ESA SPECIFICATION FOR TERABIT/SEC OPTICAL LINKS (ESTOL)

Prepared by	ESA and Industry of ESA member states
Document Type	Specification
Reference	ESA-CSC-T-SP-0001
Issue/Revision	1.0
Date of Issue	19/07/2023
Status	Approved

APPROVAL

Title	ESA Specification for Terabit/sec Optical Links (ESTOL)		
Issue Number	1	Revision Number	0
Author	ESA and Industry of ESA member states	Date	19/07/2023
Approved By	ESA-CSC	Date of Approval	19/07/2023

CHANGE LOG

ESA Specification for Terabit/sec Optical Links (ESTOL)	Issue Nr	Revision Number	Date
New document	1	0	19/07/2023

CHANGE RECORD

Issue Number 1	Revision Number 0		
Reason for change	Date	Pages	Paragraph(s)
New document	19/07/2023	All	All

DISTRIBUTION

Name/Organisational Unit

Table of Contents

List of Contributors 4
Table of Acronyms 5
Reference documents 7
1. Introduction 8
1.1. Definitions 12
1.2. Conventions 13
2. Physical Layer requirements 14
2.1. Pointing, Acquisition, and Tracking (PAT) 14
2.2. WDM requirements 15
2.3. Transmitted optical signal requirements 18
2.3.1. Modulation scheme and transmitted signal properties 18
2.3.2. Signal power 19
3. Data Link Layer requirements 22
3.1. Data rates 22
3.2. 100G and higher 22
3.2.1. Framing 22
3.2.2. FEC 23
3.3. 2.5G OOK 24
3.3.1. Framing 24
3.3.2. FEC 24
3.3.3. Scrambling 25
3.4. 10G OOK 25
3.4.1. Framing 25
3.4.2. FEC 26
3.4.3. Scrambling 26

List of Contributors

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 from June 2022 until July 2023.

The list of industrial entities and research institutes who provided inputs and reviewed the present document is the following:

- ADVA (Germany)
- Airbus Defence & Space (Germany)
- Airbus Defence & Space (Netherlands)
- Deutches zentrum für Luft und Raumfahrt (Germany)
- Henrich Hertz Institute (Germany)
- Honeywell (Canada)
- Joanneum Research (Austria)
- mBryonics (Ireland)
- Mynaric (Germany)
- Officina Stellare (Italy)
- Safran Data Systems (France)
- Scuola Superiore Sant'Anna (Italy)
- Synopta (Switzerland)
- Tesat Spacecom (Germany)
- Thales Alenia Space (Italy)
- Thales Alenia Space (Switzerland)
- TNO (Netherlands)
- Work-Microwave (Germany)

Besides, within ESA, the present document is a result of a cross-directorate effort with the support from the following Directorates:

- CSC (Directorate of Connectivity and Secure Communications)

- OPS (Directorate of Operations)
- TEC (Directorate of Technology, Engineering & Quality)

Table of Acronyms

BER	Bit Error Rate
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
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
HydRON	High Throughput Optical Network
ID	Identification
IM/DD	Intensity Modulation Direct Detection
ITU	International Telecommunication Union
LCT	Laser Communication Terminal
LEO	Low Earth Orbit
LDPC	Low-Density Parity Check
LPC	Line Product Code

MEO	Medium Earth Orbit
MSA	Multi-Source Agreement
NCG	Net Coding Gain
NR	New Radio
OCT	Optical Communications Terminal
oFEC	Open Forward Error Correction
OGS	Optical Ground Station
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), 9100-001-05 "Optical Communications Terminal (OCT)," Standard Version 3.0, 27/08/2021	Tranche 1 (T1) 9100-001-05 3.0
[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

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 taking into account particular 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) 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.

HydRON (High Throughput Optical Network) 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.

The present document, ESTOL, is the ESA's response to provide a specification for high data rate optical links (towards terabit/sec) to support the HydRON vision. HydRON vision will make use of ESTOL to foster interoperability between HydRON nodes (located in space or on ground) interconnected by means of high data rate optical links.

