# Probabilistic-Shaping DP-16QAM CFP-DCO Transceiver for 200G Upgrade of Legacy Metro/Regional WDM Infrastructure

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**Abstract:** We investigate here the capability of a newly developed CFP-DCO interface, operating at both 34 Gbaud with uniform DP-16QAM and 39 Gbaud with probabilistic-shaping DP-16QAM, for 200G upgrade of legacy metro/regional WDM infrastructure already working at 10G or 100G.
**OCIS codes:** (060.0060) Fiber Optics and Optical Communications

## 1. Introduction

Metro/regional optical transport networks are key for telecommunication operators because they aggregate the traffic coming from all types of customers (residential, business, institutional) and networks (mobile, copper/optical access, data center). As such, they are facing an exponential traffic growth requiring a continuous upgrade of their legacy WDM infrastructure, and a big pressure on the transported bit/s cost. As a consequence, the lifetime of WDM transceivers is getting shorter and shorter, and 200G per wavelength is already envisaged while 100G deployments started massively just a few years ago. In parallel, metro/regional optical networks transport a wide variety of data rates (10G, 100G, soon 200G and later 400G) over different types of transmission line (dispersion-managed when 10G channels are still used, uncompensated when only 100G channels are present) making tricky the deployment of 200G coherent WDM transceivers over such mixed data-rate transport infrastructure.

In this paper, we investigate the capability of a newly developed CFP digital coherent (DCO) interface [1] to upgrade to 200G the legacy metro/regional WDM infrastructure already working at 10G (on dispersion-managed link) or 100G (on uncompensated link). More particularly, we compare two operation modes of this 200G WDM pluggable optic interface: the 34 Gbaud uniform versus the newly developed 39 Gbaud probabilistic-shaping (PS) DP-16QAM modes [2, 3]. On mixed 100G/200G uncompensated transmission line, probabilistic-shaping provides ~1/2 BER decade (or equivalently ~2-dB OSNR) improvement compared to uniform 16QAM at any transmission distance. On mixed 10G/200G dispersion-managed transmission line, probabilistic-shaping allows to improve the maximum reach from 400 km to 1000 km. These experiments show all the potential of probabilistic shaping for 200G upgrade of legacy WDM infrastructure as well as the possibility to embed probabilistic shaping in a low-cost and low power consumption CFP-DCO interface well-adapted to the context of metro/regional transport networks.

## 2. Experimental Set-Up

The experimental set-up is depicted in Fig.1. The muxponder combined two 100 GbE data streams (at 103.125 Gbps) coming from two client QSFP28 interfaces plugged in two 100 GbE testers. The data rate after electrical multiplexing, OTN encapsulation and pilot symbols insertion was 216 Gbps. The WDM transmitter comprised one 200G CFP-DCO transceiver (including a 16-nm CMOS ASIC in the form factor) at 1550.12 nm whose signal was combined either with 59 dual-polarization (DP) QPSK channels at 100G (ranged from 1533.9 to 1557.4 nm) or with 79 NRZ on-off keying (OOK) channels at 10G (ranged from 1532.7 to 1564.3 nm) both aligned on the 50-GHz ITU grid. The 200G signal under test underwent a root-raised cosine (RRC) Nyquist filtering with a roll-off factor of 0.2 that allowed inserting it in a free spectral gap of 50 GHz (obtained by switching-off one 10G or 100G channel in the WDM multiplex). A soft-decision FEC based on a proprietary LDPC encoder/decoder with ~25% overhead, net coding gain of ~12.5 dB @ BER=$10^{-15}$, and pre-FEC BER threshold of ~$3.45 \times 10^{-2}$ was implemented. The total data rate to transport (by the 200G channel) was 272 Gbps. The corresponding symbol rate of uniform 16QAM was 34 Gbaud [3]. The PS-16QAM required a specific overhead (equal here to ~10%) that was due to the addition of a Maxwell-Boltzmann distribution matcher in front of the FEC encoder [2]. The total overhead of the PS-16QAM was thus ~44% that corresponded to a 39-Gbaud symbol rate [3]. The distribution matcher has an entropy H [P] (with P the symbol probability density function) of 3.5 bits/symbol. The CFP-DCO power consumption was 30 Watts with 16QAM and 32 Watts with PS-16QAM [3]. The constellation and spectrum of the 16-QAM and PS-16QAM formats at the output of the transceiver are represented in Fig.1. The WDM multiplex recorded in the zone where the 200G channel is inserted either with the 100G DP-QPSK or 10G NRZ-OOK channels is also shown in Fig.1.

