ESA SPECIFICATION FOR TERABIT/SEC 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: • REQ-PHY-110: updated wavelength plan. • New requirements added: REQ-PHY-120, REQ-PHY-130 and REQ-PHY-140. • REQ-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. • REQ-DLL-080: corrected OTU4 by ODU4. • REQ-DLL-100: updated formulation. • REQ-DLL-110: new requirement adding in-data plane CMP channel as an option. • REQ-DLL-120: new requirement adding a dedicated wavelength as an option.	27/10/2023	27-28	

Issue Number 2	Revision Number 0		
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Include satellite-to-ground links. Updated introduction Added following requirements: • REQ-DLL-270 to REQ-DLL-390	17/01/2024	31-32	
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Reason for change	Date	Pages	Paragraph(s)
Updated irradiance sensitivity specification, affecting following requirements • REQ-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: • REQ-PHY-010 to REQ-PHY-160	26/07/2024	10-13 14 15 16-19 16-27	

• Updated numbering of PHY requirements Updated formulation REQ-PHY-270 Updated irradiance sensitivity values, affecting following requirements: • REQ-PHY-300 to REQ-PHY-350 Updated OSNR specification, affecting following requirements: • REQ-PHY-360 to REQ-PHY-410		23 23 24	

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The “ESA Specification for Terabit/sec 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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- CSC (Directorate of Connectivity and Secure Communications)
- OPS (Directorate of Operations)
- TEC (Directorate of Technology, Engineering & Quality)

Table of Acronyms

ASM	Attached Sync Marker
BER	Bit Error Ratio
CCSDS	Consultative Committee for Space Data Systems
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
LDPC	Low-Density Parity Check
LPC	Line Product Code
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
PCTRx	Pluggable Coherent Transceiver
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
SOP	State Of Polarization
TX	Transmitter
UC	Uncertainty Cone
WDM	Wavelength Division Multiplexing

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 (10/2020)
[RD-4]	Flexible OTN long-reach interfaces	ITU-T G.709.3 (12/2020)
[RD-5]	Open ROADM MSA Specification ver 5.1	07/2019
[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, 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)	July 01, 2021
[RD-11]	CCSDS 131.5-O-1 Erasure Correcting Codes for use in Near-Earth and Deep-Space Communications, 2014.	November 2014

1. INTRODUCTION

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 do still 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 would enable the space nodes to become just another type of network node and ultimately, both space and ground segments would become an integral part of the overall terrestrial high-capacity transport network infrastructure.

The present document, ESTOL, is the ESA’s response to provide a specification for high data rate optical links (towards terabit/sec). ESTOL will be implemented and demonstrated by HydRON (High Throughput Optical Network), to foster 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 (terabit/sec in contrast to gigabit/sec), 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).