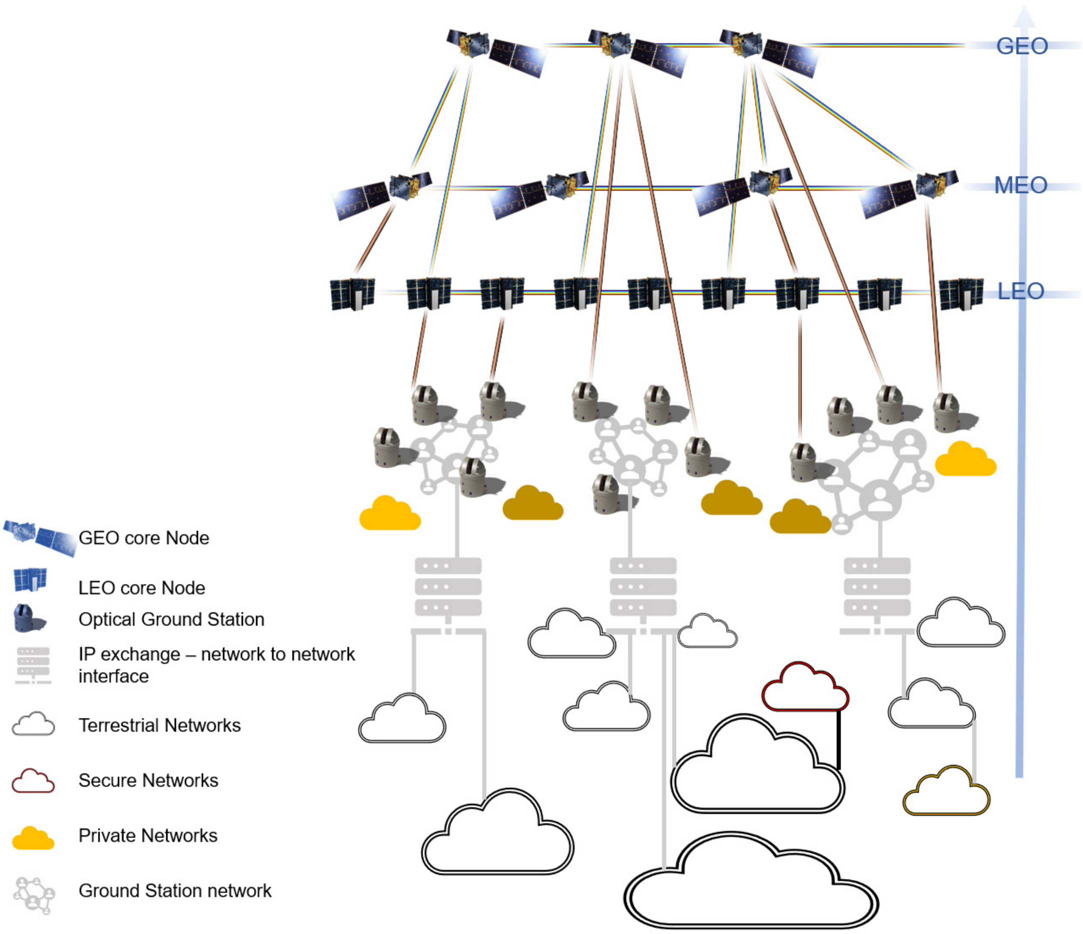

Figure 1 Vision of a high throughput optical space network bringing high data rate terrestrial connectivity to multiple space users across different orbits (e.g., LEO, MEO, GEO) and to ground users located in remote areas with no available broadband access.

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) between space nodes in various Earth orbits (LEO, MEO, GEO) at very high data rates per individual wavelength and potentially exceeding 1 Tbit/s by means of multiple wavelengths (WDM) per link and direction.

Note: the present document will be expanded at a later stage to also include the specification of the optical interface for optical ground-space links (OGSL) between worldwide distributed ground nodes and space nodes in various Earth orbits (LEO, MEO, GEO) at very high data rates per individual wavelength and potentially exceeding 1 Tbit/s by means of multiple wavelengths (WDM) per link and direction, as indicated in Figure 1.

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 in order 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.