The uncompensated transmission line was composed of twenty 100-km spans of ITU-G.652 fiber. The span losses (20 dB) were compensated by single-stage EDFAs with 4.5-dB noise figure. Two dynamic gain equalizers (DGE) were inserted after 500 and 1500 km. The WDM multiplex spectrum recorded after 2000 km is shown in Fig.1.

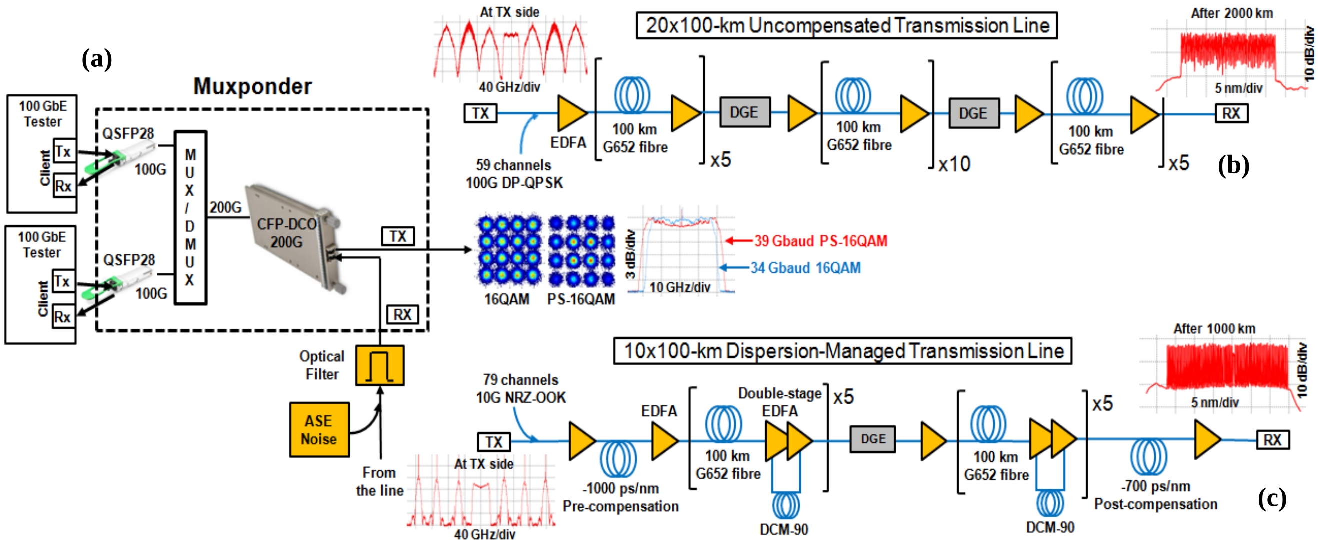


Fig.1: Set-up of the transmission experiment with (a) the 200G 16QAM/PS-16QAM CFP-DCO transceiver under test, (b) the 20x100-km uncompensated G.652 fibre line in which are coupled 59 DP-QPSK channels at 100G, and (c) the10x100-km dispersion-managed G.652 fibre line in which are coupled 79 NRZ-OOK channels at 10G. The constellation diagram of the 34 Gbaud uniform 16QAM and 39 Gbaud PS-16QAM with the corresponding spectra are also depicted at the TX output. The spectra of the WDM multiplex after the combination of the signal under test with the 100G DP-QPSK and 10G NRZ-OOK channels, and after the uncompensated and dispersion managed lines are also displayed.

The dispersion-managed transmission line was constituted of ten 100-km spans of ITU-G.652 fiber. A pre-compensation stage of -1000 ps/nm (at 1550 nm) was introduced before the line in order to have a symmetric dispersion map with respect to the zero dispersion. Dispersion-compensation modules (DCM) compensating 90 km of G.652 fiber were inserted in the inter-stage of double stage EDFAs with 6-dB noise figure that also balance DCM and fiber span losses. A DGE was placed in the middle of the transmission line. A -700-ps/nm (at 1550 nm) post-compensation stage located at the end of the link brought back to zero the cumulated dispersion. The WDM multiplex spectrum measured after 1000 km is shown in Fig.1.