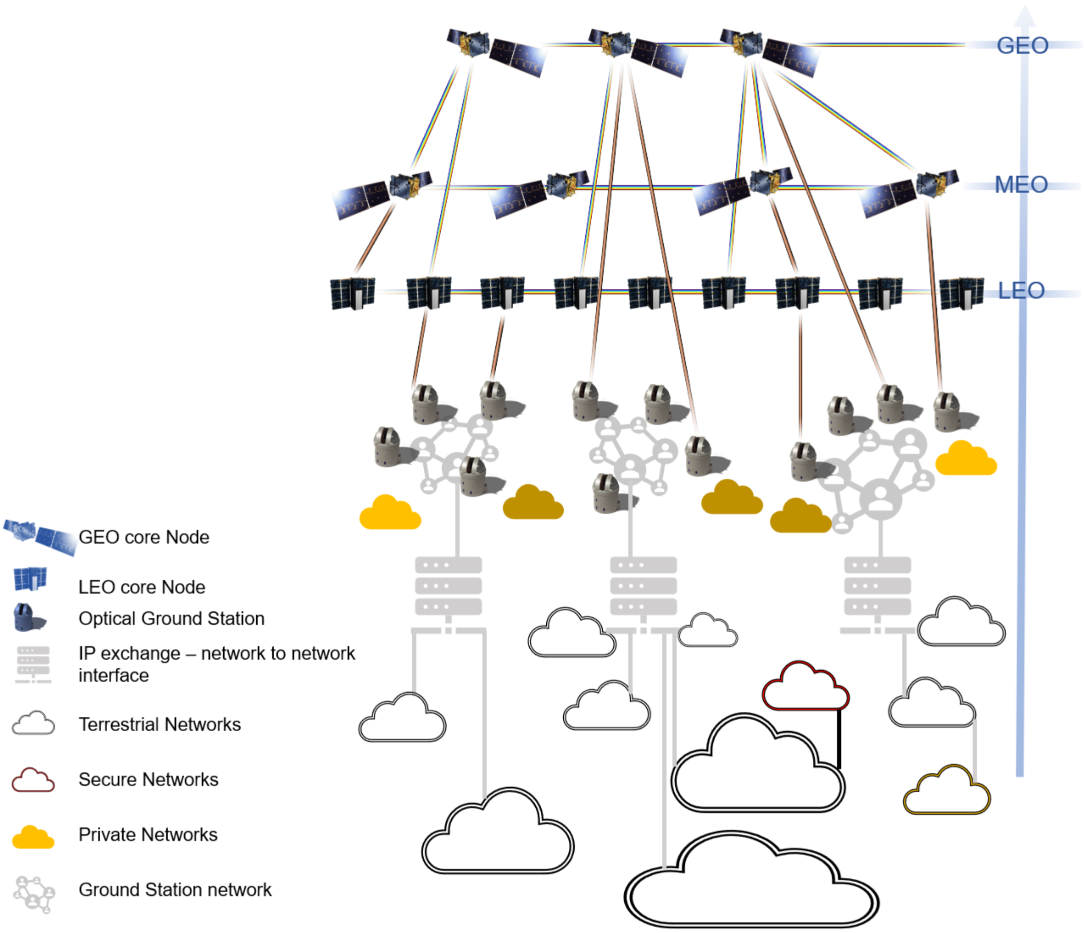


Figure 1 Vision of a high throughput optical space network bringing high data rate terrestrial connectivity to multiple space users across different orbits (e.g., LEO, MEO, GEO) and to ground users located in remote areas with no available broadband access.

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/sec 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.

