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DOI:
10.1109/LPT.2016.2632165

Document status and date:
Published: 15/01/2017

Document Version:
Typeset version in publisher's lay-out, without final page, issue and volume numbers

Single-Carrier 400G 64QAM and 128QAM DWDM Field Trial Transmission over Metro Legacy Links

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***Abstract*—We report on the results of a field trial carried out on a Telecom Italia (TI) metro link, targeting short data center interconnect (DCI) applications. The test-bed presented realistic transmission conditions such as an average ∼0.3 dB/km attenuation and usage of legacy EDFA-only. We transmitted a net bit rate of 400 Gb/s on a single carrier with 64 quadrature amplitude modulation (QAM) and 128QAM over 156 km. Error-free transmission over 80 km for single carrier DWDM 30×400G 64QAM and 30×400G 128QAM (one half of the C-Band) is reported. The net spectral efficiency, for both schemes, is 7.11 bit/s/Hz.**

***Index Terms*—Digital signal processing, digital pre-distortion, data center interconnects, high-order modulation formats.**

I. Introduction

RECENT forecasts highlight that a considerable amount of Internet traffic is migrating from long-haul backbones towards DCI [1]. In this context, development of spectral efficient and cost effective 400G coherent optical communication systems has gained significant interest, particularly for distances ≤ 80 km, which are typical of short inter DCI [2]. High order modulation formats, such as Dual Polarization (DP)-64QAM and DP-128QAM combined with a transmitter employing digital pre-distortion (DPD) and a coherent receiver using soft decision (SD) forward error correction (FEC) are among the most promising candidates to realizing future 400G single carrier optical communication transponders [3]. Utilizing DP-64QAM or DP-128QAM relaxes the bandwidth requirements on the electrical devices of the transponder, which leads to a reduction in the overall power consumption. This approach opposes to current commercial solutions based on direct-detection and multi-carrier [2]. The performance of coherent systems is, however, hindered by the higher sensitivity to quantization noise, owing to the low effective number of bits (ENOB) of the digital-to-analog-converters (DAC) and analog-to-digital-converters (ADC) (i.e., ∼5.5 and ∼6.5 respectively) [4]. Additionally, the overall system performance is degraded by linear distortions such as the low-pass transfer function and the skew between the in-phase (I) and quadrature (Q) components of the equivalent complex baseband signal [5]. Finally, the performance is hampered by the non-linear effects in the driver amplifier (DA) and dual polarization Mach-Zehnder modulator (DP-MZM), which could be effectively mitigated by implementing digital pre-distortion (DPD) at the transmitter [5]–[10]. In [5], a DPD technique based on Volterra equalizers, to compensate for the entire chain of transmitter components was experimentally validated, cf. [5, Fig. 3] for the bandwidth limitation and [5, Fig. 4] for transmitter I/Q skew. Compensation of such linear effects led to significant gains for different modulation formats enabling symbol rates up to 56 GBaud also for high order modulation formats as shown in [5, Fig. 5].

In this paper we demonstrate that adaptive DPD and powerful proprietary FEC enable the transmission of single-carrier 400G signals. We show the results of a field trial carried out on a TI legacy metro system consisting of G.652 SMF and legacy EDFA-only. In contrast to previous methods investigated in lab environments where newly engineered fibers [11], [12] and super-channel configurations were considered [13], [14], we generated single-carrier DP-64QAM and DP-128QAM 400G signals, utilizing only commercial components designed for symbol rates of ∼32 GBaud and transmitted them over a challenging test-bed. To overcome component limitations, DPD as detailed in [5] was utilized. For the DWDM signal, a carrier spacing of 56.25 GHz for both schemes was adopted, leading to a net spectral efficiency (SE) of 7.11 bit/s/Hz. The signals were transmitted over a 156 km link (single channel configuration) and a 80 km link (DWDM with 30×400G 64QAM and 30×400G 128QAM). We achieved post-FEC error-free performance with proprietary FEC. The proposed 400G single-carrier solutions jointly lower cost, power consumption and footprint, since they require fewer transponders compared to super-channel approaches as proposed in [13], [14]. To the best of the authors' knowledge this field trial presents the first published DWDM transmission of single-carrier 400G 128QAM over a deployed link.

