PMD tolerance of 288 Gbit/s Coherent WDM and transmission over unrepeatered 124 km of field-installed single mode optical fiber

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Abstract: Low-cost, high-capacity optical transmission systems are required for metropolitan area networks. Direct-detected multi-carrier systems are attractive candidates, but polarization mode dispersion (PMD) is one of the major impairments that limits their performance. In this paper, we report the first experimental analysis of the PMD tolerance of a 288Gbit/s NRZ-OOK Coherent Wavelength Division Multiplexing system. The results show that this impairment is determined primarily by the subcarrier baud rate. We confirm the robustness of the system to PMD by demonstrating error-free performance over an unrepeatered 124km field-installed single-mode fiber with a negligible penalty of 0.3dB compared to the back-to-back measurements.

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

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1. Introduction

Orthogonal multi-carrier systems [1], in which the channel spacing is equal to the symbol rate per sub-carrier, offer cost-effective high-capacity transmission with the potential for low latency. Examples of such systems are Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) [2], Coherent Wavelength Division Multiplexing (CoWDM) [3] and all-optical OFDM [4]. In each case, the frequency orthogonality condition is maintained with a different implementation of the matched filter in the demultiplexer. In CO-OFDM, the matched filter is implemented electronically after coherent detection by digital signal processing (DSP), typically using fast Fourier transform (FFT) algorithms, with high latency and limited total capacity due to the electronic bottleneck. In all-optical OFDM and CoWDM, the transmitters are fully implemented in the optical domain, using an optical comb generator and an array of data modulators. For the former, optical filtering strategies at the receiver are implemented to approximate a discrete Fourier transform [5]. In the latter case (CoWDM), simple low-cost filters are employed, but, in order to maintain the orthogonality condition, additional phase control within the transmitter is necessary [6].

CoWDM offers a simple, all-optical implementation with the potential for ultra-high capacities [7]. Since orthogonality is maintained in the optical domain, low-cost direct detection receivers can be used, thus avoiding the greater complexity and power consumption of digital coherent receivers. Although this complexity may also be avoided by using traditional single-carrier transmission systems, the higher symbol rate required by these systems to obtain the same capacity increases their susceptibility to fiber impairments. The major impairments for such direct detected systems include chromatic dispersion (CD), polarization mode dispersion (PMD) and fiber nonlinearity. OFDM, which employs electronic demultiplexing at the receiver, usually includes a few subcarriers dedicated to CD compensation. The CD tolerance of CoWDM and optical OFDM scales with the subcarrier rate [7], rather than the total bit rate. Indeed, numerical simulations have shown that CoWDM is compatible with a wide range of typical dispersion maps [8]. With regard to fiber nonlinearities, the narrow subcarrier spacing (~100MHz) makes OFDM especially sensitive to nonlinearities. This sensitivity has been attributed to the high peak-to-average power ratio, and the dominance of highly-correlated phase-matched four wave mixing products [9]. In contrast CoWDM, which typically employs a wider subcarrier spacing (~10-40GHz), has been demonstrated to have similar performance to a single subcarrier in isolation [10].

This leaves PMD as the only major impairment that might significantly degrade the performance of CoWDM for transmission beyond 10-40Gbaud. Whilst the substantial PMD tolerance of digital coherent receivers is well known [2], PMD remains a significant challenge for lower-cost direct detection systems [11]. Direct-detected optical OFDM (DDO-OFDM) has been demonstrated to have 21ps Differential Group Delay (DGD) tolerance for a 10Gbit/s total line rate (with numerical simulations) [11], which could be enhanced by polarization diversity with combined CD and PMD compensation at the receiver [12]. Whilst numerical analysis has demonstrated that the robustness of CoWDM to PMD is determined by the subcarrier symbol rate [7], there has been no direct measurement of the PMD tolerance of this format. However, to our knowledge, the highest reported ratio of PMD tolerance to capacity for a direct-detected system was achieved using a Non-Return-to-Zero (NRZ) Vestigial Side Band (VSB) format, where 3.5ps DGD tolerance was reported at 107Gbit/s total line rate [13].

