

Digital back-propagation for spectrally efficient WDM 112 Gbit/s PM m-ary QAM transmission

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Abstract: We report the performance of coherently-detected nine-channel WDM transmission over high dispersion fibers, using polarization multiplexed m-ary quadrature amplitude modulation ($m = 4, 16, 64, 256$) at 112 Gbit/s. Compensation of fiber nonlinearities via digital back-propagation enables up to 10 dB improvement in maximum transmittable power and ~ 8 dB Q_{eff} improvement which translates to a nine-fold enhancement in transmission reach for PM-256QAM, where the largest improvements are associated with higher-order modulation formats. We further demonstrate that even under strong nonlinear distortion the transmission reach only reduces by a factor of ~ 2.5 for a 2 unit increase in capacity ($\log_2 m$) when full band DBP is employed, in proportion to the required back-to-back OSNR.

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1. Introduction

The revival of coherent detection research along with multi-level advanced modulation formats is expected to enable optical transport capacity to satisfy the growing bandwidth demand due to bandwidth intense digital multimedia applications [1,2]. In particular, polarization multiplexed m-ary quadrature amplitude modulation (PM-mQAM) is a promising transmission scheme for future next-generation networks owing to its increased spectral efficiency and simple implementation. Transmission experiments ranging from PM-16QAM to 256QAM [3–5] have recently been demonstrated.

At the same time electronic mitigation of fiber impairments has been recently addressed [6], including digital back-propagation (DBP) with using inverse fiber parameters for the compensation of fiber nonlinearities [7–12]. However, unless multi channel DBP is employed, the performance is often constrained by inter-channel nonlinearity [9]. Although simplification of the DBP algorithm has already commenced [10,12], nonlinear performance bounds for this compensation scheme and the scaling of such limits for spectrally efficient high-order modulation formats are yet to be identified.

In this paper we extend our previous report [13] to a nine-channel WDM 112 Gbit/s PM-mQAM ($m = 4, 16, 64, 256$) system to identify the maximum potential performance enhancement via electronic compensation techniques, reporting for the 1st time the potential performance of a PM-256QAM employing DBP. Our results suggest that DBP has the strongest potential impact on higher-order modulation formats, and given a higher-order format, greater improvements in maximum transmittable power (10 dB), Q_{eff} (~ 8 dB), and transmission reach (~ 9), e.g. for PM-256QAM, can be achieved when moving from conventional electronic dispersion compensation (EDC) to DBP. Furthermore, we demonstrate that the achievable transmission distance after DBP simply scales in proportion to required linear optical signal-to-noise ratio (OSNR) for each constellation size, consistent with the limits imposed by four-wave mixing between signal and amplified spontaneous emission (S-ASE FWM) [11]. Three transmission regimes are identified where satisfactory performance is achieved using; conventional electronic dispersion compensation (intra-channel nonlinearity limited), single-channel DBP (inter-channel nonlinearity limited), and full-band DBP (S-ASE FWM limited).

Table 1. Simulation parameters

Modulation Format	PM-4QAM	PM-16QAM	PM-64QAM	PM-256QAM
Baud rate	28 Gbaud	14 Gbaud	9.33 Gbaud	7 Gbaud
Channel spacing	50 GHz	25 GHz	16.667 GHz	12.5 GHz
Optical mux	30 GHz	15 GHz	10 GHz	7.5 GHz
Optical demux	50 GHz	25 GHz	16.667 GHz	12.5 GHz
Simulated bits	32,768	65,536	98,304	131,072

	Loss (dB/km)	Dispersion (ps/nm/km)	Nonlinearity (1/W/km)
SSMF	0.2	20	1.5

2. Simulation setup

Figure 1 illustrates the simulation setup which comprised either one (single channel transmission) or nine (WDM transmission) 112 Gbit/s PM-mQAM channels, where the central channel was operated at 1550 nm. For all of the channels, two orthogonal polarization states derived from a continuous wave laser were modulated independently using decorrelated 2^{15} and 2^{16} pseudo-random bit sequences (PRBS). Each PRBS was coded into two multi-level symbol streams, which drove a nested Mach-Zehnder modulator. The simulation conditions ensured 16 samples per symbol and 2^{13} symbols per polarization per channel. The channel spacing and multiplexer/de-multiplexer filter bandwidths are shown in Table 1, along with the number of simulated bits.

