

On customisation of optical transceivers for cross-atmospheric satellite links

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ABSTRACT

Optical inter-satellite links are emerging as a cornerstone of next-generation non-terrestrial networks, enabling high-capacity, low-latency, and interference-resilient communication for both commercial constellations (e.g., Starlink, OneWeb, AmazonLEO) and institutional missions (e.g., HyDRON, IRIS², SDA). Their seamless integration with terrestrial architectures further underscores their strategic importance. A key challenge lies in achieving interoperability and scalability across diverse optical waveforms whilst minimizing hardware complexity, particularly in the optical front-end and digital signal processing layers. To fully exploit the benefits, we aim to consider besides optical inter-satellite links also, and especially, the optical ground to space links by introducing the channel models and considerations for selected scenarios.

Keywords: Coherent optical transceiver, optical satellite links, atmospheric turbulence, FEC

1. INTRODUCTION

Next-generation multi-orbit satellite constellations (e.g., Starlink, HyDRON, Kuiper) rely heavily on optical inter-satellite links (OISLs) and ground-space links (OGSL) to achieve high-throughput, low-latency global connectivity. Whilst commercial-off-the-shelf (COTS) coherent optical transceivers have enabled rapid deployment in low earth orbit (LEO), their performance degrades significantly under cross-atmospheric conditions, particularly during grazing incidences due to atmospheric turbulence causing scintillation and beam wander. These effects induce rapid fading, phase distortions, and signal outages—challenges not adequately addressed by terrestrial fiber-optimized designs.

The assumption that COTS transceivers can be directly and ubiquitously deployed in space is increasingly untenable. As constellations expand into higher orbits (medium earth orbit (MEO), geostationary earth orbit (GEO)) and demand robust, end-to-end optical connectivity, the dynamic, non-stationary nature of the space-to-ground channel demands transceivers that are not just adapted, but purpose-built. Without custom design, performance bottlenecks in timing recovery, equalization, and forward-error correction (FEC) resilience will limit scalability, reliability, and spectral efficiency—especially in multi-layer, multi-orbit architectures.

Communication constellations are already providing evidence of feasibility of OISLs using COTS digital coherent optics (DCO), e.g. Starlink, AmazonLEO; and explored coherent waveforms, e.g. 2.5–10 Gbps in HyDRON. Research on adaptive optics, turbulence mitigation, and channel modeling^{1,2} has advanced our understanding of atmospheric effects. Field programmable gate array (FPGA)-based reconfigurable transceivers and software-defined concepts are emerging. However, to the best of authors' knowledge, no system has yet demonstrated end-to-end resilience under realistic, time-varying atmospheric fading with full reconfigurability and on-board networking capabilities.

In the paper, we present framework for designing custom, reconfigurable optical transceivers for multi-orbit satellite constellations. The use cases are defined not only for SatCom, but also include future global navigation satellite systems (GNSS). We define a channel model for cross-atmospheric optical links, including time-varying fading, turbulence, and system-level effects. This leads to a discussion on a number of physical-layer properties that need to be considered in future customisations of optical transceivers, including signal processing and FEC.

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2. USE CASE DEFINITION

First, it is necessary to establish which use cases are to be considered. For that, we shall look into which satellite communications (SatCom) scenarios nowadays include or consider to include the optical satellite links. There are dominantly two areas of customers - commercial and governmental.

Commercial operators of satellite constellations with operational optical links are SpaceX with Starlink^{3,4}, OneWeb, Amazon with AmazonLEO and in future also Telesat with Lightspeed constellation.⁵ All of these have or plan to implement optical inter-satellite links to form mesh interconnected satellite network. Then, for the sake of simplicity, we consider as governmental customers not only directly governmental institution or European Union, but also national or international space agencies, such as ESA, NASA, UKSA and CNSA.

A notable European example of optical terminal developments are the commercially available laser communications terminals (LCTs) by TESAT.⁶ German Aerospace Center (DLR) has been conducting optical communications terminal development under its OSIRIS programme.⁷ Currently, the portfolio spans from an optical terminal integrated within 1/3 of CubeSat volume, CubeLCT, through a full payload incl. on-board computer, optical amplifier and a coarse-pointing assembly, CubeISL, to an optical terminal for quantum-key distribution demonstrations, QUBE, currently launched in its 2nd iteration and 3rd one in development.

