Unrepeatered field transmission of 2 Tbit/s multi-banded coherent WDM over 124 km of installed SMF

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Abstract: In this paper we report field transmission of a 2Tbit/s multi-banded Coherent WDM signal over BT Ireland's installed SMF, using EDFA amplification only, with mixed Ethernet (with FEC) and PRBS payloads. To the best of our knowledge, the results obtained represent the highest total capacity transmitted over installed SMF with orthogonal subcarriers. BERs below 10^{-5} and no frame-loss were recorded for all 49 subcarriers. Extended BER measurements over several hours showed fluctuations that can be attributed to PMD and to dynamic effects associated with clock instabilities.

OCIS codes: (060.4510) Optical communications; (060.2330) Fiber optics communications; (060.4230) Multiplexing.

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1. Introduction

Standardization activities for 100Gbit/s line rates are reaching completion for telecom (ITU-T G.709/Y.1331) applications, and approaching publication for datacom (IEEE 802.3ba), which will deploy dual polarization and quadrature phase-shift keying formats (DP-QPSK) [1]. Therefore, the research momentum is shifting towards 300 and 400Gbit/s solutions, as high bandwidth demand keeps growing [2]. The primary motivation for the development of 100Gbit/s technologies was the transport of high-speed Ethernet signals, rather than the traditional reduction in cost per bit, with many applications requiring transmission over modest distances (~80-120km) using existing unrepeatered optical fiber infrastructure, originally installed to support WDM and/or aggregations of 2.5Gbit/s and 10Gbit/s signals [3]. 100Gbit/s Ethernet (100GbE) field trials have also been carried out lately, reporting a frame loss rate (FLR) of 3×10^{-8} over 1520km (19 × 80km spans) of installed standard single mode fiber (SMF) [4]. In these measurements the packet size of a single Ethernet frame was 1500bytes, which translates into a corresponding bit-error rate (BER) of 3.6×10^{-4} [5].

DP-QPSK alone is insufficient to overcome impairments for the anticipated 300Gbit/s to 1Tbit/s optical transmission systems without a drastic increase in the baud rate. Therefore alternative techniques must be developed and implemented. Multicarrier systems, such as Coherent WDM (CoWDM) and optical Orthogonal Frequency Division Multiplexing (OFDM) [6–11] are strong candidates, as they offer the possibility to transmit such high capacities over existing, installed, and revenue-generating optical fibers, without recourse to disruptive and cost-prohibitive upgrades. For instance, in contrast to m-QAM solutions, for all-optical OFDM and CoWDM the optical signal-to-noise ratio (OSNR) requirements are not degraded, allowing very flexible and scalable total transmitted capacities [12,13]. Recent multicarrier field transmission experiments included the demonstration of three optical OFDM bands of 253Gbit/s (totaling 759Gbit/s of capacity) with coherent detection and off-line digital signal processing (DSP), transmitted over 764km of installed SMF (with spans varying between 72 and 80km) [14]; and a single CoWDM band of 288Gbit/s carrying Ethernet payloads, transmitted over an unrepeatered 124km of installed SMF [5].

In this paper, we report the transmission of 2.10Tbit/s (or 1.96Tbit/s after Forward Error Correction (FEC)) over installed SMF using CoWDM. This is the highest total capacity to be transmitted over installed fibre using orthogonal multicarrier techniques, to the best of our knowledge. This was achieved by using seven CoWDM bands, instead of only one [5], with a capacity per band of 299.86Gbit/s. An optical signal-to-noise ratio (OSNR) of 30.4dB per band at the output of the receiver pre-amplifier was required for all 49 subcarriers in order to achieve a BER below 10^{-5}. BER measurements over time revealed not only the dynamic effects associated with commercial clock sources, which may reduce the available OSNR margin, but also demonstrated the predicted robustness [15] of this system to polarization mode dispersion (PMD).