The 112 Gbit/s PM-mQAM signals were multiplexed and propagated over a non-dispersion managed link using single-stage optical amplifiers. The link comprised $M \times 80\text{km}$ spans of standard single mode fiber (SSMF) for transmission. The amplifiers were modelled with a 4.5 dB noise figure and 16 dB gain. For simplicity we neglected the effects of polarization mode dispersion and laser line-width in this paper. After fiber transmission, the received signals were demultiplexed, pre-amplified (constant power of 0 dBm) and coherently-detected using independent local oscillators (LOs) to give baseband electrical signals, and down sampled to 2 samples per symbol. Transmission impairments were digitally compensated in two scenarios. Firstly by using electronic dispersion compensation (EDC) alone (the back-propagation section in Fig. 1 was by-passed), employing finite impulse response (FIR) filters ($T/2$ -spaced taps) adapted using a least mean square algorithm. In the second case, electronic compensation was applied by DBP, which was numerically implemented by up-sampling the received signal to 16 samples per symbol and reconstructing the optical field from the inphase and quadrature components, followed by split-step Fourier method based solution of z-reversed nonlinear Schrödinger equation (NLSE), where the fibre is divided into small sections, representing dispersion in frequency-domain and nonlinearity in time-domain. We considered DBP using either a single (SC DBP) or all nine (full band DBP) channels. In order to determine the maximum potential performance, the step-size was chosen adaptively such that in each step the change in phase of the optical field was not more than 0.05 degrees, and the same step-size was used for all the formats.

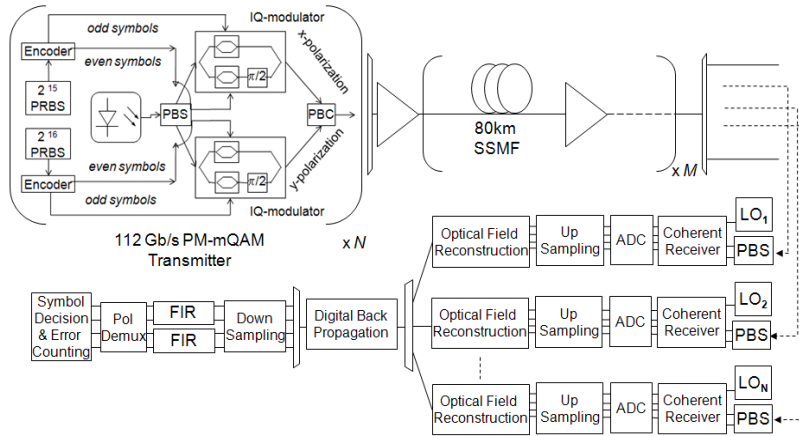


Fig. 1. Simulation setup for 112 Gbit/s PM-mQAM ($m = 4, 16, 64, 256$) WDM transmission system with N transmitters and M spans. PBS: Polarization beam splitter, ADC: Analogue to digital converter.

Polarization de-multiplexing and residual dispersion compensation was performed using a butterfly structure and symbol decisions allowed the performance to be assessed by direct error counting which was then converted into an effective Q-factor (Q_{eff}). Numerical simulations were carried out using VPItransmissionMaker® v8.5, and MATLAB® v7.10.

3. Results and discussions

Figure 2 depicts the simulated Q_{eff} as a function of launch power per channel per span for 960 km transmission of 112 Gbit/s PM-256QAM for a nine-channel WDM transmission, after EDC, SC DBP, and full band DBP. It can be seen that compensation of nonlinear fiber impairments using full band DBP enables performance beyond the conventional FEC limit (Q_{eff} of 9.79 dB), and the Q_{eff} curves follow the well-known optimum launch power phenomenon for optical transmission, where at lower launch powers, the system performance is limited by noise and the performance peaks at an optimum launch power, often referred to as nonlinear threshold (NLT). This is a well-known consequence of uncompensated fiber nonlinearities for an EDC based system or a SC DBP system. However, it can be seen that SC

DBP offers a very minimal Q_{eff} improvement compared to EDC based system. This behaviour can be attributed to transmission performance strongly constrained by inter-channel nonlinearities, such that intra channel effects are not dominant. Also, it can be observed that a NLT exists even after full band DBP, where one would expect all the deterministic intra-/inter- channel nonlinearities to be compensated. We attribute this behaviour to parametric amplification of the ASE by the signal which could not be compensated by DBP [11]. In this case, the NLT is increased by 10 dB, with an associated Q_{eff} improvement of ~ 8 dB and ~ 7.5 dB, when EDC and SC DBP are replaced by full band DBP, respectively.