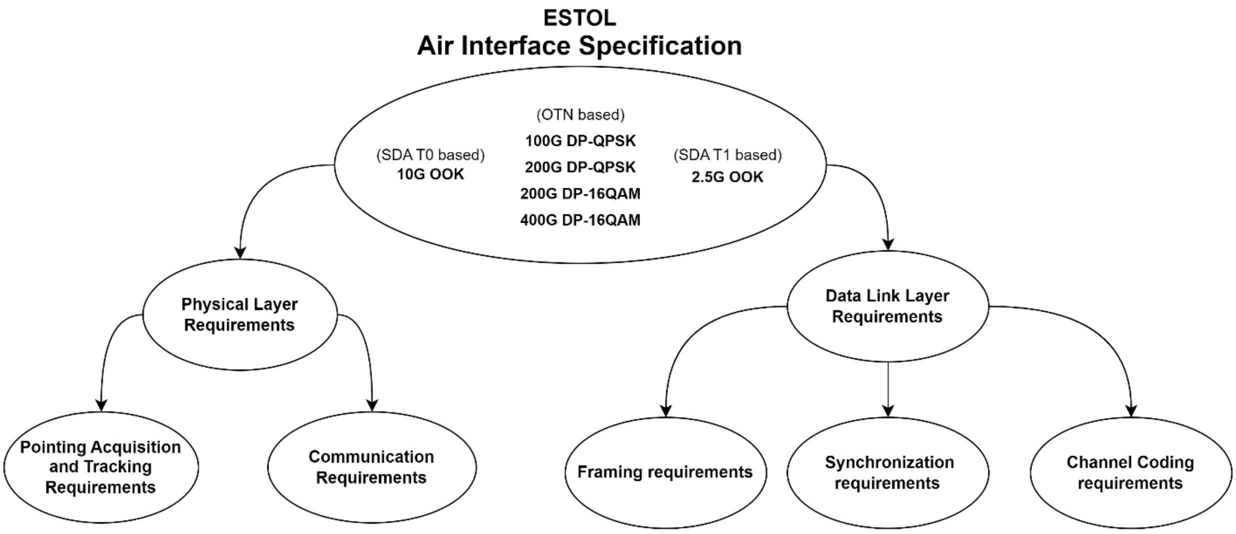


Figure 2 Air Interface specification contents

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 fibre terrestrial networks, where it became the common solution to reach terabit/sec communication links. This air interface specification targets an extension of the terrestrial network in 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 this air interface will guarantee interoperability for 100G+ future connections that allows to use technology developments of the fibre-communication market and paves the path to unprecedented high data rate satellite connections. This specification includes also 10 Gbps solutions, as intermediate step from EDRS data rates towards 100G 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.

1.1. 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). It may also include link quality information between adjacent nodes, which could be used to optimize or re-establish an 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.

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

1.2. Conventions

- Requirements can be normative text or enumerated requirements. Enumerated requirements are labelled according to the following descriptions:
    - PHY: Physical Layer requirements (Chapter 2)
    - DLL: Data Link Layer requirements (Chapter 3)
- All values defined in this document are specified end-of-life.
- Firm requirements are specified by means of “*shall*”.
- Optional (but desirable) requirements are specified by means of “*should*”.

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 stablish 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].

REQ-PHY-010 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: The process from the SDA standard is selected as baseline, with the modifications defined by the following requirements.

REQ-PHY-020 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.

REQ-PHY-030 The PAT acquisition time (defined as warm start in 2.1.6 of [RD-2]) shall be below 60 s, within the uncertainty cone.

REQ-PHY-040 The PAT acquisition time (defined as warm start in 2.1.6 of [RD-2]) should be below 30 s, within the uncertainty cone.

REQ-PHY-050 The PAT re-acquisition time shall be below 10s.
Note: the re-acquisition time is defined as the time from fine acquisition to tracking.

REQ-PHY-060 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.

REQ-PHY-070 The transmitter shall be capable of providing a sinusoidal amplitude modulated signal, defined as “tracking tone” for acquisition and tracking purposes.

REQ-PHY-080 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.

REQ-PHY-090 The tracking tone shall be settable for TX and RX at 40 and 50 kHz.

REQ-PHY-100 Additionally, the tracking tone should be settable for TX and RX at 60 and 70 kHz.

REQ-PHY-110 The deviation of the nominal tracking tone frequency from nominal shall be less than 1000 ppm.

REQ-PHY-120 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: 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.*

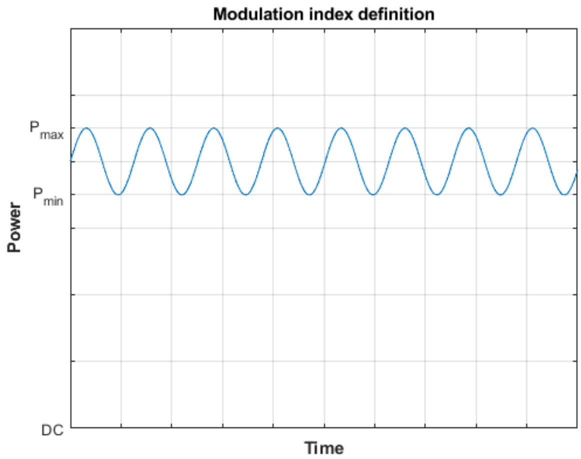


Figure 3. Modulation index definition

REQ-PHY-130 The error in the modulation index shall be not greater than 20% of the setting value.

REQ-PHY-140 The mean power of the modulated signal fraction (MMSF) into the receiver's aperture shall be at least -40 dBm.
Note: This value includes already 3 dB margin.
Note: 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.*

REQ-PHY-150 In case a beacon signal is implemented for acquisition purposes, it shall be capable of providing a tracking tone as defined previously.

REQ-PHY-160 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 from 10 Gbps up to 800 Gbps can be multiplexed together. 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 1. 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

REQ-PHY-170 Communications shall take place in the optical C-band and L-band.

REQ-PHY-180: The frequency channel grid shall use nominal central frequencies for DWDM as defined in Table 1 and Figure 4.