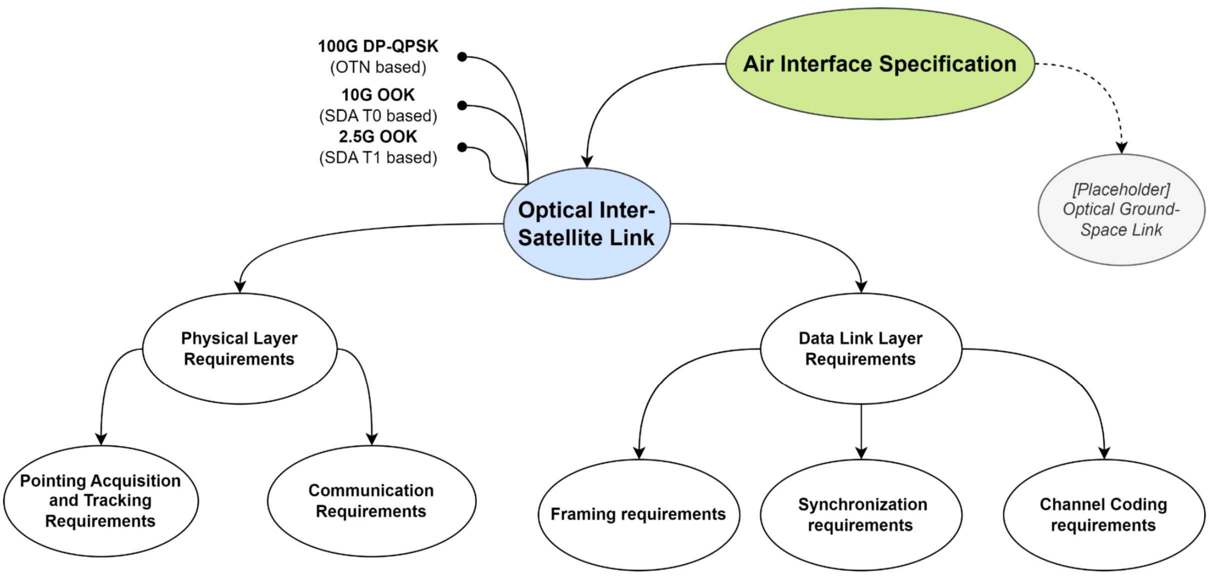

Figure 2 Air Interface specification contents

Coherent roadmap *– Future upgradability*

This specification relies upon standards describing fiber-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 for risk mitigation, 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 LCTs or between LCT and OGS (presently not covered in this document). The air interface specification should cover the elements as per Figure 1.

Beacon-aided systems: optical terminals using a dedicated laser for 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 provide 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.

LCT: Optical payload combining optical head(s), PAT mechanism(s) and electronic-photonic unit(s).

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 inter-satellite links (OISL): Optical links between LCTs 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^{-12}.

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 requirements in [RD-2], 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 PAT system shall be compatible with beacon and beaconless acquisition approaches.

REQ-PHY-030 The PAT system shall allow for a non-time tagged response from the counter terminal during coarse acquisition. From that point on both terminals transmit and receive at the same time, to minimize coarse acquisition time.
Note: a time-tagged start of the course acquisition is mandatory

REQ-PHY-040 The acquisition scan shall guarantee that the illumination duration of the receiver acquisition sensor has a duration of at least 100 μs, for each hit-event.

REQ-PHY-050 The acquisition and tracking shall be in implemented in DC, without any tracking tone.

REQ-PHY-060 The PAT acquisition time (defined as cold start in 2.1.6 of [RD-2]) shall be below 60 s.

REQ-PHY-070 The PAT acquisition time (defined as cold start in 2.1.6 of [RD-2]) should be below 30 s.

REQ-PHY-080 The PAT re-acquisition time (defined as warm start in 2.1.6 of [RD-2]) shall be below 10s.

REQ-PHY-090 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.

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.

The use of 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]. The definition considers the C-band and more concretely the part of the spectrum with the highest optical amplification efficiency based on current available technology and near-future expected developments.

REQ-PHY-100 Communications shall take place in the optical C-band and L-band.

REQ-PHY-110: The frequency channel grid shall use nominal central frequencies for DWDM as defined in Table 1 below for 17 channels per direction:

Table 1. Frequency channel grid.

Channel ID	ITU channel	center frequency (THz)	wavelength (nm)
U1	17	194.5	1541.35
U2	18	194.4	1542.14
U3	19	194.3	1542.94
U4	20	194.2	1543.73
U5	21	194.1	1544.53
U6	22	194.0	1545.32
U7	23	193.9	1546.12
U8	24	193.8	1546.92
U9	25	193.7	1547.72
U10	26	193.6	1548.51
U11	27	193.5	1549.32
U12	28	193.4	1550.12
U13	29	193.3	1550.92
U14	30	193.2	1551.72
U15	31	193.1	1552.52
U16	32	193.0	1553.33
U17	33	192.9	1554.13
L1	34	192.8	1554.94

L2	35	192.7	1555.75
L3	36	192.6	1556.55
L4	37	192.5	1557.36
L5	38	192.4	1558.17
L6	39	192.3	1558.98
L7	40	192.2	1559.79
L8	41	192.1	1560.61
L9	42	192.0	1561.42
L10	43	191.9	1562.23
L11	44	191.8	1563.05
L12	45	191.7	1563.86
L13	46	191.6	1564.68
L14	47	191.5	1565.50
L15	48	191.4	1566.31
L16	49	191.3	1567.13
L17	50	191.2	1567.95

REQ-PHY-120 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-130: 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.

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-140 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-150 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-160 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-170 LCTs 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-180 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-190 Output power tolerance: the actual output power should be within 20% tolerance of the set power value.