To ensure interoperability of satellite systems and devices implemented by various vendors and institutions, common specification or standard must be followed. The first such endeavours were Consultative Committee for Space Data Systems (CCSDS) standard 141.0-B-1 describing optical on-off keying (O3K) and high photon efficiency (HPE) configurations. These defined non-coherent OGSL for early implementations of LCTs in 1064 nm and 1550 nm including defined physical and synchronisation layer properties. Later, Space Development Agency (SDA) introduced a specification, which due to its widespread use became a de-facto standard for non-coherent LEO-to-LEO OISL. Soon after conceptualisation of the multi-orbit (LEO, MEO and GEO) HydrON system, ESA introduced the corresponding specification ESTOL for both OGSL and OISL. This includes physical and synchronisation and coding layer as well as erasure code-based higher-layer time-diversity fading mitigation option for OGSL.

GNSSs were traditionally developed independently from SatCom systems and constellations. This changed in recent years with planned introduction of optical links for data transfer in GPS. A paradigm shift was introduced with the Kepler system.⁸ There, OISLs are used for time-transfer and ranging supporting the positioning, navigation and timing functionality of future GNSS. This concept, meanwhile validated in DLR laboratory,⁹ is at heart of ESA's in-orbit-demonstration mission OpSTAR, paving path towards introduction of OISL in Galileo 2nd Generation; first time using the same physical channel for high-speed communications capable of Gbps data rates, whilst achieving ps-level time-transfer and mm-level ranging between satellites.

The gap to be closed in the state-of-art optical satellite links and therefore the focus of the paper can be summarised as follows:

- high-throughput (10 Gbps+) data transfer;
- high-accuracy (ps-level / mm-level) time-transfer and ranging functionality;
- multi-orbit capability for OISL as well as OGSL in LEO, MEO and GEO.

To the best of authors' knowledge, there are no optical terminal implementations capable of closing the gap on all three aspects simultaneously. The commercial OISL do provide high data rates, but offer limited range for multi-orbit capability.³ Those that can close both, i.e. long range ($> 40,000$ km) optical links with very high throughput, such as TESAT's SCOT135, do not, at the moment, offer high-accuracy time-transfer and ranging functionality. To close these gaps would currently be only possible with significant cost to the technical budgets (SWaP and link budget) of the respective system, e.g. by adding additional optical link or significantly increase the transmit optical power or the receiving aperture.

We propose customisation of optical transceivers, sometimes referred to as modems. The customisations are discussed separately between physical layer and synchronisation and coding layer. Before that, however, we summarise the design-driving features of the channel model.

3. CHANNEL MODEL CONSIDERATIONS

The targeted scenarios for the development of the custom transceiver can be summarised in two categories: OISLs and OGSLs. The main distinction between the two scenarios, that will be discussed in detail in this section, is to be found in the dominant source of the channel dynamics. OISLs are subject to fluctuations in the received optical power mostly due to platform micro-vibrations that induce residual pointing jitter on the optical terminal. In OGSLs, the dominant factor for channel dynamics resides in the laser beams crossing the turbulent atmosphere, experiencing distortions related to mis-pointing (beam wander) and higher-order distortions of the wavefront (resulting in a scintillation effect).

3.1 OISLs

OISLs represent today the vast majority of the operated optical links. These are more and more used in communications constellations. The physical link is operated in the vacuum, so there are no significant optical propagation effects apart from the free-space loss. The dynamic component on the optical channel is driven by residual pointing jitter as a result of the satellite micro-vibrations. Given the high directivity of the optical beam (with a divergence from 10s to 100s of μrad), the slight mis-pointing can lead to significant losses in the link budget.¹⁰ This effect is described by a Rayleigh distribution and can be treated as a margin for link budgeting purposes, typically in the range of 1 to 2 dB in pointing loss. In this subsection an example for an OISL link budget is shown, considering two main scenarios: LEO-to-LEO, typical for constellation shells; LEO-to-GEO, longest link for multi-orbit scenario. Terminal sizes are considered as follows: 80 mm optical terminals for LEO-LEO links, 135 mm optical terminals for LEO-GEO links. The resulting Link Budget (Received Optical Power or ROP) in Table 1 is to be considered at the entry point of the pre-amplifier.

Table 1: OISLs Link Budgets for exemplary scenarios.