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2. Experimental setup

The experimental setup used for the field demonstration of the 2Tbit/s CoWDM is illustrated in Fig. 1. A mixed format signal was used, which was obtained by aggregating one 10.7Gbit/s Pseudo Random Binary Sequence (PRBS) with a 2^{31}-1 pattern length from a pulse pattern generator (PPG) and three FEC encoded 10 Gigabit Ethernet (10GbE) WAN PHY (9.953Gbit/s) streams. The single PRBS tributary was used in order to monitor the system performance and identify impairments. This tributary was replaced at a later stage with a forth Ethernet stream to verify the performance of a 2TbE system. An optical 10GbE test stream, generated from an Ixia XM2 performance tester with a frame size of 64 bytes, was converted into the electrical-domain signal with a SFP + transponder, and was then FEC encoded using an Intel® IXF30007 EFEC100 board (resulting in a line rate of 10.7Gbit/s). The FEC encoded data, generated from the non-inverting output of the line-side of the board, drove a differential amplifier to give two Ethernet data streams into the 4:1 multiplexer. The other inverting output provided the third Ethernet data stream. Delay lines were used to decorrelate the first two Ethernet streams by 16 and 31 bits respectively when referenced to the third stream. The PPG, used to generate the PRBS, was synchronized with a line-side reference clock at 669.32MHz extracted from the 10GbE signal by the EFEC100 board. The single PRBS together with the three FEC encoded Ethernet data streams were then electrically multiplexed up to 42.84Gbaud, and the outputs of the subsequent D flip-flop (DFF) were used as the signal sources for each of the odd/even subcarriers in the CoWDM transmitter, with pattern de-correlation implemented by electrical delay lines.

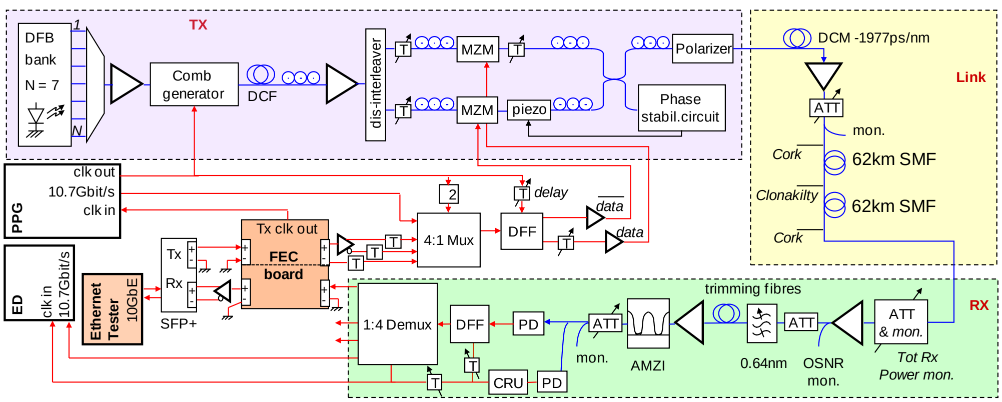

Fig. 1. Experimental setup for 2Tbit/s transmission over 124km of field-installed SMF.

We extended the previously reported configuration of the CoWDM transmitter from one seed wavelength [5,16] to seven distinct seed wavelengths from individual distributed feedback (DFB) lasers separated by 385.52GHz (*DBF bank* with *N = 7* on Fig. 1). Each seed wavelength generated a band of 7 optical subcarriers separated by 42.84GHz; and, due to the use of a single comb generator [5], guard-bands of 85.67GHz were introduced to minimize the interference between bands [16]. A total of 49 optical subcarriers were generated at the transmitter output with a flatness of ~3dB. The resulting 2Tbit/s signal was then transmitted over a chromatic dispersion pre-compensated fiber link, using EDFAs only. The link consisted of a dispersion compensating module (DCM with D ~–1977ps/nm), followed by an in-line EDFA (25dB maximum gain and 4.9dB noise figure), a variable optical attenuator, and the installed SMF link that formed part of BT's optical transmission network in Ireland (see Fig. 1). The 124km of field-installed SMF was looped-back at Clonakilty to our laboratory in Cork. The associated 26dB of fiber loss is a challenge in terms of OSNR, as it would be for all unrepeatered links of similar reach. The trade-off between OSNR and nonlinear penalties [5] dictated an optimized total signal launch power of + 16.9dBm. At the receiver side, the total received power was controlled by a variable optical attenuator, which introduced an additional 3dB insertion loss, and the received OSNR was monitored after the first receiver amplifier.