REQ-PHY-200-260 The minimum irradiance delivered at the entrance of the receiver aperture of the optical head unit shall be larger than the value specified in the table below for the corresponding modulation of the optical channel.

Requirement	Modulation	Irradiance
REQ-PHY-200	DP-QPSK 100 Gbps	30 µW/m²
REQ-PHY-210	DP-QPSK 200 Gbps	100 µW/m²
REQ-PHY-220	DP-16QAM 200 Gbps	250 µW/m²
REQ-PHY-230	DP-16QAM 400 Gbps	800 µW/m²
REQ-PHY-240	IM/DD-OOK 2.5 Gbps	12.5 µW/m²
REQ-PHY-250	IM/DD-OOK 10 Gbps	50 µW/m²

Note: the irradiance specifies the combined minimum signal level for acquisition, tracking and communications.

Note: the power values specified in this document do not include margin. Following margins can be considered:

- *a system margin >1dB for communications at the receiver part and at the transmitter part is to be included (e.g., in total 2dB communications link-budget margin).*
- *a system margin >2dB for tracking at the receiver part and at the transmitter part is to be included (e.g., in total 4dB tracking link-budget margin).*
- *a system margin >3dB for acquisition at the receiver part and at the transmitter part is to be included (e.g., in total 6dB acquisition link-budget margin)*

REQ-PHY-260-310 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)**
REQ-PHY-260	DP-QPSK 100 Gbps	20 dB
REQ-PHY-270	DP-QPSK 200 Gbps	25 dB
REQ-PHY-280	DP-16QAM 200 Gbps	28 dB
REQ-PHY-290	DP-16QAM 400 Gbps	30 dB
REQ-PHY-300	IM/DD-OOK 2.5G	12 dB
REQ-PHY-310	IM/DD-OOK 10G	15 dB

Note: the specification defines the minimum optical S/(N+I) to be guaranteed by the transmitter at the entrance of the receiver aperture, available for acquisition, tracking and communications. The optical S/(N+I) at the aperture allows a maximum of 3 dB penalty in the receiver optical chain before the transceiver.

REQ-PHY-320 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-330-350 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-330	400G	10 ps
REQ-PHY-340	200G	12.5 ps
REQ-PHY-350	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-360 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 3 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.

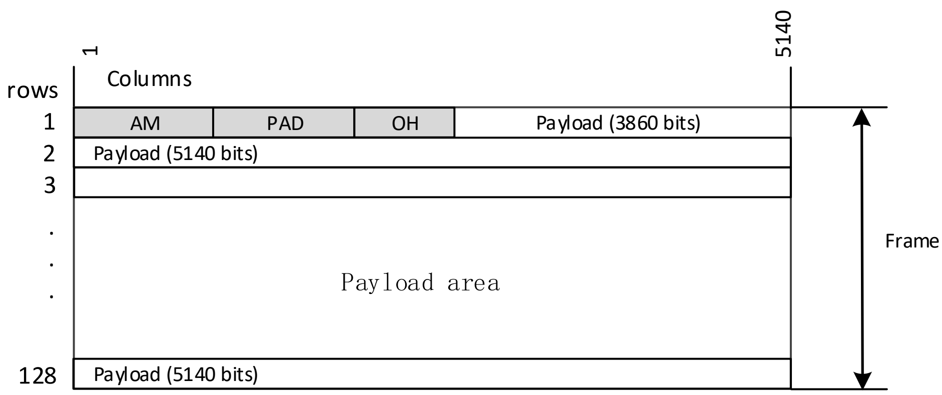

Figure 3. FlexO frame structure.

REQ-DLL-080 The client format shall support both OTU4 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 each OTU4 or OTUCn signal shall be used to transport the control and management plane data.

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 **Error! Reference source not found.**):

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.

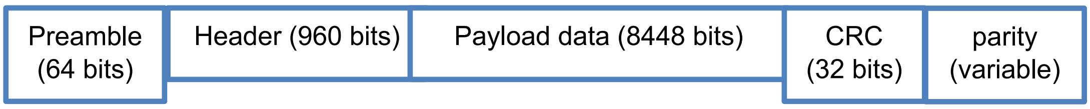

Figure 4. 2.5G OOK frame structure.

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 (Low Density Parity Check) 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 5):

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

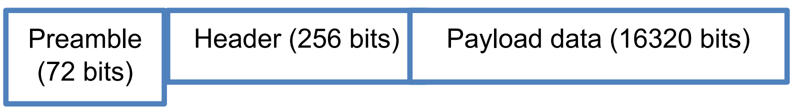

Figure 5. 10G OOK frame structure.

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].