	LEO-LEO	LEO-GEO
Link Distance [km]	3900	42000
Tx Terminal Diam. [mm]	80	135
Rx Terminal Diam. [mm]	80	135
Tx Power [dBm]	33	43
Tx Gain [dB]	101.2	105.7
Rx Gain [dB]	104.2	108.7
Free-Space Loss [dB]	-270.0	-290.6
Tx Optical Loss [dB]	-0.7	-0.7
Tx Pointing Loss [dB]	-2.0	-2.0
Rx Optical Loss [dB]	-2.5	-2.5
Rx Coupling Loss [dB]	-3.0	-3.0
Received Optical Power [dBm]	-39.8	-41.4

As just mentioned, these tables are exemplary. In general the link budget can be scaled by tuning the transmitting power and the optical terminal sizes, while leaving the system-level assumption as is. Notably though, when refining the link budget it should be kept in mind that the optical losses of the terminal may change e.g. due the presence of a central obscuration. Figure 1 shows parametric curves for link budget, using the same assumptions as for Table 1, by changing the terminal size and the optical transmitting power. In Figure 1a, change in terminal size is considered symmetrical, i.e. the transmitter (Tx) terminal scales equally with the receiver (Rx) terminal); in Figure 1b the LEO terminal is kept at 135 mm, while the GEO Rx terminal scales up. This approach was picked with the rationale that due to satellite platform limitations it is unlikely to have terminals larger than 135 mm in LEO orbit. Red dashed lines serve the references for the ROP levels to guarantee communication performances at 10 Gbps or 100 Gbps, assuming a receiver sensitivity of 5 photons-per-bit.¹¹

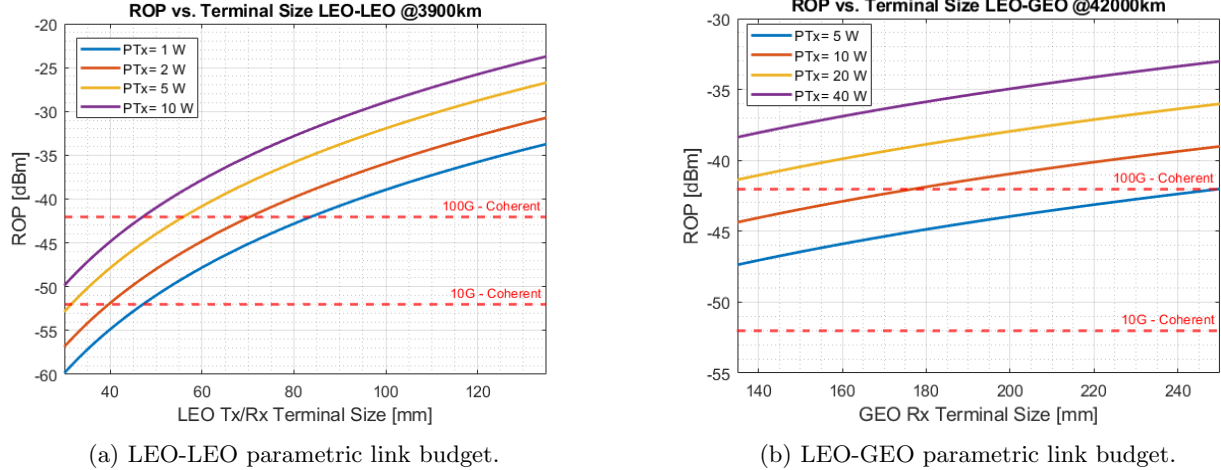


Figure 1: Parametric link budgets for LEO-LEO and LEO-GEO OISLs, for terminal size and Tx power.

3.2 OGSLs

OGSLs are expected to become part of the global communications infrastructure in the coming years, following the already successful demonstrations of the past years. To become a viable solution, OGSLs though require a more distributed ground network (to ensure weather diversity and avoid cloud blockage) and stable channels in the up- and downlink directions. The dominant factor for channel dynamics resides in the laser beams crossing the turbulent atmosphere, experiencing distortions related to mis-pointing (beam wander) and higher-order distortions of the wavefront (resulting in a scintillation effect). Furthermore, the two link directions (uplink and downlink) experience significant different dynamics, due to the typical differences between the ground system (Optical Ground Station, OGS) and the satellite system, and the different interaction with the atmosphere. In the Downlink direction, the scintillation effect is the most significant dynamic contributor in the link budget, when coupling the free-space distorted wavefront into the fibre of the coherent chain. The coupling performance, that depends on the line-of-sight turbulence strength and the adaptive optics system, can be the determining factor on whether the communication link is successful or not. In the Uplink direction, the combination of beam-wander and high-order wavefront distortion provide the most significant dynamic losses in the channel.

