
23	105	150	152						
12	15	104	166						
89	94	118	147						
23	101	125	197						
26	139	153	158						
76	112	124	180						
15	48	119	170						
51	62	107	166						
19	91	157	198						
4	15	26	100						
72	88	155	193						
67	111	136	165						
0	114	143	191						
19	30	74	143						
38	127	132	139						
11	92	155	183						
0	17	28	79						
77	79	148	156						
34	52	101	136						
3	27	64	86	152	160				
8	14	131	155	173	182				
8	17	94	135	139	170				
7	22	66	113	144	149				
28	31	114	120	125	167				
17	48	84	139	151	186				
88	135	140	142	163	169				
59	81	113	120	176	192				
76	81	125	163	180	182				
8	15	26	51	97	179				
11	19	33	58	84	87	92	115	186	190
54	56	60	63	68	82	107	149	171	175
4	8	19	21	27	35	50	66	133	192
23	27	51	76	94	98	109	145	152	190
9	27	46	55	160	172	181	184	188	193
1	10	49	57	65	98	132	134	163	186
3	28	40	96	115	121	142	154	159	187
22	101	104	119	130	135	137	143	156	198
4	35	61	82	116	118	170	177	193	199
1	6	18	49	70	87	103	105	124	162

Table 12. Accumulator indices for Code 80

67	477	502													
319	514	601													
49	606	683													
74	343	517													
266	327	620													
82	223	356													
91	104	646													
174	240	659													
371	477	540													
507	584	709													
112	143	321													
73	580	679													
110	169	620													
402	493	664													
106	353	580													
182	448	709													
61	194	315													
126	597	671													
26	247	265													
243	534	705													
80	575	609													
548	565	615													
99	248	329													
219	380	717													
247	320	402													
14	456	515													
203	380	678													
106	367	388													
166	504	553													
228	349	430													
58	597	624													
220	242	481													
281	450	643													
314	405	519													
305	486	523													
31	157	542													
199	344	397													
463	500	581													
83	256	617													
81	107	588													
379	538	560													
246	547	596													
402	508	527													
215	286	472													
9	294	400													
341	350	708													
28	226	397													
138	353	680													
83	96	453	622												
303	377	402	484												
267	486	541	552												
167	513	554	684												
265	280	478	711												
289	464	522	655												
348	454	459	605												
36	130	469	563												
206	229	456	683												
13	99	500	522												
265	519	582	588												
210	289	383	512												
217	253	260	272	306	328	331	362	364	391	449	478	531	581	614	703
14	31	90	96	140	210	276	310	325	339	361	455	504	529	539	573
10	84	111	144	150	193	206	296	323	333	338	487	565	588	635	649
64	111	235	246	263	291	349	457	494	504	562	613	652	660	666	673

Table 13. Accumulator indices for Code 61

150	1050	1210														
584	819	1112														
951	1179	1232														
549	881	1001														
557	777	1346														
203	914	1269														
14	324	956														
700	1047	1283														
1111	1165	1177														
817	1296	1368														
150	162	334														
407	451	684														
212	657	1355														
221	667	860														
503	536	597														
258	914	1262														
641	1030	1265														
110	200	267														
243	316	963														
113	550	1104														
160	1066	1359														
701	940	1147														
205	806	818														
204	359	1273														
318	347	1260														
25	752	1239														
885	1078	1166														
87	648	1029														
144	260	1000	1020													
46	782	818	1338													
305	321	757	1209													
487	631	971	1007													
474	602	771	1325													
29	114	460	644													
47	611	890	1267													
665	932	957	1360													
33	233	325	986	1183												
152	212	392	444	1021												
384	915	975	1207	1337												
142	642	710	1035	1078												
72	182	361	418	494	629	678	967	1095	1103	1139	1255	1272	1310	1352	1365	1382
90	148	169	243	256	293	347	366	404	529	679	799	836	1039	1097	1232	1241
80	124	256	502	521	583	615	652	655	757	940	1041	1082	1086	1162	1168	1351
50	197	201	217	251	308	362	417	536	570	691	702	961	1140	1306	1333	1359