At the receiver side, the 200G channel at 1550.12 nm was extracted by a 50-GHz flat-top optical filter and sent into the coherent receiver of the CFP-DCO. After analog-to-digital conversion, real-time digital signal processing (DSP) is performed in the 16-nm CMOS-ASIC with the following steps: signal down-sampling, re-timing, frequency-domain equalization, MIMO time-domain equalization, carrier frequency offset recovery, carrier phase recovery, FEC and probabilistic shaping decoding. A graphical user interface (GUI) allowed to control pre-FEC and post-FEC errors and to measure in real-time the bit error rate (BER). Two testers placed after the electrical de-multiplexer measured the BER of the two 100-GbE flows.

**3. Results on mixed 100G/200G uncompensated transmission line**

We first analyze results obtained on mixed 100G/200G uncompensated transmission line (see Fig.2 & Fig.3). For both 16-QAM and PS-16QAM, the back-to-back (BtB) performance is determined. The FEC limit (measured at BER ~ $3.45x10^{-2}$) is reached for an OSNR (in 0.1 nm) of 17.3 dB with uniform 16-QAM and 15.4 dB with PS-16QAM: probabilistic shaping appreciably improves the BtB OSNR sensitivity of ~2 dB, offering as we will observe it later significant gain in transmission distance. The poorer pre-FEC BER floor observed at high OSNRs with probabilistic shaping is due to the higher symbol rate of PS-16QAM with respect to 16QAM. Fig.2 presents our optimization of the span input power per channel performed on the uncompensated transmission line for various distances. What we firstly detect is a shift towards lower values of the optimum span input power per channel when the distances are increased: ~1 dBm per channel is required at 300 km or 500 km when ~0 dBm is needed at 1000 km, 1500 km or 2000 km. The second notable observation is that, for a given transmission reach, PS-16QAM has the same optimum span input power per channel than uniform 16-QAM: probabilistic shaping does not seem to improve the non-linear robustness of the 16QAM format, as PS-16QAM constellations have exactly the same average power than 16QAM constellations (as foreseen by the probabilistic shaping theory [2]). Finally, in Fig.3, the pre-FEC BERs and OSNRs corresponding to the optimum span input powers per channel (determined in Fig.2) are reported over the BER versus OSNR graph for each distance and each modulation format. Uniform 16QAM allows error-free transmission (without error on the 100-GbE flows) up to 1500 km, while PS-16QAM reaches 2000 km with more than 1.5-dB OSNR margin with respect to the FEC threshold. PS-16QAM has also ~ 1/2 BER decade gain over 16QAM for each of the transmission reach under study, or equivalently (if we consider that ASE and non-linear noise are Gaussian) 2-dB OSNR gain (indeed, the BtB sensitivity curves of Fig.3 have a slope of 1/4 BER decade per dB-OSNR).

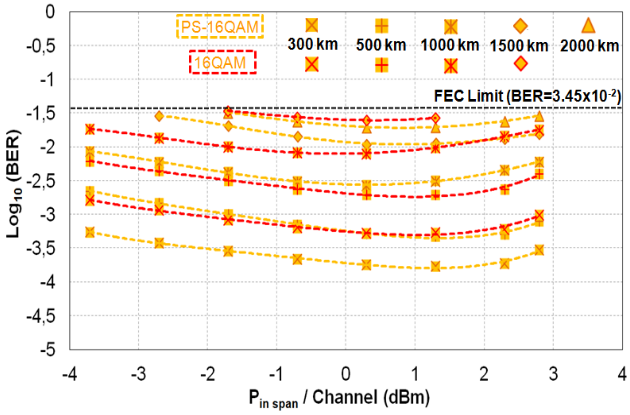


Fig.2 : Pre-FEC BER versus span input power per channel (P in span / Channel) for the various transmission distances and the two modulation formats under study in the case of the mixed 100G/200G uncompensated transmission line.