In Table 2 example of a link budget for a bi-directional OGSL is shown. This is computed at 30 degrees of elevation, assuming strong turbulence conditions. The coupling loss for the downlink is reported under the term "beam wander + scintillation margin", given the highly dynamic aspect of this effect. "Atmospheric margin" includes the atmospheric absorption, the aerosol attenuation and margin for potential thin clouds in the optical path.

3.3 Effects of the Channel Dynamics on the transceiver

The factors driving the dynamics of the received optical power were discussed in the previous subsections. In this subsection the effects of such dynamics from the perspective of the optical receiver will be discussed. Free-Space Optical Communications for satellite applications mostly relies on pre-amplified receiver systems. Typically, the pre-amplifiers operate in Automatic Gain Control (AGC). This means that the pre-amplifier not only amplifies the ROP to an operational value for the receiver, but it also acts on the intensity fluctuations, providing an optical signal intensity as stable as possible to the receiver. The performance of the receiver does not depend on the input signal intensity per se, rather on the input signal quality, in terms of Optical Signal-to-Noise (OSNR), then converted to electrical SNR (eSNR) in the physical layer after signal demodulation.

The stochastic occurrence of deep fades in the turbulent channel will require a solution for time-diversity for the Digital Signal Processing (DSP) and the FEC schemes used by the transceivers. As discussed in,¹ combining the channel simulation with a receiver noise model, it is possible to obtain an estimate on the SNR range. For

Table 2: OGSLs Budgets, Uplink Direction, for exemplary scenarios.

	Uplink	Downlink
Sat Altitude [km]	625	
OGS Altitude [m]	600	
Elevation Angle [deg]	30	
Link Distance [km]	1115	
Sat Terminal Diam. [mm]	135	
OGS Telescope Diam. [mm]	800	
OGS Tx Beam Divergence [μ rad]	60	
Tx Power [dBm]	40.0	37.0
Tx Gain [dB]	93.5	105.7
Rx Gain [dB]	108.7	124.2
Tx Optical Loss [dB]	-2.0	-0.7
Tx Pointing Loss [dB]	-0.5	-2.0
Rx Optical Loss [dB]	-2.5	-3.0
Rx Coupling Loss [dB]	-3.0	-
Free-Space Loss [dB]	-259.1	-259.1
Atmospheric Margin [dB]	-2.5	-2.5
Beam Wander + Scintillation Margin [dB]	-9.5	-15.0
System Margin [dB]	-3.0	-3.0
ROP [dBm]	-39.9	-18.4

coherent receivers, it is observed that the beating between the Local Oscillator of the receiver and the optical Amplified Spontaneous Emissions (ASE) noise represents the most significant noise source for the receiving system, at the photo-electrical conversion. Other relevant noise sources are the Signal-ASE beating noise, the ASE-ASE beating noise, and the shot noise. These noises sum up linearly, with the assumptions that they are all Additive White Gaussian Noises (AWGN). Table 3 describes the formulation for the main noise contributions.

Table 3: Main noise structure components for a pre-amplified coherent system. For additional information please refer to.¹²

Noise Component	Formulation
Shot Noise	$\sigma_{\text{shot}}^2 = 2qR(P_{\text{RX}}G + P_{\text{LO}})MFB_e$
LO-ASE Noise	$\sigma_{\text{LO-ASE}}^2 = 4R^2P_{\text{LO}}S_{\text{ASE}}B_e$
Signal-ASE Noise	$\sigma_{s\text{-ASE}}^2 = 4R^2GP_{\text{RX}}S_{\text{ASE}}B_e$
ASE-ASE Noise	$\sigma_{\text{ASE-ASE}}^2 = 2R^2S_{\text{ASE}}^2B_e(2B_O - B_e)$

The pre-amplified receiver model works on the assumptions of fixed noise figure F for the pre-amplifier; fixed operating point of the optical power at the input of the receiver (output of the pre-amplifier $P_{\text{RX}}G$); fixed coherent receiver characteristics such as LO power P_{LO} , responsivity of photodiodes R , electrical and optical bandwidths B_e and B_O .