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In this paper, for the first time, we experimentally investigate the PMD tolerance of a 288Gbit/s (41.25Gbaud/subcarrier) direct-detected CoWDM system, employing NRZ on-off-keying (OOK) modulation format, without forward error correction (FEC) or DSP. We show that the PMD tolerance of such a system can achieve a greater than 4-fold improvement over single-carrier NRZ when scaled up to 288Gbit/s. Furthermore, we confirm this robustness to PMD by demonstrating the performance of this system over an unrepeatered 124km installed single-mode fiber with a negligible 0.3dB penalty at a bit error rate (BER) of 10^{-9}.

2. PMD tolerance of Coherent WDM

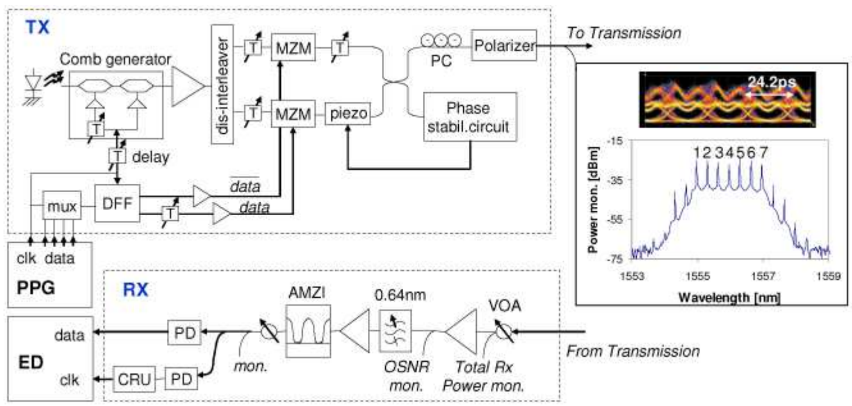

Fig. 1. 288Gbit/s CoWDM experimental set-up.

The direct-detected CoWDM setup is illustrated in Fig. 1, where the transmitter (TX) was composed of a single DFB laser (centered at 1556nm) that generated seven subcarriers using two cascaded Mach-Zehnder modulators (MZMs). The resulting optical comb had a flatness of 0.5dB with a side mode suppression ratio (SMSR) of ~12dB. Even and odd subcarriers were then separated by a dis-interleaver with around 40dB extinction ratio, and independently modulated with 41.25Gbit/s NRZ-OOK data and de-correlated data-bar patterns respectively. The 41.25Gbit/s data patterns were generated by electrically multiplexing four 10.3125Gbit/s 2^{31}-1 pseudo-random binary sequences (PRBS) from a commercial pulse pattern generator (PPG). Delay lines and an electrically driven piezo fiber-stretcher enabled optimization of the data time delays and optical phases respectively. In order to ensure that adjacent subcarriers were orthogonal at the output of the transmitter [3], the fiber-stretcher was controlled by a phase stabilization circuit. The circuit monitored beats between the signal observed at the second output of the data encoder (detected with a 50GHz photodiode) and the 41.25GHz clock signal from the PPG, which were combined in a mixer. A polarization controller (PC) and a polarizer ensured that the subcarriers were all co-polarized. The total capacity was 288Gbit/s, corresponding to an Information Spectral Density (ISD) of 1bit/s/Hz. Figure 1 also shows the 288Gbit/s NRZ-OOK CoWDM spectrum at the output of the transmitter, which had an almost rectangular spectrum with some broadening at its edge due to the low SMSR.

At the receiver (RX), as per Fig. 1, a variable optical attenuator (VOA) was placed before the low noise pre-amplifier (4.3dB noise figure) to control the received signal power, and to vary the optical signal-to-noise ratio (OSNR) at the output of the receiver preamplifier. In order to select each subcarrier for BER measurements, two concatenated filters were used. The 0.64nm band-pass filter was used to select the subcarrier of interest, while the asymmetric Mach-Zehnder interferometer (AMZI), with a free spectral range of ~85GHz, improved suppression of the adjacent subcarriers. The resultant demultiplexed signal was split and sent to various items of diagnostic equipment, including a conventional NRZ clock recovery unit (CRU), optical spectrum analyzer, eye-diagram monitor, and a photodiode (PD) prior to the error detector (ED) in 40Gbit/s detection mode.