Table 14. Accumulator indices for Code 44

93	486	1930																	
196	943	1240																	
54	367	1051																	
741	1124	1497																	
1025	1702	1768																	
78	912	1955																	
1026	1410	1504	1609																
1120	1339	1676	1814																
985	1488	1523	1971																
1075	1421	1593	1998																
307	833	1502	1970																
300	397	1723	1852																
121	426	794	1849																
171	304	359	1776																
47	73	189	205	226	244	360	483	492	719	896	990	997	1088	1101	1235	1338	1542	1691	1714
75	216	283	378	401	440	444	447	708	779	793	832	885	890	971	1194	1249	1662	1786	1797

Table 15. Accumulator indices for Code 20

762	848	2293															
106	357	2848															
331	1473	2870															
1243	1521	2342															
1794	1807	2151	2332														
87	530	735	2540														
28	144	345	390	830	869	1048	1134	1153	1517	1923	2237	2290	2391	2618	2799	2811	2852
209	264	364	928	1117	1267	1493	1513	1675	1791	1838	1942	1959	2090	2196	2334	2509	2754

ANNEX B. PERFORMANCE OF THE ERASURE CODES

This annex provides simulation results on the erasure codes performance for the proposed code-rates in the specification.

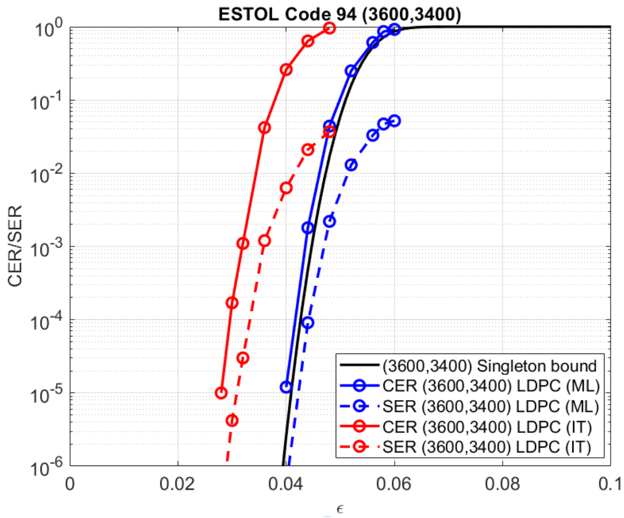


Figure 27. Performance of Code 94 (n=3600, k=3400, rate 0.94) over the memory-less BEC.

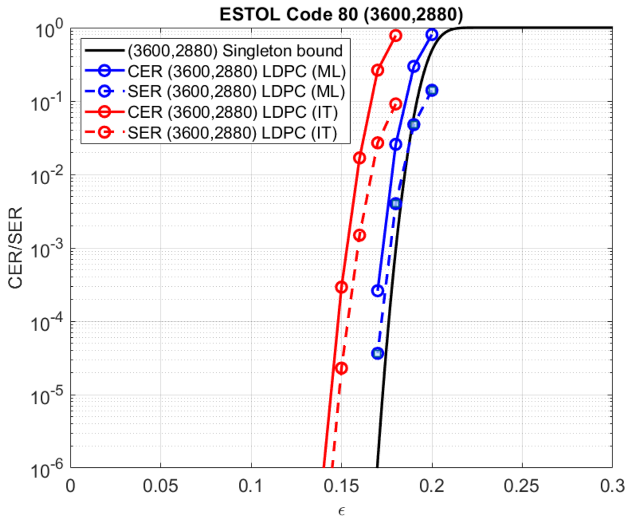


Figure 28. Performance of Code 80 (n=3600, k=2880, rate 0.8)) over the memory-less BEC.

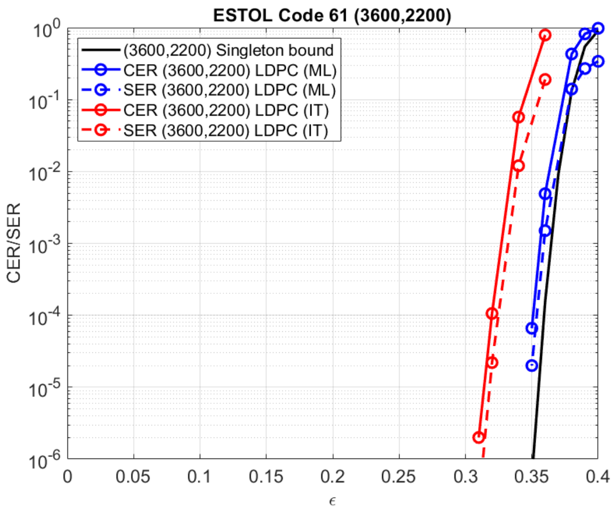


Figure 29. Performance of Code 61 (n=3600, k=2200, rate 0.61) over the memory-less BEC.