With these assumptions, there is a linear correlation between the Received Optical Power (ROP) at the input of the pre-amplified receiver and the resulting SNR at the photo-electrical conversion. This enables the derivation of a ROP-SNR curve for the given receiver model. This curve can be treated as a look up table: combining a ROP time series, generated by either phase-screen propagation simulations or analytical power vector generators,² with the ROP-SNR, it is possible to obtain a dynamic SNR time series. This SNR time series can be plugged for modelling and investigation of DSP and FEC simulations. Figure 2 shows an intensity power vector, with fades typical of an OGSL link. The received optical power values were coupled with estimated eSNR values for a 100 Gbps DP-QPSK receiver.

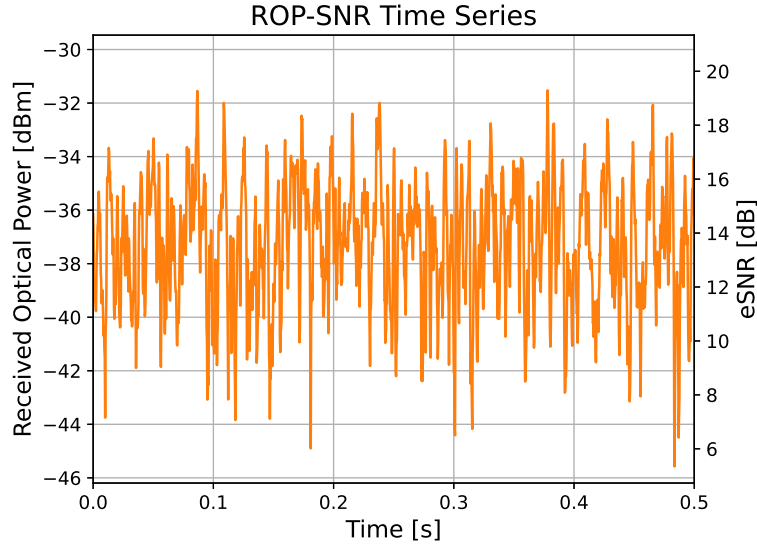


Figure 2: Example of an intensity power vector for an OGSL Link, with corresponding estimated eSNR values.

4. CUSTOM TRANSCEIVER PHYSICAL-LAYER CONSIDERATIONS

In the following chapter, we discuss custom transceiver design and implementation considerations, focusing on physical-layer aspects. Coding aspects are covered in the next Chapter.

First, channel aspects are considered. Introduced in the previous section, the combination of low received optical power and presence of fades are the design driver in the transceiver structure and algorithm selection. Reported in^{13,14} and NASA’s TBIRD mission, the occurrence of fades has detrimental impact on the coherent optical transceiver performance. The main cause of this is the timing recover algorithm used in terrestrial systems optimised for AWGN-like fibre-optic channels. The fades then lead to a loss of lock, which takes several milliseconds to recover after the fade event, thus virtually extending the fade duration. A more substantial analysis was performed in^{15,16} comparing various options for optimisation of such algorithms from the channel perspective, but also in presence of Doppler.

Furthermore, adapting timing recovery algorithms and in particular their custom implementation enables tight synchronisation between two platforms, allowing for ps-level time-transfer (and ranging) for GNSS.¹⁷ This demonstration shows how the same transceiver structure can be employed for both SatCom and GNSS, enabling resilient and scalable high-throughput data transfer and high-accuracy time-transfer and ranging over a single physical optical channel.

Depending on the accuracy required for time-transfer functionality, some system aspects need to be considered in the transceiver structure. These include effects such as change rate of polarisation state but also polarisation mode dispersion. Their value drives not only the algorithm structure but also its implementation complexity. In this respect, one needs to consider the integration aspects of such transceiver in tight coordination with the remaining optical terminal architecture.

Last, but not least, the entire protocol stack may need to be adapted or extended beyond common specifications and standards. In high-accuracy applications, the timestamp resolution needs to be extended, e.g. in some scenarios additional bits needed to be added to SDA-defined timestamps to reach sub-ps performance. Such customisation require corresponding flexibility from specifications, e.g. by including fields for future use, but also from the transceiver implementation. One solution for future-proofing the implementation is the use of reprogrammable platforms, e.g. FPGAs. Keeping in mind their increased SWaP-load, hybrid architectures are proposed; combining ASIC for low-level performance-critical and static algorithms such as frequency and phase compensation with FPGA-based implementations of more flexible functionalities such as framing and timing recovery allows one to introduce SW-defined transceiver for satellite links.