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Here, the received OSNR is defined per band, and is given by the ratio between the signal measured in a CoWDM band (~2.5nm) and the noise in 0.1nm bandwidth.

A pre-amplified direct detection receiver was implemented, as described in [5], which employed an asymmetric Mach-Zehnder Interferometer (AMZI) and a 0.64nm filter for subcarrier selection. Additional dispersion trimming fibers were introduced between the two receiver EDFAs in order to compensate for most of the residual chromatic dispersion. The data monitor output of the 40Gbit/s error detector (ED) (shown as a DFF in Fig. 1 for clarity) was launched to a 1:4 demultiplexer to separate the PRBS and the three 10GbE signals. The BER of the PRBS tributary and the FLR of one of the Ethernet tributaries were monitored at all times. A 40G clock at the receiver was recovered by a clock recovery unit (CRU) to synchronize the demultiplexer and provide a reference clock for PRBS BER measurement. The FEC board contained separate transmitter and receiver circuits (with a common power supply). Therefore, for Ethernet FLR measurements, the receiver side of the FEC board decoded the data using a 10G clock, recovered from the demultiplexed 10GbE line signal, which was independent of the clock generated in the transmitter circuit. The Ethernet tester also recovered an independent clock for FLR measurements.

3. Results and discussions

The BER and FLR of each optical subcarrier were measured, but for clarity, Fig. 2 only shows the BER performance after transmission for the best (#25, 1552.74nm) and the worst performing (#48, 1562.77nm) subcarriers, since the remaining 47 BER measurements were contained between these two edge performances. At the maximum received power of –12dBm (Fig. 2(a)), the BER of the worst performing subcarrier (#48) was 1.3×10^{-5}. This power level was determined by the total transmitted power level (+ 16.9dBm) before the link, the losses from the 124km of SMF, the optical attenuator and the monitor module. The band containing subcarrier #48 (called band #7) had an OSNR of 30.8dB (Fig. 2(b)). For the best performing subcarrier (#25), belonging to band #4, a BER of 3×10^{-9} was achieved with an OSNR about 1dB higher. Figure 2(c) shows the transmitted eye-diagrams for the best (#25) and worst (#48) subcarriers with the crosstalk between adjacent subcarriers remaining minimized at the centre of the eye after transmission over fiber [6].

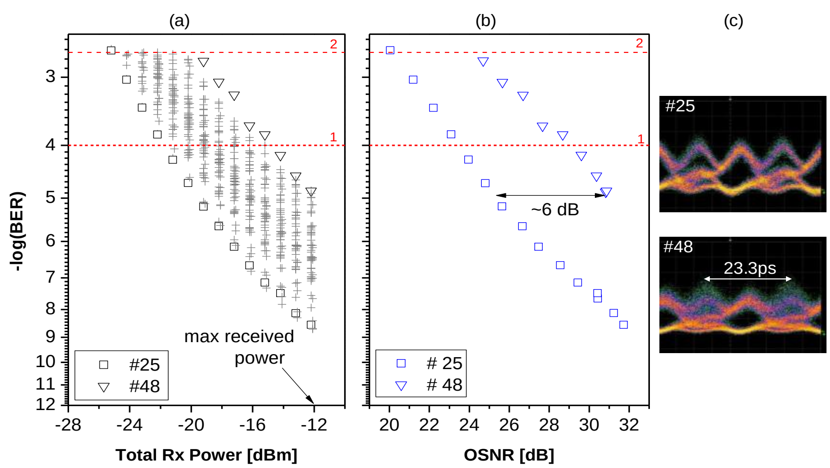

Fig. 2. BER performance after transmission for the best (#25) and worst (#48) subcarriers in terms of (a) total received power, and (b) received OSNR. Grey crosses are all the other 47 subcarriers, represented only on the left graph for clarity. The dashed lines in red represent the threshold for (1) the used FEC board and (2) an enhanced FEC threshold of 2×10^{-3}. (c) Respective eye-diagrams at maximum received power.