II. Field trial description

The experimental setup used for the field trial is shown in Fig. 1. It depicts (**a**) the transmitter setup for the generation of channel under test (CH_{UT}) and neighboring channels (CH_{neigh}), (**b**) the field trial link, (**c**) the OTDR trace of the link, and (**d**) the receiver.

The authors would like to thank the FP-7 IDEALIST and the BMBF funded SASER-Sigfried projects for supporting this work.

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Manuscript received xxx 19, zzz; revised January 11, yyy.

Modulation Format	Baud Rate (GBaud)	Net Bit Rate (Gb/s)	FEC Overhead	FEC Threshold	Spacing Used (GHz)	Sp.Efficiency (bits/s/Hz)
DP-64QAM	45.25	400	25%	4.2E-02	56.25	7.1
DP-128QAM	42.0	400	35%	6.0E-02	56.25	7.1

TABLE I: Field trial transmission configurations

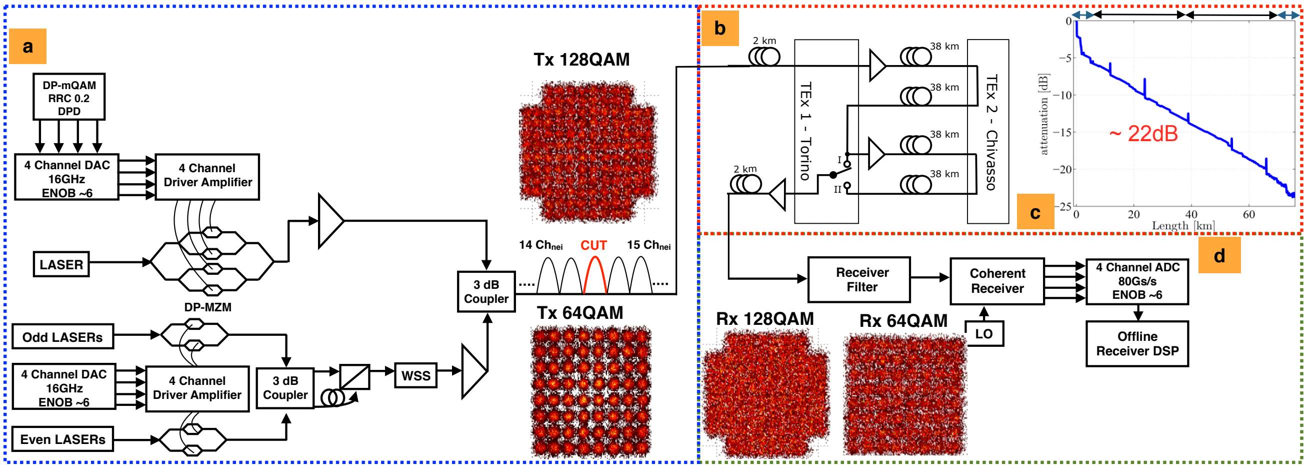

Fig. 1: Experimental link setup: (**a**) Transmitter (Torino) with test and neighboring channel setup; (**b**) Link (connecting Torino, TEx1 and Chivasso in a loop back configuration at TEx2); (**c**) The OTDR trace of 80 km link; (**d**) Receiver at Torino.

A. Transmitter Setup

The transmitter, detailed in Fig. 1(**a**), consists of commercial DAC, DA and DP-MZM. The DAC has a bandwidth of 16 GHz (at 88 GHz sampling rate), ENOB of 5.5 [4], and a sampling rate range of 62-92 GHz. We chose a sampling rate of 88 GHz, which was a good trade-off between device stability and bandwidth. For the ADC the highest possible sampling rate of the device, i.e. 80 GHz, was utilized.