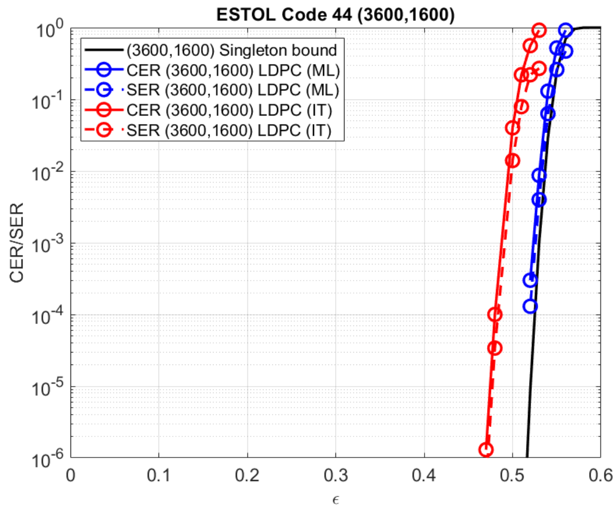


Figure 30. Performance of Code 44 (n=3600, k=1600, rate 0.44) over the memory-less BEC.

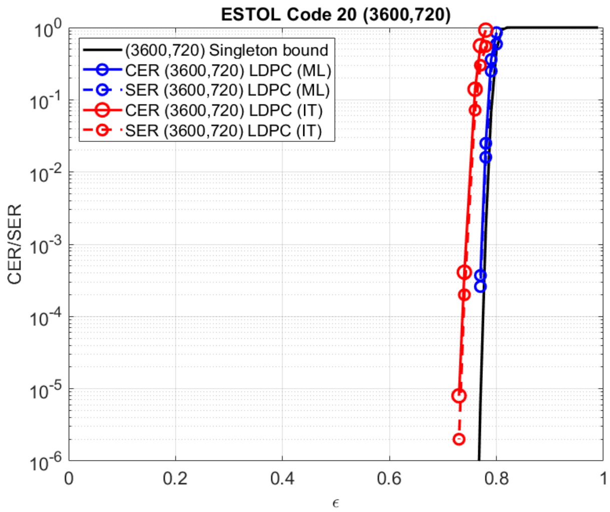
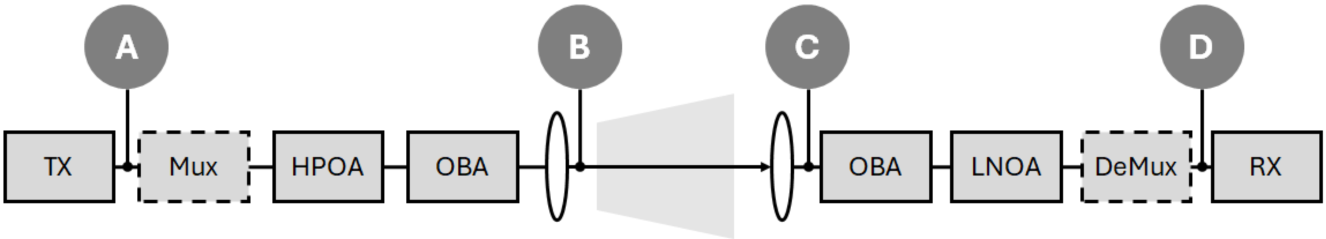


Figure 31. Performance of Code 20 (n=3600, k=720, rate 0.20) over the memory-less BEC.

ANNEX C. PHYSICAL LAYER ASSUMPTIONS

C.1 General system diagram

This annex summarizes the assumptions in the physical layer specification in section 2, based on the COTS coherent components. The following figure represents a generic communications system.