We believe that the 6dB difference (at 10^{-5}) observed in the required OSNR between the best and worst subcarriers can be attributed to: a) the wavelength sensitivity within the comb

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generation module (see optical spectrum in Fig. 3 (left-axis)); b) the residual gain variation in the optical amplifiers; c) phase errors between adjacent comb lines after transmission [16]; and also d) to polarization mode dispersion (PMD) [15]. An improvement of the flatness of the 49 subcarriers would guarantee an equal OSNR for all subcarriers. This enables the launch power of all subcarriers to be increased to the nonlinear threshold, therefore improving the OSNR and BER of the worst subcarriers. The average receiver sensitivity at a BER of 1×10^{-5} across the measured sensitivities for all of the 49 subcarriers (filled diamonds in Fig. 3) was ~–15.5dBm. A BER of 2×10^{-15} is required to achieve a FLR of 10^{-12} when transmitting an Ethernet frames [5], which corresponds to a pre-FEC BER of 10^{-4} when using a Reed Solomon RS(255,239) code [17]. Since the EFEC100 board used here employed an RS(255,239) coding format, one can infer from Fig. 2 that a 3dB received power/OSNR margin was obtained. Moreover, the removal of additional loss from the system (i.e variable attenuator and power monitor) could improve this margin even further.

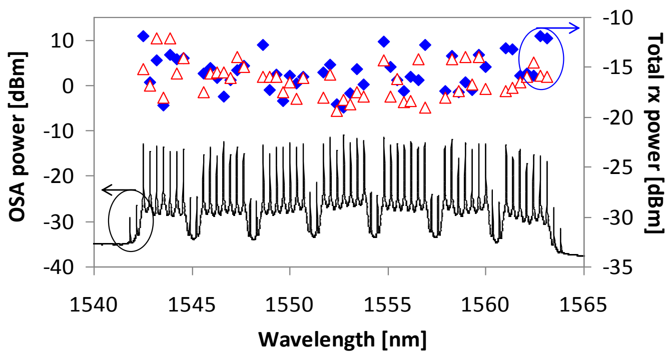

Fig. 3. Left: received optical spectrum after transmission with a resolution bandwidth of 0.02nm. Right: total received power at BER of 1.0×10^{-5} (filled diamonds) and at FLR of 2.3×10^{-10} (open triangles).

Figure 3 also shows the Ethernet performance of all the 49 subcarriers. The maximum number of frames (4.3×10^9) allowed in the Ethernet tester for a single run was set. No frame-losses were observed for any of the 49 subcarriers for the received total power shown in Fig. 3 (open triangles), suggesting a frame loss rate of ~2.3×10^{-10}. When replacing the PRBS tributary with an Ethernet stream, no frame losses were observed for all four FEC-encoded Ethernet WAN PHY streams of the optical subcarrier #19. We believe this represents the first attempt of 2TbE transmission over an unrepeatered installed fiber.

BER measurements were taken over time (Figs. 4(a)-4(b), blue lines) during the FLR measurements, whilst simultaneously monitoring the error signal from the phase stabilization controller (Figs. 4(a)-4(b), green lines). The results for subcarriers #18 and #29 are shown in Figs. 4(a) and 4(b) respectively. A clear correlation between the bit-error bursts and glitches in the phase error signal is clearly observed. For the same period of time, no frame losses were observed on the Ethernet format, due to the magnitude of the bursts being below the FEC threshold of the EFEC100 board used. The glitches in the phase error signal were, in turn, due to fluctuations in the synchronizing clock signal. The 669.32MHz clock from the FEC board (which itself was recovered from the Ethernet stream) was connected to the clock input of the PPG (as in Fig. 1), synchronizing the entire experiment. The 10.7GHz clock monitor output from the PPG was monitored using a RF spectrum analyzer during the measurements. The peak-to-peak magnitude of the observed fluctuations is shown in Fig. 4(c), where the yellow trace illustrates the clock spectrum during a single 200ms sweep, and the blue trace illustrates the maximum amplitude over an extended observation period (> 1 min). Whilst the variations in the clock frequency were well within the specifications for a SDH node in hold-over mode [18], we believe that the observed frequency fluctuations were coupled to the error bursts as follows. CoWDM is critically dependent on the phases of adjacent subcarriers [19]. As shown