Integral part of the optical transceivers is the photonics, including not only lasers and receivers, but also modulators, hybrids for optical mixing and filters. Currently available components can be categorised into a) bulk components with dedicated function, optical and electrical interfaces and drivers, e.g. optical modulators, and b) photonically integrated components available as complete assemblies either as integrated receivers, incl. hybrids, balanced photoreceiver stages and amplifiers or directly as fully integrated, so-called analogue coherent optics (ACO). As such front-ends are optimised in their functionality, structure, interfaces and performance, i.e. bandwidth, both optical and electrical, customisation on transmitted protocol or waveform requires customisation also of the photonics. Photonic integrated circuits have been investigated at DLR for use in future GNSS and in optical SatCom scenarios.¹⁸ An important aspect to consider is also their radiation robustness, which remains an understudied field.^{19,20}

Finally, after the physical layer, error correcting codes are discussed in the next Section. For fading channels, such as the one encountered in OGSLs, these need to be considered in combination with an appropriate time-diversity scheme. Since the fading causes outages over larger chunks of bits, one can either flag and retransmit entire blocks of data via an automatic repeat request (ARQ) protocol, spread the errors over larger blocks using interleavers²¹ or use erasure codes for correcting of entire packages.²² Especially the latter is considered beneficial in terms of performance and use of on-board resources - even more so when considering data rates of several tens or even hundred Gbps.

5. FORWARD ERROR CORRECTION

In this section, we discuss candidate FEC solutions for the low-data-rate coherent modes, up to 10 Gbps. The main constraints guiding the analysis are: low complexity, so that the FEC can be implemented on-board a satellite on an FPGA; high coding gain, to close the link budget for several scenarios at a target bit error rate (BER) equals to 10^{-9} over a fading-free, AWGN-dominated channel; rate flexibility and the availability of existing decoder implementations.

Wireless and optical standards propose a broad range of code families: classical hard-decision algebraic codes (Reed-Solomon, Bose-Chaudhuri-Hocquenghem, and their concatenations, e.g. International Telecommunication Union (ITU)-T G.975/G.975.1²³); serial turbo-like codes;²⁴ low-density parity-check (LDPC) codes;^{25–30} and product/staircase codes.^{31,32} Algebraic codes were discarded in our analysis despite their low complexity, owing to 3 dB penalty with respect to the Shannon limit at the target BER. Serial turbo codes and some LDPC families (AR4JA,²⁵ DVB-S2²⁶) are, at present, limited by existing decoder implementations to a few hundreds Mbps up to few Gbps. Staircase codes like Open FEC,³¹ Concatenated FEC,³² and, more generally, serial concatenations of algebraic codes or product codes, require large decoder memory. Of the remaining candidates, three LDPC-based solutions were selected for a more detailed analysis: SDA,³⁰ ITU passive optical networks (PON),²⁸ and CCSDS O3K.²⁷

5.1 Candidate Code Families and Trade-Offs

Three LDPC code families were retained for a detailed performance assessment: the LDPC codes adopted by the SDA Optical Communications Terminal (OCT) standard,²⁹ a subset of the 3GPP 5G-New Radio (NR) base-graph-1 family;³⁰ the LDPC code specified by the IEEE 25/50 G PON standard;²⁸ and the CCSDS O3K LDPC code,²⁷ recommended for non-coherent optical communications. Table 4 summarizes their main structural properties.

The SDA and PON code families both derive every supported rate from a *single* mother parity-check matrix, by puncturing parity bits (SDA) or by shortening the information word (PON, e.g., guided by a protograph EXIT analysis³³); a single encoder/decoder pair therefore covers the whole rate range. The O3K code instead specifies an independent parity-check matrix for each of its two rates: the common lifting factor allows some reuse of logic and computational units, but both parity-check matrices must be stored, and the code uses the largest blocklength of the three families (30720 vs. ~ 17 k bits). Because each O3K code is optimized for a single, fixed rate rather than obtained by puncturing or shortening a mother code, it can be designed closer to capacity: the original code family³⁴ spans rates from 2/5 to 9/10 with a small gap to the Shannon limit, although only the rate-1/2 and rate-9/10 codes were eventually retained in the CCSDS O3K recommendation. This design freedom is reflected in the coding gains of Table 4, and FPGA implementations of the O3K code

Table 4: Candidate LDPC code families for the optical PHY layer. The coding gains are relative w.r.t. an uncoded scheme for a target BER= 10^{-9} and 10 iterations of the NMS decoder.