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In a direct-detected back-to-back CoWDM system, the optimum subcarrier phase relationship is a π/2 step between each subcarrier. The transmitted eye shape (Fig. 1) then exhibits a significant spread of energy across the bit period. In this experiment, because both subcarriers adjacent to the subcarrier under test were carrying identical data, a significant dip was observed in the middle of the eye diagram. The subcarrier phases could be adjusted to pre-compensate for the delay response of the AMZI, and may be fine tuned to accommodate any residual link dispersion [14] or additional dispersion within the receiver due to, for example, the optical filters. In a practical system with independent data carried on each subcarrier, the seven wavelengths would be routed through seven different modulators, and eight levels would be observed in the transmitted eye diagram.

In order to characterize the PMD tolerance of a 288Gbit/s NRZ-OOK CoWDM system, the setup illustrated in the inset of Fig. 2 was implemented. To emulate the PMD of a transmission fiber link, a polarization scrambler (Adaptif Photonics A3200) and a commercial PMD emulator (JDS Fitel PE4) were deployed between the transmitter and receiver. The polarization scrambler was set to select randomly one of 52 states of polarization (SOP) at a rate of 100kHz (the clock recovery bandwidth - Centellax MC39R46M- may have influenced the receiver sensitivity).

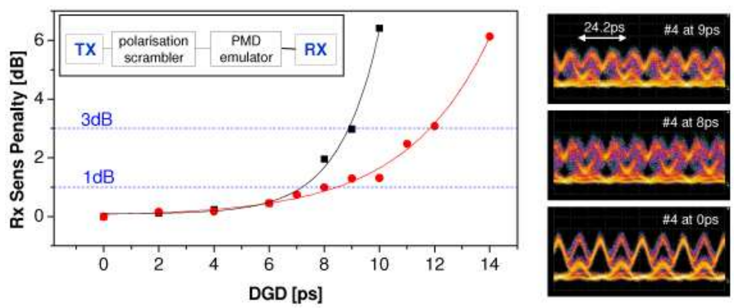

Fig. 2. (Left): RX sensitivity penalty versus fixed DGD for 41.25Gbit/s single channel (red circles) and for 288Gbit/s CoWDM (black squares). (Inset) Experimental setup for PMD tolerance evaluation. (Right): Received eye diagrams for subcarrier #4 for different DGD.

Figure 2 shows the penalty for subcarrier #4 calculated from the receiver sensitivity at a BER of 10^{-9} with respect to its value at 0ps DGD. This figure also shows, for comparison purposes, a 41.25Gbit/s NRZ-OOK single channel, which was obtained by switching off the comb generator and keeping the same receiver configuration. This would be similar to a conventional 40Gbit/s WDM system with 100GHz spacing. The experimental results were fitted with single exponentials, which allowed the penalties to be estimated. We compared the results with the numerical simulations presented in [15], where, for a NRZ-OOK signal, a DGD equivalent to 30 percent of the bit period led to 1dB penalty. In our single channel measurement (Fig. 2), the 1dB receiver sensitivity penalty occurred at a DGD of 8.5ps, slightly better then the numerically predicted 7.3ps, which implies that the measurements above overestimate the PMD tolerance by 1.2ps. On the other hand, for the 288Gbit/s CoWDM signal, the 1dB penalty occurred at 7.2ps. The PMD tolerance was degraded by a modest 5% at the 1dB mark, and at 12% at 3dB, compared to the single channel case. We attribute this penalty to the in-band crosstalk. As may be seen in the eye diagrams (Fig. 2), the crosstalk was concentrated in the crossing regions, which shortened the duration of the eye openings and thus reduced the receiver phase margin. However, CoWDM still compared favorably with conventional WDM, as the ISD was increased by more than a factor of 2, showing only a slight penalty in the PMD tolerance. The measurements above (Fig. 2) show the penalties for fixed DGD values. However, the first order DGD of installed fiber varies in time and follows a Maxwellian distribution that falls-off to low probabilities at ~3 times the average value. It was previously shown with numerical simulations that a 298Gbit/s CoWDM system had a 1.3dB Q-factor penalty for 3ps of mean DGD when compared to a conventional WDM system [7]. This result is therefore consistent with the experimentally measured