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in Fig. 5, the relative phase was stabilised by comparing the phase of the 40GHz beat signal between adjacent subcarriers and a clock reference. Due to a finite difference in the effective delay |T1 – T2| between the two signals combined at the phase stabilization circuit, slight changes in the clock frequency induced sudden glitches in the phase error signal. These, in turn, cause transients in the phase differences between adjacent subcarriers, which impact the error rate. The maximum phase error observed was typically up to 0.15 (see Fig. 4), or 3% when referenced to its peak-to-peak value. By considering that the BER varies over 4 orders of magnitude when varying the phase error [20], a degradation of up to 2 orders of magnitude is expected for a phase error of 3%. A more stable clock reference, or a reduced delay offset at the phase stabilization circuit, would eliminate this intermittent effect. From Figs. 4(a) and 4(b), we notice that such intermittent errors (1 order of magnitude BER change) effectively reduced the margin of the system by ~2 or 3dB due to the slope of the BER characteristic (Fig. 2).

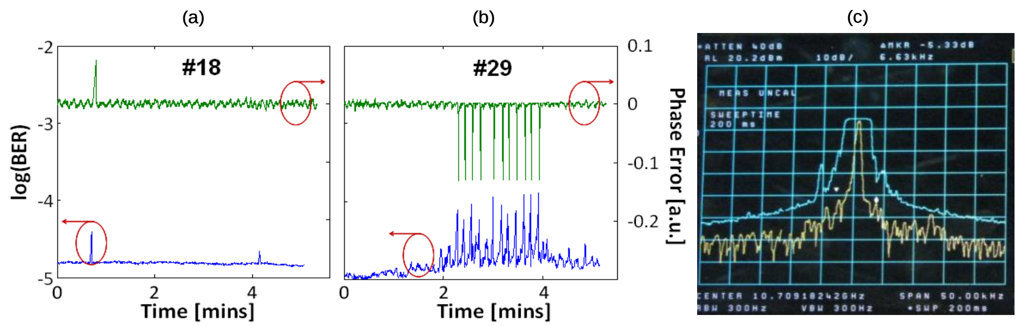

Fig. 4. BER variation (left axis- blue) and phase error (right axis- green) for the PRBS tributary of subcarriers (a) #18 and (b) #29. The BER gating window was set to 100ms. (c) RF spectral analysis of the clock output of the FEC board.

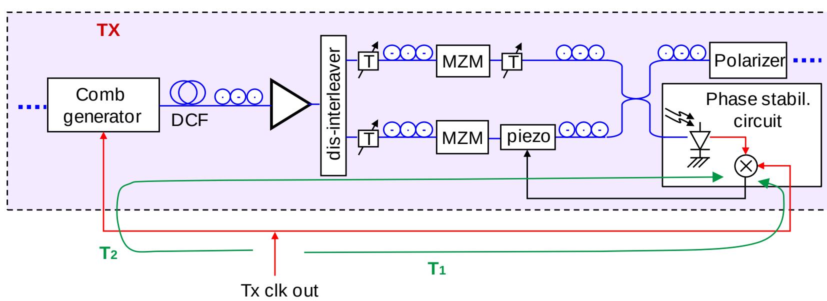

Fig. 5. Details of the phase stabilization circuit inside the transmitter. The different paths and the associated time delays of the signals mixed at the phase stabilization circuit are also indicated in green.

The BER performance of the PRBS tributary for a random subcarrier (#19) at the maximum received power (–12dBm) was monitored over 6 hours to estimate the impact of dynamic effects in the field-installed fiber. The BER variation against time, plotted in Fig. 6, shows fluctuations in the BER of up to two orders of magnitude with a peak BER of ~1×10^{-5}. We attribute these variations mainly to PMD, but the features from 5 hours onwards might also be due to a memory overload of the algorithm used, which probably stopped the active phase control. The feedback control was implemented on a PC, which stored all the phase error values. At the end of the measurement cycle (from 5 hours onwards), the feedback delay was increased due to increasing memory usage. The results in Fig. 6 can also be illustrated as a probability density function (PDF) of log(BER), as per Fig. 7(a). In this case, the PDF shows two distinct peaks: the one with the greater amplitude corresponding to a typical Maxwellian distribution associated with PMD, and the other peak can be attributed to

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either: the proximity of the field-installed fiber cable to a major transport link, or the response of the phase-stabilization circuit to the intermittent frequency modulation present on the synchronizing clock that was discussed earlier.