ESTOL #	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	U18	U19	U20	U21
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 #	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20	L21
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

Figure 4. ESTOL Wavelength plan

REQ-PHY-190 Channels U1 and L1 (highlighted in Table 1 and Figure 4) shall be reserved for OOK IM/DD.

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

REQ-PHY-200 Coherent modulation data channels shall be allocated into the channels U2-21 and L2-L21 starting in U2/L2.

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

REQ-PHY-210 Multiple WDM channels shall be allocated in consecutive increasing ESTOL channel numbers.

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

REQ-PHY-220 Bidirectionality of optical links: All optical links shall be bidirectional (either symmetric or asymmetric in terms of user data rate).

Rationale: This 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.

REQ-PHY-230: The isolation between Rx and Tx shall be based on spectral separation and split the band into an upper and lower frequency region as seen in Table 1.

Note: the isolation band between both beam directions will limit the maximum number of possible WDM channels that can be implemented. Typically, the isolation band is ~10 nm wide.

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

REQ-PHY-240 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

REQ-PHY-250 The symbol rates for each modulation shall be chosen among the ones included in the table below:

Type of detection scheme	Type of modulation scheme	Symbol rate (per polarisation if applicable)
Coherent	DP-QPSK or DP-16QAM	31.5 Gbaud or 62 Gbaud [RD-5]
IM/DD	OOK	2.5Gbaud or 10 Gbaud

REQ-PHY-260 Doppler frequency offset pre-compensation: the Doppler effects shall be accommodated to a level such to avoid additional penalties compared to the frequency offset allowed in [RD-5] for coherent detection schemes.

2.3.2. Signal power

REQ-PHY-270 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.

REQ-PHY-280 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: 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.

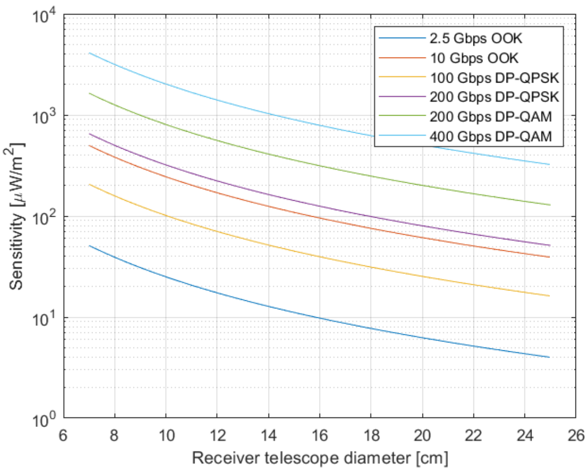
REQ-PHY-290 Output power tolerance: the actual output power should be within 20% tolerance of the set power value.

REQ-PHY-300-350 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 as follows:

		Space terminal	**Ground terminal**
	Modulation	$\boldsymbol{P_{RX}}$	$\boldsymbol{P_{RX}}$
REQ-PHY-300	DP-QPSK 100 Gbps	-31.7 dBm	-23.7 dBm
REQ-PHY-310	DP-QPSK 200 Gbps	-26.7 dBm	-18.7 dBm
REQ-PHY-320	DP-16QAM 200 Gbps	-23.2 dBm	-15.2 dBm
REQ-PHY-330	DP-16QAM 400 Gbps	-19.7 dBm	-11.7 dBm
REQ-PHY-340	IM/DD-OOK 2.5 Gbps	-37.1 dBm	-29.1 dBm
REQ-PHY-350	IM/DD-OOK 10 Gbps	-27.2 dBm	-19.2 dBm

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

Note: the total collected power P_{RX} includes the required signal level for both communications and acquisition and tracking system. The ground terminal values consider additional optical and coupling losses, to account for (e.g.) reduced mean coupling efficiency.
Note: following information shall be provided to guarantee a compatibility among terminals: maximum transmit power, transmit divergence and terminal aperture diameter(s).
Note: 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	101 µW/m²
DP-QPSK 200 Gbps	320 µW/m²
DP-16QAM 200 Gbps	803 µW/m²
DP-16QAM 400 Gbps	2018 µW/m²
IM/DD-OOK 2.5 Gbps	25 µW/m²
IM/DD-OOK 10 Gbps	244 µW/m²

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.