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penalty of 2dB for 9ps fixed DGD (Fig. 2). In summary, 288Gbit/s NRZ-OOK CoWDM offers a sufficiently robust transmission system in presence of 2.4ps mean DGD. For example, in a typical fiber link with a 0.1ps/√km PMD coefficient, the PMD tolerance of 288Gbit/s CoWDM would thus allow a link of up to 570km without the need of PMD compensation.

Table 1. PMD tolerance comparison between different formats using fixed DGD values.

	1 [13]	2 [11]	3	4
Bit Rate	107Gbit/s	10Gbit/s	41.25Gbit/s	288Gbit/s
Format	NRZ-VSB	4-QAM DDO-OFDM	NRZ-OOK	NRZ-OOK CoWDM
ISD [bit/s/Hz/pol]	1	1	0.4	1
DGD for 1dB penalty	3.5ps	21ps*	8.5ps	7.2ps
DGD for 1dB penalty at 288 Gbit/s	1.3ps	0.7ps	1.2ps	7.2ps

* obtained from simulated mean DGD.

Table 1 shows the comparison with some alternative direct-detected modulation formats. In order to provide a direct comparison, all results are scaled up to 288Gbit/s whilst maintaining the same ISD. The seven-subcarrier CoWDM offers a greater than 4-fold improvement in the DGD tolerance when compared to other formats (taking into account the 1.2ps measurement error). The use of a polarization-diverse coherent receiver with digital PMD compensation could also increase the maximum tolerable DGD, but only at the expense of considerable increase in complexity [16].

3. Unrepeatered field-installed 124km performance

We previously reported the transmission of a 288 Gbit/s Ethernet signal over unrepeatered 124km of field-installed fiber link, between Cork City and Clonakilty (County Cork, Ireland), in BT Ireland's network [17]. In that experiment, in order to achieve a frame-loss rate better than 10^{-10} (corresponding to a BER of 10^{-14}), the system employed power levels that brought it into the nonlinear transmission regime. The resulting nonlinear penalties of up to 4dB obscured the impact of PMD. In order to illustrate the PMD tolerance of CoWDM, we repeated the performance measurements without Ethernet frames at lower launch power levels. The single loop of 124km (62km + 62km), shown in Fig. 3, had a total loss of 26dB and a net dispersion of ~1970ps/nm, measured by the Devaux technique [18]. Separate EDFAs (25dB gain, 23dBm output power, and 4.9dB noise figure) were inserted before and after the installed SMF fiber. A dispersion compensating module (−1977ps/nm) and additional dispersion trimmers were inserted after the second EDFA. VOAs were used to optimize the power launched both into the installed SMF (+ 6dBm/subcarrier) and the dispersion post-compensating fibers (0dBm/subcarrier).

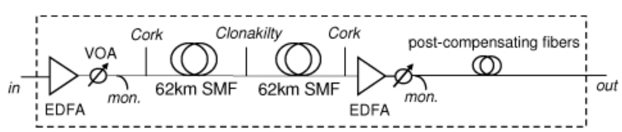

Fig. 3. 124km BT Ireland field-installed link.

For back-to-back measurements, the relative phase between odd and even subcarriers was set to one value for all subcarriers that gave the best average receiver sensitivity. However, after transmission over the fiber, the optimum phase varied with wavelength as a result of residual dispersion, and was therefore adjusted before measurement of each subcarrier.