Table I summarizes the system parameters used in the experiment. The payload consists of random segments of a PRBS sequence of order 32. After the insertion of three overhead (OH) contributions, soft-decision (SD)-FEC, OTN (4.7%) and training symbols (4%) [15], the bits are mapped into m-QAM symbols. Digital spectral shaping is applied by root-raised-cosine filtering with roll-off 0.2. To compensate for the linear and non-linear effects of the transmitter, DPD as described in [10] is implemented and samples are uploaded onto the DACs.

Two independent setups, one for the CH_{UT} and the other for CH_{neigh} are implemented. For both CH_{neigh} and CH_{UT}, the same DACs were used. All transmitter and local oscillator lasers are continuous wave external cavity lasers, with a linewidth of 100 kHz. The four amplified electrical signals out of the DA drive the DP-MZM resulting in a DP signal CH_{UT} at net 400 Gb/s. Odd and even neighbors are generated by emulating polarization division multiplexing. The polarization emulator delay was ∼5ns. A wavelength selective switch (WSS) suppresses one of the neighbor channels at the CH_{UT} frequency and the resulting signal is combined with the CH_{UT}. The transmit spectrum always consists of 15 neighbors on the right and 14 on the left of the CH_{UT}, resulting in 30 WDM transmit channels, shown in Fig. 1(**a**). The CH_{UT} frequency is varied for C-band measurements. The obtained DWDM channels are then amplified and finally transmitted (both 64QAM and 128QAM) over a grid of 56.25 GHz, thus achieving a net SE of 7.11 bit/s/Hz. Transmitted and received constellations for both modulation formats are shown as insets in Fig. 1. An exemplary transmit spectrum of the 30×400G 64QAM channels is displayed in Fig. 2, with the CH_{UT} at 1556.45 nm. One of the channels is lower than the rest because of a defective LASER. However since the defective channel is distant from the CH_{UT}, we can safely assume that it has minimal effect on the overall non-linear system performance.

B. Link Description

The transmission link is shown in Fig. 1(**b**) and consists of multiple pairs of G.652 SMF fibers deployed between Torino and Chivasso in Italy. In Torino, a 2 km link connects the TI laboratory to a first telephone exchange 1 (TEx 1) where legacy EDFAs are located; Chivasso exchange (TEx 2) is 38 km away and is reached crossing three other intermediate TExs (Stura, Settimo and Volpiano). Different fiber pairs of length 76 km (38 + 38) are looped back and forth between TEx 1 and TEx 2, and in the end, toward the laboratory, through TEx 1. As a result, a total link length of 80 km was provisioned for WDM experiments (switch in position I at TEx 1) while a 156 km connection was used for single channel case (switch in position II). The measured link attenuation was around 0.3 dB/km [16] as reported in the OTDR trace in Fig. 1(**c**). This value takes into account fiber loss, splices, connector losses, etc. The attenuation is compensated at TEx 1 by legacy EDFAs with 6.5 dB noise figure. This link represents a typical metro network infrastructure characterized by several lumped attenuations and reflections, and hence is a real challenge for high capacity transmission experiments.

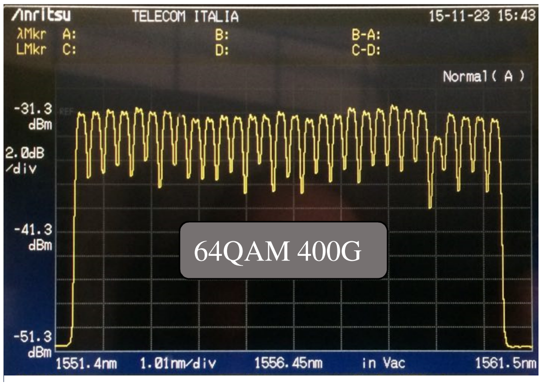

Fig. 2: DWDM spectrum for 30×400G 64QAM after 80 km.

