Interoperable Coherent WDM interfaces at 400G and 800G

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Abstract: 400G coherent WDM interfaces were recently standardized by multi-source agreement and standardization forums to enable interoperable operation across DCI, metro/regional and IPoWDM networks of transceivers from various vendors with DSP of different suppliers. The work is under progress for 800G WDM interfaces with the objective to deal with the same use cases at 800G as at 400G. OpenROADM is elaborating for the first time an interoperable probabilistic constellation shaping specification that addresses this need.

1. Introduction

During many years, the WDM domain was dominated by system suppliers that logically proposed their proprietary solutions and technologies. This proprietary environment offered the space to innovate and allowed an unbelievable progress of optical transport networks that were able to cope with traffic increase for 25 years. Thereby, coherent technology enabled an incredible growth of data rate carried by wavelengths from 10G in the middle of 2000's decade to 100G in the early 2010's years, 400G today and soon 800G. However, for data center interconnect (DCI) and metro/regional applications, the lack of openness and interoperability of WDM systems appeared as a real weakness for service providers for both the control (i.e., management) and data (i.e., transceiver) planes. While in the Ethernet area (managed by IEEE [1]) interworking and openness is a reality since a long time, it was not still the case in the WDM domain few years ago. Fortunately, Multi-Source Agreement (MSA) organizations like the Optical Internetworking Forum (OIF) [2], OpenROADM [3], and OpenZR+ [4] but also standardization bodies like ITU-T (more particularly Q11/15) [5] started to break the vendors' lock-in and fostered the emergence of interoperable WDM transceivers at 100G, 200G, 400G and soon at 800G.

Optical communications are thus at a key moment of their history. Indeed, for the first time, the form factor of Ethernet client and short/medium-reach WDM line interfaces can be identical with QSFP-DD, leading to the same bandwidth density for 400G grey (or Ethernet client) and colored (or WDM) optics. That clearly opens the way to disruptive applications like IP over WDM (IPoWDM), potentially allowing major simplification, significant cost reduction and substantial power savings in optical transport networks. More generally, DCI and metro/regional networks require interoperable, low cost and power efficient WDM pluggable optics at the highest possible data rate to carry the ever-increasing traffic demands. Thus, having interoperable 400G and 800G coherent WDM transceivers is crucial.

In this paper, we review the steps that have conducted to the emergence of the interoperable 400G coherent WDM interface specifications in OIF [2], OpenROADM [3] and OpenZR+ [4] forums and we give the status of the work led to have soon interworking 800G coherent WDM interfaces for DCI, metro/regional and IPoWDM applications [6,7]. More particularly, we report the on-going work of the OpenROADM forum on probabilistic constellation shaping (PCS) [7] to build, for the first time, a specification of interoperable 800G coherent WDM interface with PCS able to cope with the challenging OpenROADM requirements like maximum transmission reach, number of crossed reconfigurable optical add/drop multiplexers (ROADM) or power consumption limitation.

2. Interoperable 400G WDM interfaces

The road towards interoperability in the WDM field has known a renewed interest with the work done on coherent 100G WDM interfaces and the associated interoperable forward error correction (FEC) code. The OpenROADM forum under the impulse of service providers (with the support of equipment vendors) decided to build a MSA specification for 100G WDM transceivers [3] to be used in metro/regional optical transport networks equipped with ROADMs. OpenROADM chose the Staircase SC) FEC [8] with 7% overhead as interoperable FEC for 100G WDM interfaces. It was followed by ITU-T which elaborates the G.709.2 *"OTU4 long-reach interface"* standard [5] specifying the SC-FEC as interoperable FEC for 100G coherent WDM systems. When combined with differential encoding, it made 100G coherent WDM interfaces fully inter-workable.

This first step carried out at 100G was essential to favor a large adoption of interoperability for short and medium-reach WDM interfaces. 400G was the first bit rate where interoperability is considered as a normal feature. OIF in the early 2020's years built the 400-ZR MSA [2] for DCI. The 400-ZR optical interfaces can be plugged indifferently in Ethernet switches or IP routers if the transceiver form factor is compliant with the equipment. They particularly address IPoWDM applications, and transport of 400-GbEthernet (GbE) data flows on 40 to 120-km range if optical amplifiers are inserted or not in the system (see Fig.1a). Essentially, the 400-ZR transceivers exploit the C-band and are tunable. They use dual-polarization (DP) 16QAM at 59.84-Gbaud and an interoperable FEC called C-FEC based on the concatenation of an inner Hamming and outer Staircase codes with an overhead of 14.8% [2]. The 400-ZR transceivers require an optical signal-to-noise ratio (OSNR) in back-to-back (BtB) higher than 26-dB in 0.1-nm [2].

