1800 km 16QAM Transmission With a 400G QSFP-DD Coherent Pluggable

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Abstract *We demonstrate real-time long-haul transmission with 400G digital subcarrier-multiplexed QSFP-DD coherent pluggable in a live production network, achieving a record post-FEC-error-free reach of 1800-km with 400G-16QAM, 80% longer than all previously publicly announced records.*

Introduction

Coherent pluggable optics are essential in IP over DWDM (IPoDWDM) networks[1], where transceivers can be directly hosted by routers and replace independent transponders. This marks a significant shift from traditional optical networks, providing operators with an alternative to traditional transponders[2],[3] and allowing for optimized network architectures[4],[5]. This is particularly relevant as coherent pluggable optics could carry a significant proportion of IP traffic in service provider networks, covering most of the links up to 1000 km[6]. Traditional transponders would still remain necessary for long-haul systems.

In this context, we conducted a field trial over the US live production network of Arelion[7], where we utilized 400G 16-QAM Quad Small Form Factor Pluggable Double Density (QSFP-DD) coherent transceivers based on Digital Subcarrier Multiplexing (DSCM)[8]–[10]. The Channel Under Test (CUT) was added to an open Optical Line System (OLS) with several existing Wavelength Division Multiplexing (WDM) channels that transport live traffic at different data rates and distances. We examined different operating modes of the QSFP-DD module[8], demonstrating the capability of deploying a Point-to-Point (P2P) coherent pluggable working alongside existing transponders on the same OLS.

DSCM transmission, as opposed to single-carrier, improves tolerance to fiber nonlinearities and Enhanced Equalization Phase Noise (EEPN)[3],[11], and also provides fine spectral granularity to protect against penalties from cascaded ROADMs[12]. As a result, it allows us to achieve long reaches at higher data rates[3]. This technology, together with SiGe ASIC, high-bandwidth TROSA, and advanced PIC technology, comprises the foundation for the high performance reported in this contribution.

In this paper, we report the longest transmission distance achieved using QSFP-DD coherent pluggable on a live production network, which extends by 80% the previously publicly announced record[13]. We achieved 1800 km post-FEC error free using 400G 16QAM and 3130 km using 200G QPSK.

Live production network and trial testbed

The live production network is illustrated in Fig. 1. The trial took place in the US between the cities of Dallas (DAL), Memphis (MEM), and Chattanooga (CHA), see Fig. 1(a). We tested three different links: Fig. 1(b) 900 km from DAL → MEM, using 400G-16QAM; Fig. 1(c) 1800km using 400G-16QAM and 300G-8QAM, MEM → DAL → MEM with loopback in DAL; and Fig. 1(d) 3130 km with 200G-QPSK, DAL → CHA → DAL, with loopback in CHA. The links traverse two ROADMs and three Add/Drop sites. The average distance between amplifiers is ∼92 km with a mean fiber loss of ∼0.204 dB/km. Finally, apart for the ROADM-to-ROADM connections, all spans utilize hybrid/Raman amplification. For example, the 900 km link consists of 9 spans equipped with hybrid/Raman amplifiers. The channel allocation of the live network is reported in Fig. 2(a), where the CUT (orange dashed box) is surrounded by live traffic on both sides of the spectrum, see Fig. 2(b).

In the following sections, we describe the tests carried out on the three links depicted in Fig. 1(b-d), along with their corresponding results. For all considered cases – i.e., 400 Gb/s, 300 Gb/s and

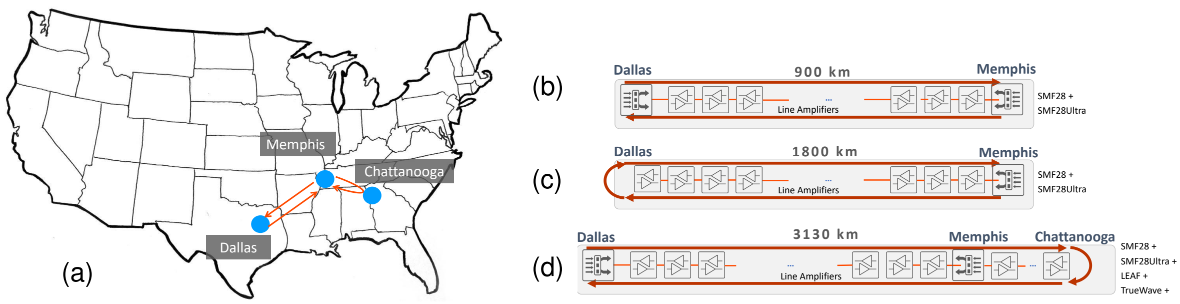


Fig. 1: (a) Live production network; (b-d) The three routes considered for the field trial.