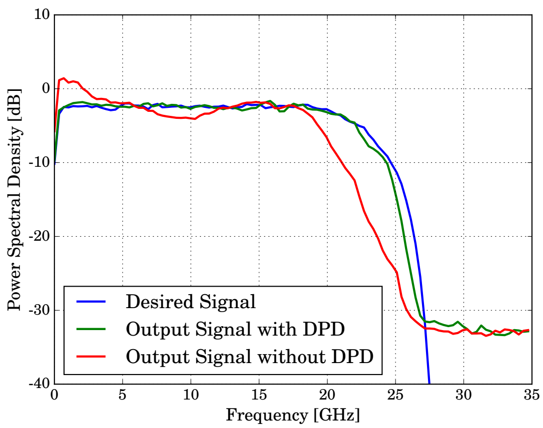

Fig. 3: Power spectral densities for three signals: desired (blue), without DPD (red) and with DPD (green).

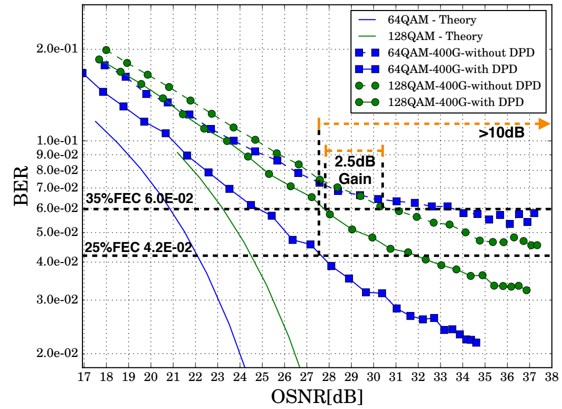

Fig. 4: Back-to-back measurements for 64/128QAM.

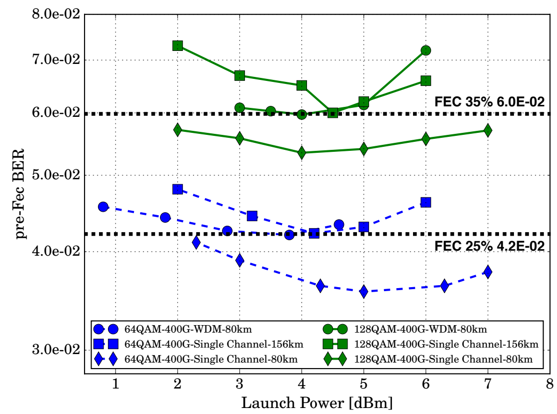

Fig. 5: Launch power optimization for 64/128QAM.

C. Receiver Processing

The employed receiver is detailed in Fig. 1(**d**). At the receiver, the DWDM signal is first amplified and the CH_{UT} is filtered and converted into the electrical domain using a coherent front-end. The LO frequency was adjusted to within 200 MHz of the frequency of the CH_{UT} for intra-dyne detection. A four-channel 80 GSa/s ADC (with 18 GHz bandwidth) is employed to capture shots of $5 \cdot 10^5$ samples per tributary. The stored samples were post-processed offline with the DSP algorithms [15]. The performance is finally assessed in terms both of pre-FEC BER and post-FEC BER. In this experiment, SD-FEC based on LDPC codes were employed. To account for hardware constraints and to enable simple hardware implementation, structured irregular repeat-accumulate (SIRA) block LDPC codes [17] with a variable overhead were used.

III. Results and Discussion

Fig. 3 displays the power spectral densities (PSD) of the received signals. A clear improvement is provided by DPD proposed in [5], [10], where the digitally pre-distorted curve (green) quite well matches the desired one (blue). We would like to point out that the TX I/Q skew is also compensated and the phase spectrum is similar to the one reported in [5]. The back-to-back (b2b) performance, presented as pre-FEC BER versus $OSNR_{0.1\ nm}$, is visualized in Fig. 4. DPD achieves a significant OSNR gain of > 10 dB for 64QAM and ~ 2.5 dB for 128QAM at their respective FEC thresholds. The b2b performance is mainly limited by the electrical bandwidth of the transmitter and the significant quantization noise at the DAC and ADC.