REQ-PHY-360-410 The minimum in-band optical signal-to-(noise + interference) ratio (i.e., optical S/(N+I)) at the transmitter 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)
REQ-PHY-360	DP-QPSK 100 Gbps	20 dB
REQ-PHY-370	DP-QPSK 200 Gbps	25 dB
REQ-PHY-380	DP-16QAM 200 Gbps	28.5 dB
REQ-PHY-390	DP-16QAM 400 Gbps	32 dB
REQ-PHY-400	IM/DD-OOK 2.5G	12 dB

REQ-PHY-410	IM/DD-OOK 10G	15 dB

Note: 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: 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 (REQ-PHY-300 to REQ-PHY-330) were calculated.

REQ-PHY-420 The maximum peak PDL 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 < 1.5 dB for coherent systems.

REQ-PHY-430-450 The maximum PMD (average) 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 the values specified in the table below, for the respective data-rate for coherent systems.

Requirement	Data-rate	Maximum PMD (average)
REQ-PHY-430	400G	10 ps
REQ-PHY-440	200G	12.5 ps
REQ-PHY-450	100G	15 ps

Note: the PMD tolerance limits includes the transceiver-transmitter maximum X-Y skew. The PMD tolerance at the aperture allows a maximum of 3 dB PMD increase in the receiver optical chain before the transceiver.

REQ-PHY-460 The maximum changing rate in SOP over all PMD and PDL values at the receiver aperture of the optical head unit shall be < 25 krad/s for coherent systems.

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 to a large extent on existing terrestrial standards (such as the OpenROADM v.5.1 specification [RD-5]) and other space (SDA T1 [RD-2], [RD-7]). In particular,

- the 100G coherent air interface relies 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 0 for both the framing structure and the FEC (Reed-Solomon).

3.1. Data rates

REQ-DLL-010-060 The air interfaces shall offer the user data rates specified in the table below per wavelength based on the respective air interface (at the respective symbol rate).

Requirement	User net data rate (upper bound)	Air interface	Symbol rate
REQ-DLL-010	99.5328 Gbps	100G DP-QPSK	31.5 Gbaud
REQ-DLL-020	2 x 99.5328 Gbps	200G DP-16QAM	31.5 Gbaud
REQ-DLL-030	2 x 99.5328 Gbps	200G DP-QPSK	62 Gbaud
REQ-DLL-040	4 x 99.5328 Gbps	400G DP-16QAM	62 Gbaud
REQ-DLL-050	1.174 Gbps - 2.221 Gbps*	2.5G IM/DD OOK	2.5 Gbaud
REQ-DLL-060	6.121 Gbps	10G IM/DD OOK	10 Gbaud

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

3.2. 100G and higher

3.2.1. Framing

REQ-DLL-070 The 100G and higher air interfaces shall implement OpenROADM v.5.1 specification [RD-5].

Note: 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. Alignment Markers (AM), Padding (PAD) and OverHead (OH) are inserted in the first row of each FlexO frame. The FlexO payload and overhead areas are fully protected with oFEC.

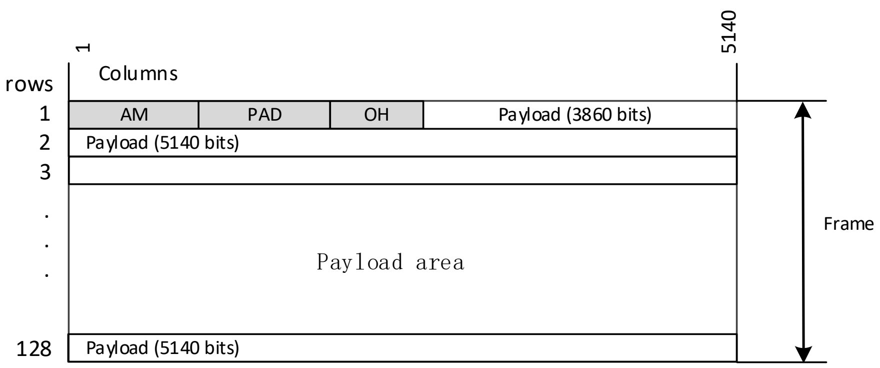


Figure 6. FlexO frame structure.