Interoperability of 400G transceivers in metro/regional networks was addressed by the OpenROADM [3] and OpenZR+ [4] forums. OpenZR+ is focused on the transport of 400-GbE data frames while OpenROADM encapsulates the 400-GbE flows into optical transport network (OTN) containers. As for 400-ZR, IPoWDM is one of the targeted applications of OpenROADM / OpenZR+ transceivers. Thanks to the Open-FEC (O-FEC) which is more efficient than the C-FEC, the 400-ZR+ (ZR+ for both OpenROADM and OpenZR+) interfaces cover metro/regional distances with multiple fiber spans, optical amplifiers, and ROADMs, as shown in fig. 1b). They use DP-16QAM at 63.14-Gbaud (respectively, 60.13-Gbaud) for 400G-OpenROADM (respectively, 400G OpenZR+) applications and the new interoperable O-FEC (based on block-braided codes) with 15.3% overhead [9]. The 400G-OpenROADM and 400G-OpenZR+ transceivers have a required OSNR (ROSNR) in 0.1-nm of 24-dB [3,4] in BtB.

From its side, the ITU-T Q11/15 working group in the G.709.2 *"OTU4 long-reach interface"* recommendation [5] validates the choice of OIF and OpenROADM / OpenZR+ regarding the C-FEC and O-FEC for 400-ZR and 400-ZR+, respectively, as well as the corresponding application-specific (i.e., 400-ZR or 400-ZR+) bit-to-symbol mapping of 16QAM. Indeed, the bit-to-symbol mapping of 16QAM is different for the 400-ZR and 400-ZR+ transceivers.

Table I below summarizes the main features of the interoperable FEC chosen for the WDM field by the main standardization bodies for 100G [5,8], 400-ZR [2] and 400-ZR+ [3,4] optical transceivers.

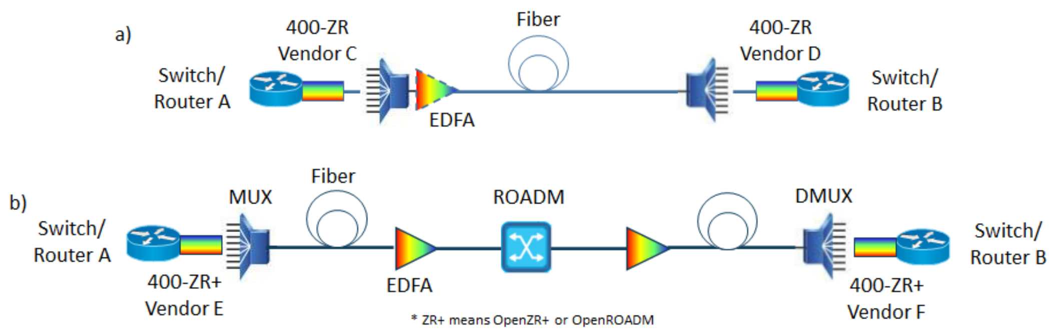

Fig. 1. (a) Typical architecture of an IPoWDM data center interconnect (DCI) link using 400-ZR optical transceivers, (b) typical architecture of an IPoWDM metro/regional link using 400G-OpenROADM / OpenZR+ (called here 400-ZR+) optical transceivers.

Table I. Interoperable FEC for WDM field at 100G and 400G.

	Pre-FEC BER @ FEC Threshold	Overhead	Coding Gain @ 10^{-15}
SC-FEC for 100G WDM applications	4.5×10^{-3}	7 %	9.4 dB
C-FEC for 400-ZR	1×10^{-2}	14.8 %	10.8 dB
O-FEC for 400G OpenZR+/OpenROADM	2×10^{-2}	15.3 %	11.6 dB

Table II. OpenZR+ interoperability plugfest ROSNR at the O-FEC threshold [11].

EXFO OSA		Tx									
		Vendor A	Vendor B	Vendor C	Vendor D	Vendor E	Vendor F	Vendor G	Vendor H	Vendor I	Vendor J
Rx	A	20.8	20.9	20.7	21.5	21.6	21.5	22.1	21.5	21.3	21.2
	B	20.9	20.9	20.7	21.4	21.6	21.5	22.1	21.6		21.3
	C	21.9		21.5	22.6	22.5	22.2	22.0	22.5	23.0	24.6
	D	21.5	21.5	21.3	21.8	22.0	21.8	22.0	22.0	22.3	24.1
	E	21.3	21.2	21.0	21.9	21.8	21.7	21.9	21.8	22.2	24.0
	F	21.9	21.8	21.4	22.8	22.6	21.9	22.6	22.1	22.8	25.4
	G	21.5	21.4	21.0	21.9	21.9	21.6	22.0	21.8	22.3	24.3
	H	21.9	21.7	21.4	22.8	22.6	22.1	22.5	22.0	23.3	25.1
	I	21.9		21.6	23.2	23.7	22.5	23.3	22.4	22.2	21.9
	J	22.5	22.4	22.2	24.0	24.2	23.0	24.1	23.1	22.7	22.7
EVM (%rms, OIF, no-noise, 7 tap, 1000 pts)		12.0	11.3	*	*		11.6	12.5	11.3	11.9	