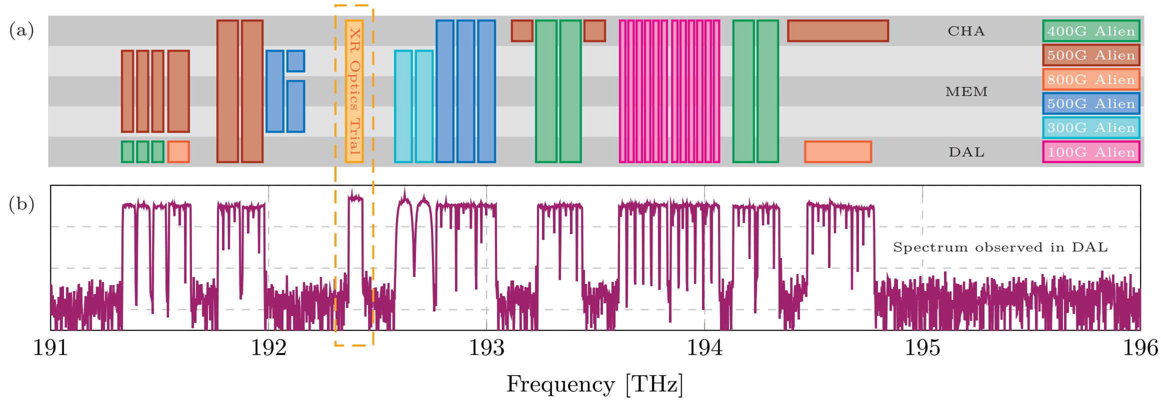


Fig. 2: (a) Channel allocation in the Arelion's live network; (b) Optical spectrum between DAL and MEM for the 1800 km link.

200 Gb/s – the client Ethernet traffic was also externally tested and confirmed to be error-free.

900 km Link: MEM $\rightarrow$ DAL, 400 Gb/s-16QAM

Fig. 3 shows the received spectrum of the CUT over the MEM $\rightarrow$ DAL link. The signal is transmitted from MEM ROADM, travels 900 km, and is measured at the receiver of the DAL QSFP-DD module. The TX power of the QSFP-DD modules at both ends was set to -4 dBm. This matched the power expected at the ROADM add ports, so that the 60.5 GBd dual-polarization 16QAM signal (i.e., 16 DSC $\times$ 3.78 GBd = 60.5 GBd) would be at the same power as the other existing production wavelengths in the system.

Fig. 4(a) shows sample constellation diagrams for the Digital Subcarriers (DSCs) using 16QAM at $\sim$3.78 GBd per DSC. The received 400 Gb/s constellation points pass through the FEC engine of QSFP-DD digital coherent receiver and result in post-FEC error-free transmission with $\sim$2.5 dB Optical Signal-to-Noise-Ratio (OSNR) margin. OSNR margin indicates the amount of AWGN noise that can be added to the system

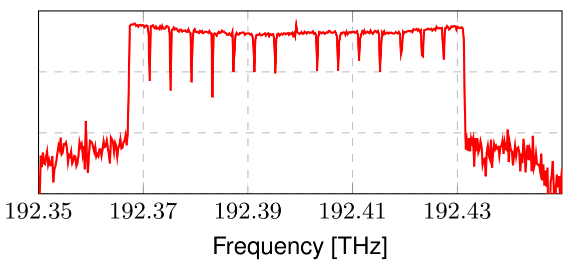


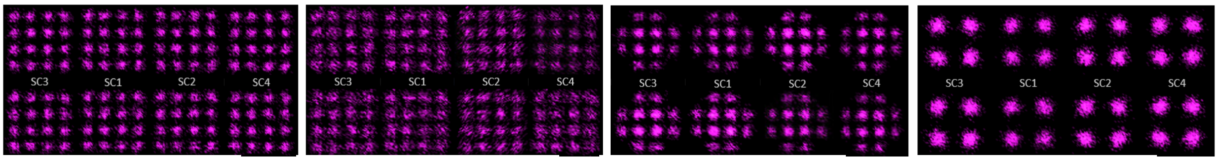
Fig. 3: Received 400G optical spectrum in DAL, 900 km link.

while still maintaining error-free transmission.

The initial test over the 900 km link used a 100 GHz optical passband created at the Add/-Drop and Express nodes of the network by adjusting the Wavelength Selective Switch (WSS) configuration of the OLS. We also tested passbands of 87.5 GHz and 75 GHz to observe the effect on the received signal and the performance of all DSCs. The table in Fig. 5(a) shows the received OSNR margins in both directions (DAL Rx and MEM Rx) for the three passband settings. As expected, the narrower optical passband had a slight impact on the OSNR margin. Close examination of the received optical spectrum shows attenuation of the outer DSCs with 75 GHz passbands compared to 100 GHz passbands, as seen in Fig. 5(b). This is due to the rolloff of the cascaded ROADM filters. In this network, over the 900 km link, even a 75 GHz passband can be tolerated with at least 1.8 dB of OSNR margin.