REQ-DLL-080 The client format shall support both ODU4 and 100GbE signals.

REQ-DLL-090 The client format should support both OTUC1/OTUC2/OTUC3 and 100GbE/200GbE/400GbE signals.

REQ-DLL-100 The GCC0 channel defined for OTU frames shall be used to transport the control and management plane traffic.

REQ-DLL-110 Control and management traffic should be multiplexed in the data-plane as packets.

REQ-DLL-120 Control and management traffic should be transmitted/received in the U1/L1 optical channels using OOK IM/DD as defined in section 3.3 and section 3.4.

3.2.2. FEC

REQ-DLL-110 The post-FEC BER of the 100G air interface shall provide quasi-error free communication.

REQ-DLL-120 The FEC for the 100G, 200G, and 400G air interfaces shall implement oFEC as defined by [RD-10].

3.3. 2.5G OOK

3.3.1. Framing

REQ-DLL-130 The 2.5G OOK air interface shall implement the frame structure described in Section 3.4.1 of [RD-2] that includes (see Figure 7):

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)) (8448+32 bits)
d) then a variable number of parity bits.

Preamble (64 bits)	Header (960 bits)	Payload data (8448 bits)	CRC (32 bits)	parity (variable)

Figure 7. 2.5G OOK frame structure.

REQ-DLL-140 The data plane shall be mapped in DATA frames (FRAME_TYPE 01), as defined in [RD-2].

REQ-DLL-150 The CMP transport channel shall be mapped in MGMT frames (FRAME_TYPE 10), as defined in [RD-2].

3.3.2. FEC

REQ-DLL-160 The post-FEC BER of the 2.5G OOK air interface shall provide quasi-error free communication.

REQ-DLL-170 The FEC for the 2.5G OOK air interface shall be the 5G New Radio LDPC as described in 3GPP document [RD-8] with code-rate between 0.5 and 0.9.

REQ-DLL-180 The 2.5G OOK air interface shall implement for the payload bits 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].

REQ-DLL-190 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.

3.3.3. Scrambling

REQ-DLL-200 All portions of the 2.5G OOK frame, except for the Preamble Sequence, shall be scrambled prior to transmission as described in 3.4.2.3 of [RD-2].

3.4. 10G OOK

3.4.1. Framing

REQ-DLL-210 The 10G OOK air interface shall implement the frame structure described in Section 2.6.3.1 of [RD-7] consisting of (see
Figure 8):

a) a preamble sequence (72 bits)
b) concatenated with a fixed-length header (256 bits)
c) a fixed-length payload carrying 16320 information bits.

Preamble (72 bits)	Header (256 bits)	Payload data (16320 bits)

Figure 8. 10G OOK frame structure.

REQ-DLL-220 The data plane shall be mapped in DATA frames (FRAME_TYPE 01), as defined in [RD-2]

REQ-DLL-230 The CMP transport channel shall be mapped in MGMT frames (FRAME_TYPE 10), as defined in [RD-2]

3.4.2. FEC

REQ-DLL-240 The post-FEC BER of the 10G OOK air interface shall provide quasi-error free communication.

REQ-DLL-250 The FEC for the 10G OOK air interface shall as follows:

- Information bits shall be protected by CRC's (Section 2.6.3.6.1 of [RD-7]., header: 16 bits, payload: 32 bits)
- Fixed-rate (shortened) Reed-Solomon code shall be used for the frame Header (Section 2.6.3.6.2 of [RD-7])
- Fixed-rate Reed-Solomon code shall be used for the frame Payload (Section 2.6.3.6.3 of [RD-7]).

3.4.3. Scrambling

REQ-DLL-260 The 10G OOK air interface shall apply the scrambler and Line Product Code (LPC) from the CCSDS Orange Book [RD-6]. The scrambler follows Section 3.3.2.3.3.1 of [RD-6].

3.5. Time diversity for bidirectional satellite-to-ground links

This section is currently under discussion, and it will be updated in the next issues of this specification.