Recently, we presented an end-to-end interoperable 400-GbE optical transmission on 927-km [10] that integrates the most advanced 400G interoperable pluggable optics covering the needs of Ethernet client (IEEE 802.3 400GBASE) [1], DCI (OIF 400-ZR) [2], and metro/regional (400G-OpenROADM) [3] networks. The generated 400-GbE data flows seamlessly cross three interoperable sections, i.e., 2-km 400GBASE-FR4, 8x100-km 400G-OpenROADM and 125-km 400-ZR standard single-mode fiber lines. The 400G optics used here come from various vendors and embed interoperable DSP chips provided by various suppliers, ensuring the full interoperability of the experimental set-up, that constituted in 2022 a world first [10]. More recently, OIF and OpenZR+ shew an experiment in which 400-ZR and 400-ZR+ interfaces of ten different vendors were associated together to demonstrate interoperability on a single span (75-km) and multi-spans (80+80+100+100-km) transmission line for DCI and metro-regional applications, respectively [11]. As shown in the table II above, all the 400-ZR+ transceivers in the bookended mode had a ROSNR in BtB largely lower than the ROSNR of ~24-dB in 0.1-nm required by the OpenZR+ MSA. In the interoperable modes, the ROSNR ranged from 20.7-dB up to 25.4-dB, namely ~4.7-dB of difference. On the hundred associations under test, only seven coming all from the same vendor (e.g., vendor J) were not compliant with the ROSNR (~24-dB) of the OpenZR+ MSA.

3. Interoperable 800G WDM interfaces

OIF and OpenROADM recently started to specify 800G WDM interfaces for short and medium-reach applications.

OIF counted on a new interoperable FEC to find the OSNR margin required by the ″800G Coherent″ MSA [6]. Abandoning the C-FEC, OIF chose the O-FEC as OpenROADM for 400G. The O-FEC allows to recover ~0.8-dB OSNR margin compared to the C-FEC and permits to address the ″800G Coherent″ use case, namely 80 to 120-km transmission range with an optical amplifier inserted in the system. The ″800G Coherent″ ROSNR in BtB is ~27-dB on 0.1-nm, namely only ~1-dB more than 400-ZR, while the transmitter (Tx) OSNR is improved by ~1-dB (e.g., ~35-dB at 800G against ~34-dB at 400G). The ″800G Coherent″ transceivers exploit the C-band from 193.775-THz up to 196.025-THz, are tunable and aligned on the 150-GHz ITU-grid, while using DP-16QAM at ~118-Gbaud as modulation format.

OpenROADM also targets 800G WDM applications [7]. But the challenge is upper compared to ″800G Coherent″ because the transmission reach is significantly longer with multiple fiber spans, optical amplifiers, and ROADMs to pass through. The O-FEC (already used for 400G) is kept at 800G that means that no gain is expected from this side. The proposal was thus made to use probabilistic constellation shaping (PCS) [12] to recover the OSNR margin required by the 800G OpenROADM use cases. Compared to 118-Gbaud (Ethernet) and 124-Gbaud (OTN) DP-16QAM with respective BtB ROSNR of ~27-dB and ~27.2-dB in 0.1-nm, PCS DP-16QAM at 131-Gbaud allows to improve the OSNR performance by more than 1-dB. With an entropy of ~3.6 bits/symbol and ~3.78 bits/symbol for the Ethernet and OTN applications, respectively, PCS DP-16QAM at 131-Gbaud has a ROSNR of ~25-dB and ~26-dB, respectively. Combined with a Tx OSNR of ~37-dB, it should allow to cover the 800G OpenROADM use cases with 150 or 175-GHz channel spacing even if some adaptations of the ROADM configuration should be necessary (e.g., less add/drop ports, use of fixed MUX/DMUX instead of combiner/splitter, direct attach of the add/drop Tx/Rx to the wavelength selective switch). The table III below summarizes the main features of the OIF ″800G Coherent″ and OpenROADM MSA 800G optical specifications v6.0 [6,7].

Table III. Main features of the OIF ″800G Coherent″ specifications (draft) and OpenROADM MSA 800G optical specifications v6.0

	OIF 800G Coherent DP-16QAM	800G OpenROADM DP-16QAM	800G OpenROADM PCS DP-16QAM
Baud Rate	118-Gbaud	118/124-Gbaud	131-Gbaud
Application	Ethernet	Ethernet/OTN	Ethernet/OTN
Tx OSNR (0.1-nm)	35-dB	37-dB	37-dB
FEC	O-FEC	O-FEC	O-FEC
ROSNR (in 0.1-nm)	27-dB	27/27.2-dB	25/26-dB
Channel Spacing	150-GHz	150-GHz (tbc)	175-GHz (tbc)

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