1800 km Link: MEM $\rightarrow$ DAL $\rightarrow$ MEM (optical loopback in DAL), 400Gb/s-16QAM

The 1800 km test uses the same optical path as the 900 km test described above, but the signal is looped back at one end, so it traverses double the distance. For this test, we used the QSFP-DD module in MEM and looped back the signal in DAL. The constellations received in the Rx DSP in the QSFP-DD module in MEM are shown in Fig. 4(b). The OSNR margin of the 400G was measured to be $\sim$0.75 dB. As expected, although



(a) 16QAM, 900 km (b) 16QAM, 1800 km (c) 8QAM, 1800 km (d) QPSK, 3130 km

Fig. 4: Measured constellation diagrams. (Samples from 4 DSCs. Other DSCs are similar.)

lower than the 900 km case, this margin is still sufficient for deployment in a live production network.

1800 km Link: MEM → DAL → MEM (optical loopback in DAL), 300Gb/s-8QAM

Some network operators may require more than 0.75 dB of OSNR margin to ensure network reliability. The QSFP-DD modules utilized in this work support several modulation formats. We tested 8QAM over the same 1800 km link described above. This operation mode provides 300 Gb/s of traffic capacity per pluggable, compared to the 400 Gb/s provided by 16QAM. The constellations received in 8QAM mode over the 1800 km link are shown in Fig. 4(c). Note that this modulation format is actually implemented as a 4D-8QAM, which makes it a subset of 16QAM[14]. In this configuration, the worst-case OSNR margin was measured to be ∼3.25 dB.

3130 km Link: DAL → MEM → CHA (optical loopback in CHA), 200Gb/s-QPSK

The next test case was a 3130 km link from DAL, through MEM, to CHA, looped back, and returning to DAL. This was tested in QPSK mode, with 200 Gb/s of total capacity. The constellations received in the DAL QSFP-DD module are shown in Fig. 4(d). Over this 3130 km link, the minimum OSNR margin was ∼4.5 dB.

200 Gb/s of client Ethernet traffic was tested and was error-free. This is an indication that links considerably longer than 3130 km can be supported by the proposed coherent pluggable in QPSK mode. Furthermore, the QSFP-DD module Rx DSP measured ∼40,000 ps/nm of chromatic dispersion, well below the upper limit of the chromatic dispersion compensation that coherent pluggables can support in this mode.

(a)

Passband Width [GHz]	OSNR Margin [dB] in DAL	OSNR Margin [dB] in MEM
100	2.5	2.7
87.5	2.1	2.3
75	1.8	1.9

(b)

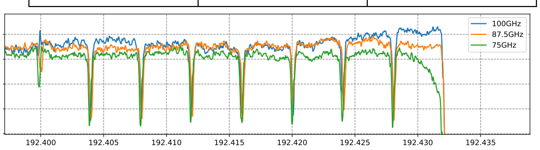


Fig. 5: (a) Measured OSNR margin in DAL and MEM with different passbands, 400G-16QAM, 900 km; (b) Filter rolloff observed at DAL with 3 passband widths. (Only the right-hand side of the spectrum is shown).

900 km Link: 16QAM, 200Gb/s-16QAM capacity in a 50 GHz passband

In previous tests, we looked at the performance of the coherent pluggable using 16QAM, 400 Gb/s mode with 100 GHz, 87.5 GHz, and 75 GHz optical passbands. The final test carried out in this field trial was to pass 200 Gb/s using 8-DSC-16QAM mode passing through a 50 GHz optical passband, as there are many legacy DWDM systems deployed with 50 GHz fixed filters. Our aim was to examine the applicability of the proposed QSFP-DD module in these networks.

For this test, the QSFP-DD modules in DAL and MEM were configured for 16QAM modulation, with only the middle 8 DSCs enabled, providing 200 Gb/s of capacity. This signal passes through 50 GHz filters with minimal impairment. In this case, the minimum OSNR margin was ∼3.5 dB. 200 Gb/s of client traffic was tested and was error-free. This indicates that the coherent QSFP-DD pluggables used in 16QAM 8-DSCs mode are suitable also for 50 GHz legacy systems.

Conclusions

We report on a field trial carried out on the Arelion US backbone network. We used a P2P coherent QSFP-DD pluggable over a live production network alongside existing WDM transponders. We show post-FEC error-free transmission with a significant OSNR margin over 1800 km with 400G 16QAM and 3130 km with 200G QPSK, respectively. This solution demonstrates the ability to mix coherent pluggables with other transponders on the same open OLS to enable a diversity of solutions in an open optical architecture.

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