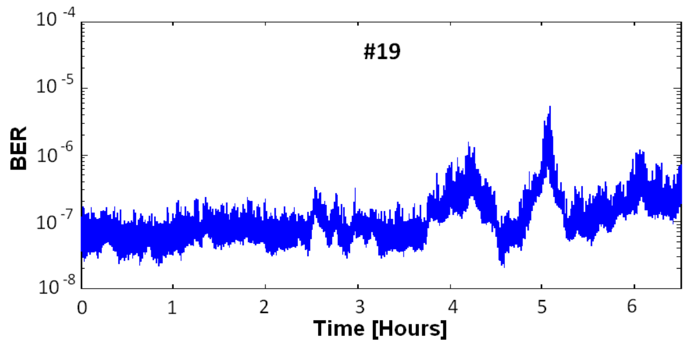

Fig. 6. Long term BER measurement over time for subcarrier #19. The BER gating window was set to 100ms.

We estimated the outage probability, which is defined as the probability that a system outage occurs, to understand how the observed effects degraded the system performance. An outage occurs whenever the BER is greater than 10^{-12} after FEC decoding. From the PDF values in Fig. 7(a), one can calculate the complementary cumulative probability which is plotted in Fig. 7(b) (blue dots). The complementary cumulative probability is defined as the probability that the BER is greater than a certain value (x-axis). The outage probability will then correspond to the intercept between the complementary cumulative probability and the FEC threshold. We consider two extrapolations from the complementary cumulative probability, the first omitting the infrequent high BER events giving an upper bound on the outage probability of 2×10^{-6} (point A in Fig. 7(b)) and the second including these events, giving a lower bound of 3×10^{-12} (point B). Consequently, at full received power, this particular subcarrier delivered an outage probability below the widely used specification of 10^{-5} [21]. The outage probability could be substantially improved if an enhanced FEC board (at a BER threshold of 2×10^{-3} for an interleaved RS(1023,1007)/BCH(2047,1952) code from [17]), represented as a dashed red line #2 in Fig. 7(b), were used, with values below 8×10^{-9} (point C).

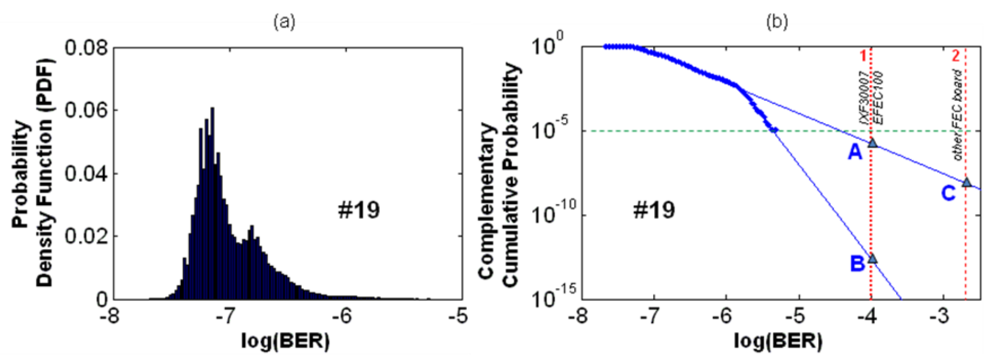

Fig. 7. (a) Probability Density Function (PDF); and (b) complementary cumulative probability calculated from the long term BER measurement relative to an average performance subcarrier (#19). The blue lines are extrapolating slopes from the data, and dashed red lines represent FEC thresholds as from Fig. 2. The green dashed line represents a desirable outage probability [21].

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4. Conclusions

We reported a 2Tbit/s CoWDM transmission over an unrepeatered 124km link, achieving the highest total capacity over an installed fiber link when using orthogonally multiplexed subcarriers. Fluctuations in the BER over time were primarily attributed to PMD and clock instabilities. In every case the worst case BER was below the FEC threshold and frame loss free Ethernet performances were observed for all optical subcarriers, indicating the robustness of the present system configuration against PMD.

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