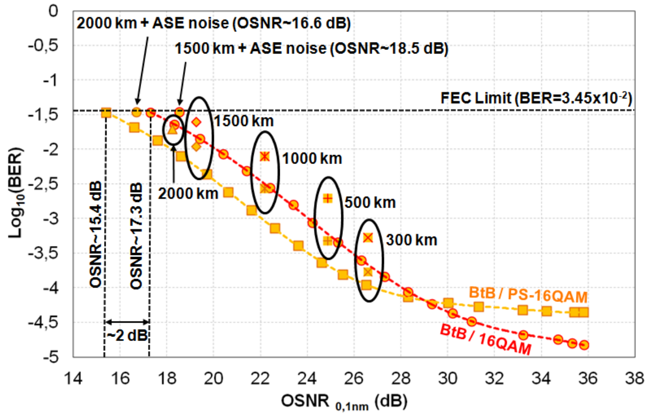


Fig.3: Pre-FEC BER versus OSNR in BtB and after transmission (over the various distances investigated in Fig.2). The BER vs. OSNR points corresponding to the optimum of the BER vs. P in span / Channel curves (of Fig.2) are reported.

## 4. Results on mixed 10G/200G dispersion-managed transmission line

The same measurements are performed on the mixed 10G/200G dispersion managed transmission line. In Fig.4a), we determine the optimum span input powers per channel for the various distances under study, while in Fig.5 we report on the BER versus OSNR graph the pre-FEC BERs and OSNRs corresponding to these points. We notice once more that PS-16QAM and uniform 16-QAM have exactly the same optimum span input power per channel for each of the transmission reach under study. PS-16QAM still outperforms 16QAM: error-free transmission distance without errors on the 100-GbE flows is achieved after 1000 km with PS-16QAM (without any extra OSNR margin) and after 400 km with 16QAM (with ~1.7-dB OSNR margin). In order to recover some margins with PS-16QAM at 1000 km, a guard-band of 100 GHz, 150 GHz and 200 GHz is introduced (Fig.4b) between the 200G channel under test and its 10G neighbors. A slight performance improvement not exceeding 1/4 BER decade is measured.

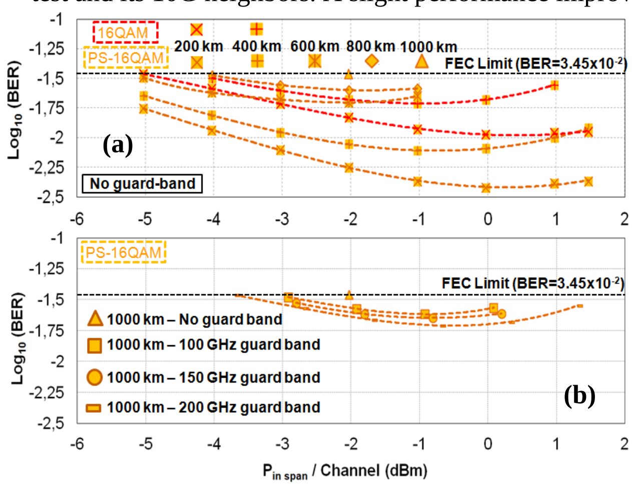


Fig.4: (a) Pre-FEC BER versus span input power per channel (P in span / Channel) for the various distances and the two modulation formats under study in the case of the mixed 10G/200G dispersion-managed transmission line with no guard-band, (b) with a guard-band insertion of 100 GHz, 150 GHz, and 200 GHz at 1000-km.


Fig.5: Pre-FEC BER versus OSNR in BtB and after transmission over the various distances investigated in Fig.4a). The BER vs. OSNR points corresponding to the optimum of the BER vs. P in span / Channel curves (of Fig.4a) are reported.

## 5. Conclusions

We have shown here the efficiency of a newly developed 39 Gbaud probabilistic-shaping DP-16QAM CFP-DCO transceiver for 200G upgrade of legacy metro/regional WDM infrastructure already working at 10G or 100G on 50-GHz ITU grid. Our results show the large gain in performance provided by probabilistic-shaping and the possibility to embed it in a low-cost and low power consumption CFP-DCO interface.


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[3] J. Li *et* al., "Field Trial of Probabilistic-Shaping-Programmable Real-Time 200-Gb/s Coherent Transceivers in an Intelligent Core Optical Network," Asia Communications and Photonics Conference (2018)