A 1. TX: transmitter transceiver
2. Mux: multiplexer
3. HPOA: high power amplifier
B 4. OBA: optical bench assembly

C 1. OBA: optical bench assembly
2. LNOA: low-noise amplifier
3. DeMux: demultiplexer
D 4. RX: receiver transceiver

Figure 32. Generic communication system

C.2 Averaged polarisation mode dispersion (mPMD)

The openROADM MSA [RD-5] specifies that the transceiver (D) in reception tolerates the following maximum mPMD values, with an OSNR penalty below 0.5 dB:

- 100G at 31.6 GBaud: 30 ps
- 200G at 31.6 GBaud: 30 ps
- 200G at 63.1 GBaud: 25 ps
- 400G at 63.1 GBaud: 20 ps

This tolerance value is assumed to be allocated half at the transmitter and half at the receiver. Therefore, the specification in **ESTOL-SIG-XX620-XX650** at C convers half of the tolerance value, and it assumes that the other half of the value is expended between A and B. That means that the receiver communication chain cannot introduce more than half of the tolerance value, to guarantee that the penalty related to mPMD remains below 0.5 dB.

C.3 Polarization dependent loss (PDL)

The openROADM MSA [RD-5] specifies that the transceiver (D) in reception tolerates a maximum instantaneous polarization dependent loss as follows:

- 100G and 200G at 31.6 GBaud: 6 dB
- 200G and 400G at 63.1 GBaud: 4 dB

The penalty related to the PDL is specified as follows:

- 0.5 dB OSNR penalty for PDL < 1 dB
- 1.0 dB OSNR penalty for PDL < 2 dB
- 2.5 dB OSNR penalty for PDL < 4 dB
- 4.0 dB OSNR penalty for PDL < 6 dB

Then openZR+ MSA [RD-5] specifies that the transceiver (D) in reception tolerates a maximum instantaneous polarization dependent loss as follows:

- 100G at 30GBaud and 200G-400G at 60GBaud
  - 3 dB for an additional OSNR penalty less or equal than 1.3dB, when change in SOP is less or equal than 1 rad/ms.
  - 3.5 dB for an additional OSNR penalty less or equal than 1.8dB, when change in SOP is less or equal than 1 rad/ms.

Considering all these values, 3 dB was selected as the maximum PDL value, with the allocation of half value for the transmitter and half for the receiver. Therefore, the specification in **ESTOL-SIG-XX550-XX570** at C convers half of the tolerance value, and it assumes that the other half of the value is expended between A and B. That means that the receiver communication chain cannot introduce more than half of the tolerance value, to guarantee that the penalty related to PDL remains below 1.75 dB, under any condition.

The penalty of 1.75 dB for 3 dB PDL has been linearly interpolated from the values provided by the openROADM MSA. It is noted that the OSNR penalty specification has a linear behaviour between PDL values 2 dB and 6 dB.

This selection was based on the following points:

- The SoP change rates in openROADM and openZR+ MSAs specify the capability of the optical transceiver to deal with this phenomenon, with the optical fibre in terrestrial networks as one major contributor.
- The requirements on receiver sensitivity shall not be over dimensioned unnecessarily, because they have a direct impact on optical terminal size, maximum link distances and transmit power. Therefore, the OSNR penalty due to this effect should be kept as low as possible, within reasonable assumptions.

- The PDL is terminal development specific, and it can vary significantly depending on the design approaches. However, a maximum PDL of 3 dB (1.5 dB for transmitter and 1.5 dB for receiver) is considered reasonable. Values much lower than 1.5 dB are expected for typical optical communications terminals, which should accommodate at least a factor of two margin in typical developments.

C.4 State of polarization (SoP) change rate

The openROADM MSA [RD-5] specifies that the transceiver (D) in reception tolerates a maximum SoP change rate as follows:

- 100G at 31.6 GBaud: 300 krad/s
- 200G at 31.6 GBaud: 80 krad/s
- 200G at 63.1 GBaud: 300 krad/s
- 400G at 63.1 GBaud: 80 krad/s

At those maximum values, the OSNR penalty is 1 dB.

Then openZR+ MSA [RD-5] specifies that the transceiver (D) in reception tolerates a SoP change rate as follows:

- 100G at 30GBaud and 200G-400G at 60GBaud: minimum 50 krad/s in the low transmission mode

At this maximum value, an additional OSNR penalty is below or equal 0.5 dB.