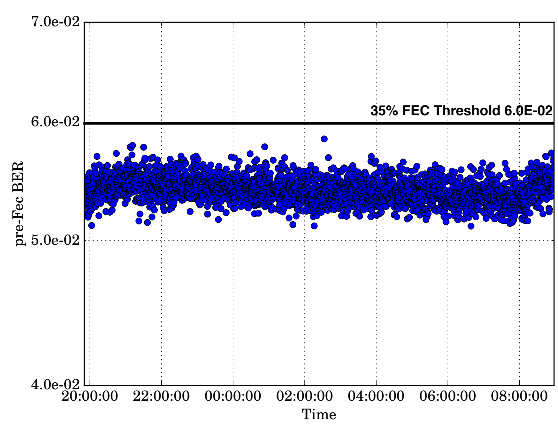

Fig. 6: Long term measurement for DP-128QAM 400G single channel over 80 km

Fig. 5 shows launch power optimization for the two modulation formats without and with DPD. All measurements

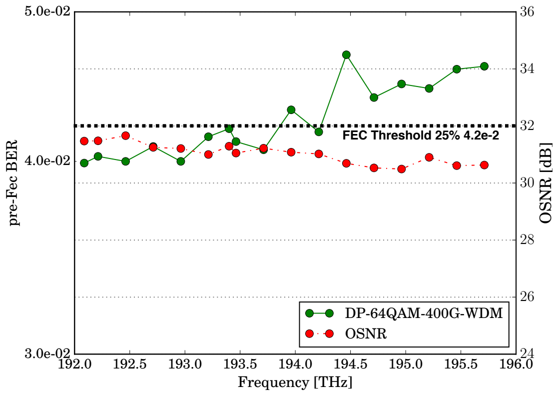

Fig. 7: C-Band measurements.

were carried out at a channel frequency of 193.4 THz. We observe that for single channel transmission over 80 km, the pre-FEC BER is well below the FEC threshold for both modulation formats and the optimum launch power is around 5 dBm for 64QAM (received OSNR ∼32 dB) and around 4 dBm for 128QAM (OSNR ∼32.3 dB). In case of DWDM transmission over 80 km, the optimum launch power for both schemes is decreased by ∼1 dB with respect to the single-channel case because of the non-linear effects in the fiber, and the pre-FEC BER is just at the FEC threshold. The high optimal launch power is due to the high symbol rate and the considerable attenuation accumulated over the span, (∼0.3 dB/km). An additional curve (denoted by ■) shows single channel transmission performance over 156 km. Fig. 6 reports a long-term measurement (∼13 hours) for the case of single channel for 128QAM over 80 km. Note that post-FEC BER was zero in all cases where the pre-FEC BER was below the FEC threshold. Being this an offline measurement, the measured time duration in Fig. 6 corresponds to 12 ms real time. It is clear from the results in Fig. 5 that DWDM transmission over 80 km and single channel transmission over 156 km is quite challenging, but it is essential to point out that the considered scenario presents extreme conditions. On the other hand, the proposed solution could be one of the configurations of a flexible transponder, being exploited for shorter links or under less challenging conditions. Fig. 7 shows the pre-FEC BER versus frequency for DP-64QAM 400G when tuning the $\mathrm{CH_{UT}}$ over the C-band. The measurements were carried out at the previously determined optimum launch power. We notice, that in the high frequency region BER is slightly above the FEC threshold (and consequently post-FEC errors occurred). We assume that this effect is due to non-optimized power settings for the high frequency region and with individual power and EDFA optimization a performance similar to that at lower frequencies could be achieved for all frequencies.

IV. Conclusions

We carried out a field trial over a 80 km TI legacy metro link targeting DCI applications. We propagated 30×400G 128QAM WDM and 30×400G 64QAM single-carriers over 80 km G.652 deployed fiber with an average measured attenuation of ∼0.3 dB/km by using legacy EDFA-only. The experiment was conducted by utilizing only available commercial components and advanced digital pre-distortion techniques and SD-FEC. With the employed 56.25 GHz channel spacing both formats achieve a spectral efficiency of 7.11 bit/s/Hz. However, owing to the lower symbol rate 128QAM offers potentially an even higher spectral efficiency at the expense of a larger FEC overhead (and hence more complex FEC).

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