	SDA (5G-NR)	ITU 25/50G PON	CCSDS O3K
Mother matrix	9216×17664	3072×17664	17920×33280 , 4608×32256
Lifting factor Z	384	256	128
Blocklength	9984, 11136, 12672, 16896	up to 17664	30720 (fixed)
Rate range	0.50, 0.67, 0.76, 0.85	0–0.85	0.5, 0.9
Rate adaptation	puncturing	shortening	different codes
Coding gain [dB]	10.85, 10.00,	8.60	10.64, 8.42
E_b/N_0	9.60, 9.00		

family achieving throughputs of 10 Gbit/s already exist.³⁴ Both the SDA and O3K LDPC codes have flight heritage and are already used in some COTS optical transceivers, whereas, to the authors’ knowledge, the PON solution lacks flight experience.

All three families were evaluated over the binary phase shift keying (BPSK) AWGN channel, under belief propagation (BP) and layered normalized min-sum (NMS) decoding,^{35,36} with a limited number of iterations (10 and 20). Because the reported thresholds are expressed per real dimension, they carry over directly to the dual-polarization quadrature phase shift keying (DP-QPSK) signal used on the link, under the assumption of Gray-mapped, independent in-phase/quadrature and polarization branches. At the target BER, the measured coding gains range from about 8.4 to 10.9 dB in E_b/N_0 (equivalently 8.9 to 13.9 dB in E_s/N_0) over the 0.5–0.85 rate range, with a gap to the BPSK-constrained Shannon limit of about 1–1.5 dB for SDA and PON, and, as noted above, of only 1 dB for O3K. The PON and O3K codes show no visible error floor above BER= 10^{-9} ; the SDA code family instead shows a slope change close to the target BER, whose severity depends on the decoder implementation: more pronounced under plain BP than under NMS. This indicates that a real-hardware implementation must carefully choose the decoding algorithm and the quantization of both the channel soft inputs and the internal decoder messages, so as not to worsen the error floor for applications requiring BER= 10^{-9} . For these reasons, all three code families remain viable candidates for the optical laser terminal FEC.

One notable mention, the PON LDPC code was designed originally with 25 and 50G data rate in mind, making it an interesting candidate also for larger data rates beyond 10G. Whereas SDA and O3K LDPC code families lack of known higher data rate implementations.

6. CONCLUSION

The transition from COTS-based optical transceivers to purpose-built, custom-designed systems is no longer a matter of preference, it is a necessity for the next generation of multi-orbit, cross-atmospheric satellite networks. Whilst current systems have demonstrated the feasibility of deploying COTS coherent optics in LEO, their performance under atmospheric turbulence reveals fundamental limitations in resilience, scalability, and multi-orbit interoperability. The dynamic, time-varying nature of the space-to-ground optical channel, characterized by scintillation, beam wander, and rapid fading, cannot be mitigated by terrestrial-optimized DSP chains or fixed FEC schemes.

This paper has demonstrated that customization is not a deviation from standardization, but a strategic enabler of performance, flexibility, and future-proofing. By developing a channel model that captures the full spectrum of atmospheric and system-level effects—including pointing jitter, turbulence, and radiation-induced impairments—we establish a foundation for transceiver design that is truly channel-aware. Our analysis of FEC candidates (SDA 5G-NR, ITU 25/50G PON, CCSDS O3K) confirms that while all offer strong coding gain, O3K and 5G-NR provide the best balance of rate flexibility, low error floor, and FPGA-friendly implementation, especially under fading conditions.

Crucially, we advocate for a hybrid hardware architecture—combining ASICs for high-efficiency, fixed functions, e.g., ADC/DAC, basic equalization, with reconfigurable FPGAs or SoCs for adaptive, software-defined PHY-layer and network functions. This enables on-board gNB-like capabilities, dynamic FEC switching, and resilient timing recovery essential for maintaining lock during outage events and enabling ps-level time-transfer in future GNSS applications.

The path forward is clear: customization is not a risk but the only way to achieve robust, high-capacity, cross-atmospheric optical connectivity at scale. DLR is committed to this effort through validating designs under realistic conditions, and accelerating the transition from concept to flight-ready transceivers.

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