In Fig. 4(a) the received eye diagrams are shown for subcarriers #4, #5, #6 and #7 after 124km transmission. For a subcarrier in the center of the band (e.g. #4), the 'one' level shows a strong 80GHz beat frequency, which was a specific artifact of the two-modulator configuration used here [6]. Variations between the eye-diagrams were due to the required

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tuning of the transmitter phases, which had to take into account the residual dispersion of the link [14] and receiver filters, in addition to restoring the channel orthogonality. This resulted in the concentration of the energy of each subcarrier towards the centre of its eye and movement of interference with its neighbors to the edge of eye. However the shape of the residual crosstalk, now located at the eye crossings, became channel dependent.

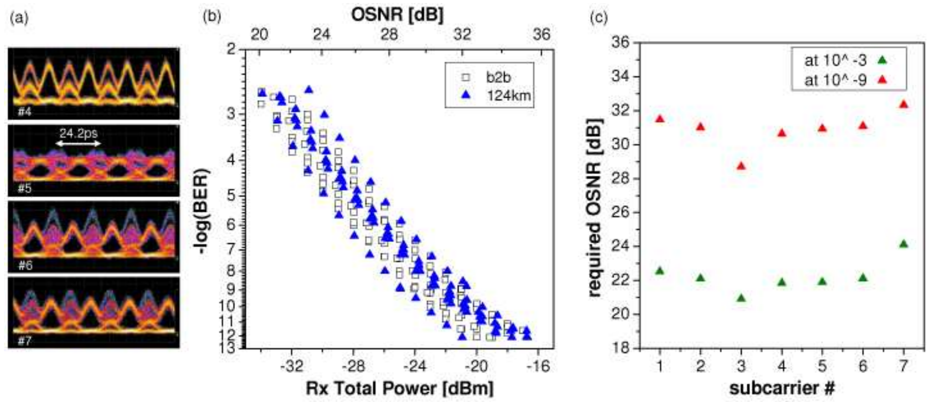

Fig. 4. (a) Received eye diagrams for subcarriers # 4, #5, #6 and #7 after transmission. (b) Measured BER curves against received total power for back-to-back (squares) and after transmission (triangles). (c) Required OSNR after 124km for each of the seven subcarriers.

The BER measurements for all the seven demultiplexed subcarriers are plotted in Fig. 4(b). Due to the saturation effects within the optical amplifier chain, the relationship between the OSNR and received power was not linear. The total received power was used as the measure of receiver sensitivity (bottom x-axis), and the corresponding OSNRs are also shown (top x-axis). It may be seen that the receiver sensitivity penalty of the 288Gbit/s signal (as an average of the seven subcarriers) after 124km transmission was a negligible 0.3dB, appreciably better than the previously reported 4dB [17]. The OSNR at the output of the receiver pre-amplifier was defined as the ratio between the signal, integrated over the full CoWDM band, and the noise within a 0.1nm bandwidth. We estimate that the OSNR at the photodiode prior to the error detector has a small degradation of no more than 0.2dB, due to the presence of a second receiver amplifier (Fig. 1). The OSNRs required at the receiver input for each subcarrier to achieve a target BER of 10^{-3} and 10^{-9} respectively were on an average ~22dB and ~31dB, as shown in Fig. 4(c). The difference of about 4dB between the subcarrier BER curves was probably due to non-ideal output from the comb generator, such as the relative phase shift between neighboring subcarriers differing from $\pi/2$, together with variations in the power uniformity over time. We suggest that the emergence of a potential error floor was due to the finite available OSNR from the transmitter.

4. Conclusions

We have experimentally demonstrated, for the first time, that the PMD tolerance of a CoWDM system is determined primarily by the subcarrier baud rate, and not the total bit rate. This confirms our earlier theoretical predictions. We have also demonstrated error-free transmission of 288Gbit/s CoWDM over a 124km unrepeatered installed fiber link with a negligible penalty of 0.3dB. While offering the same ISD of 1bit/s/Hz, 288Gbit/s NRZ-OOK CoWDM can offer a greater than 4-fold improvement in PMD tolerance over competing direct-detected techniques with equal capacity. This benefit, together with the low cost of direct detection, the high ISD, and the robustness against CD and nonlinearities, makes direct-detected CoWDM an ideal candidate for high-capacity transmission over metropolitan area networks.

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