- 100G at 30GBaud and 200G-400G at 60GBaud: maximum 300 krad/s in the high transmission mode

At this maximum value, an additional OSNR penalty is below or equal to 1 dB.

From all these values 50 krad/s was selected as the maximum allowed SoP change rate, with the allocation of half value for the transmitter and half for the receiver. Therefore, the specification in **ESTOL-SIG-XX700-XX730** at C convers half of the tolerance value, and it assumes that the other half of the value is expended between A and B. That means that the receiver communication chain cannot introduce more than half of the tolerance value, to guarantee that the penalty related to SoP change rate remains below 0.5 dB, under any condition.

This selection was based on the following points:

- The SoP change rates in openROADM and openZR+ MSAs specify the capability of the optical transceiver to deal with this phenomenon, whose main contributor is the optical fibre in terrestrial networks.

- The requirements on receiver sensitivity shall not be over dimensioned unnecessarily, because they have a direct impact on optical terminal size, maximum link distances and transmit power. Therefore, the OSNR penalty due to this effect should be kept as low as possible, within reasonable assumptions.
  The SOP change rate is terminal development specific, and it can vary significantly depending on the design approaches. However, a SOP change rate of 50 krad/s (25 krad/s for transmitter and 25 krad/s for receiver) is considered reasonable. Values much lower than 25krad are expected for typical optical communications terminals, which should accommodate at least a factor of two margin in typical developments.

ANNEX D. COMPLIANCE MATRICES

This section defines the compliances matrices for both space and ground terminals.

D.1 Compliance matrix for space terminals

	ESTOL-PAT-00XXX	ESTOL-PAT-G00XXX	ESTOL-WDM-00XXX	ESTOL-SIG-00XXX	ESTOL-SIG-S31XXX ESTOL-HCO-00XXX ESTOL-HCO-31XXX	ESTOL-SIG-S32XXX ESTOL-HCO-00XXX ESTOL-HCO-32XXX	ESTOL-SIG-S33XXX ESTOL-HCO-00XXX ESTOL-HCO-33XXX	ESTOL-SIG-S34XXX ESTOL-HCO-00XXX ESTOL-HCO-34XXX	ESTOL-HCO-LOT-00XXX	ESTOL-SIG-S41XXX ESTOL-OOK-41XXX ESTOL-OOK-LOT-41XXX	ESTOL-SIG-S43XXX ESTOL-OOK-43XXX ESTOL-OOK-LOT-43XXX	ESTOL-TDV-XXXX
ESTOL 100G DP-QPSK	x		x	x	x				x			
ESTOL 200G DP-QPSK	x		x	x		x			x			
ESTOL 200G DP-16QAM	x		x	x			x		x			
ESTOL 400G DP-16QAM	x		x	x				x	x			
ESTOL 2.5G OOK	x		x	x						x		
ESTOL 10G OOK	x		x	x							x	
ESTOL Time Diversity												x

D.2 Compliance matrix for ground terminals

	ESTOL-PAT-00XXX	ESTOL-PAT-G00XXX	ESTOL-WDM-00XXX	ESTOL-SIG-00XXX	ESTOL-SIG-G31XXX ESTOL-HCO-00XXX ESTOL-HCO-31XXX	ESTOL-SIG-G32XXX ESTOL-HCO-00XXX ESTOL-HCO-32XXX	ESTOL-SIG-G33XXX ESTOL-HCO-00XXX ESTOL-HCO-33XXX	ESTOL-SIG-G34XXX ESTOL-HCO-00XXX ESTOL-HCO-34XXX	ESTOL-HCO-LOT-00XXX	ESTOL-SIG-G41XXX ESTOL-OOK-41XXX ESTOL-OOK-LOT-41XXX	ESTOL-SIG-G43XXX ESTOL-OOK-43XXX ESTOL-OOK-LOT-43XXX	ESTOL-TDV-XXXX
ESTOL 100G DP-QPSK	x	(x)	x	x	x				x			
ESTOL 200G DP-QPSK	x	(x)	x	x		x			x			
ESTOL 200G DP-16QAM	x	(x)	x	x			x		x			
ESTOL 400G DP-16QAM	x	(x)	x	x				x	x			
ESTOL 2.5G OOK	x	(x)	x	x						x		
ESTOL 10G OOK	x	(x)	x	x							x	
ESTOL Time Diversity												x