Figure 3a–3d qualitatively depict the difference in performance between a full band DBP system where the reach is set to give a BER of approximately 10^{-3} (Q_{eff} of 9.79 dB) at the optimum launch power, and the corresponding EDC system at the same transmission distance, for PM-mQAM ($m = 4, 16, 64, 256$). It is clear that when using EDC alone, the constellation diagrams are degraded for all the modulation schemes considered. However, the use of full band DBP enables identification of the mean location of individual symbols. Note that in both cases, the noise distribution looks symmetric and appear to follow bi-Gaussian distribution. We attribute the Gaussian noise distributions in this configuration to the short correlation length due to highly dispersive transmission, sufficiently randomizing the nonlinear interactions.

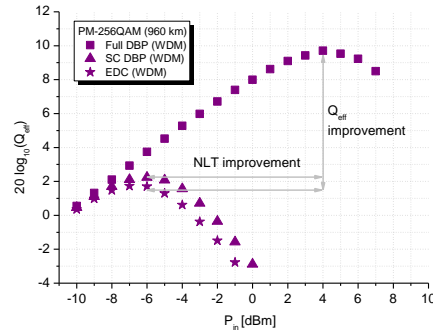


Fig. 2. Q_{eff} as a function of launch power per channel per span for 112 Gbit/s PM-256QAM after 960 km. EDC only (stars), SC DBP (triangles), full band DBP (squares).

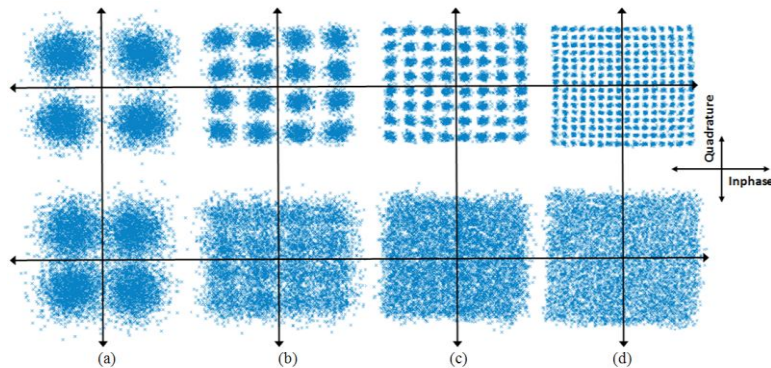


Fig. 3. Constellation maps after full band DBP (top) and EDC (bottom) for nine-channel WDM 112 Gbit/s PM-mQAM ($m = 4, 16, 64, 256$), NLT at BER of 10^{-3} after full band DBP in all the cases. a) PM-4QAM after 17,200 km, b) a) PM-16QAM after 6,640 km, C) a) PM-64QAM after 2,640 km, d) a) PM-256QAM after 960 km.

To determine the maximum performance with electronic compensation techniques, we first established the maximum reach for each format (Fig. 4), for both single-channel and nine-channels WDM transmission, where each data point was taken from a NLT plot, such as Fig. 2. We establish various transmission regimes where EDC, SC DBP (for WDM case

only), and full band DBP may be successfully used. It can be seen that both for single-channel and WDM systems, the transmission reach after full band DBP scales directly with the modulation order giving a decrease in reach of ~ 2.5 times for an increase in $\log_2 m$ of 2. Note that the minimal difference between the performance of full band DBP for single-channel (filled triangles) and WDM (filled squares) cases is due to additional filtering effects in the WDM case. Nevertheless, as observed in Fig. 2, the maximum available transmission reach after full band DBP is limited. Recently, we have identified the source of such effects to be signal-ASE FWM, where the ASE is parametrically amplified by the signal power such that the noise amplification quadruples if the signal power is doubled [11]. We also measured the OSNR at each data point for full band DBP (single-channel and WDM), and the required OSNR at the distance where a BER of 10^{-3} was obtained, as shown in Fig. 5, along with the theoretical required OSNR for a purely linear system. In both cases, we observe that the curves have a slope of approximately 2.25 dB per unit of capacity, with an offset of 2.5 ± 0.5 dB representing the implication of the tradeoff between OSNR and the nondeterministic nonlinear interactions between the signal and ASE. Note that since the slopes in Fig. 5a are identical for a given configuration, the relative reach of a given constellation after full band DBP may be estimated simply from the change in required back-to-back OSNR.

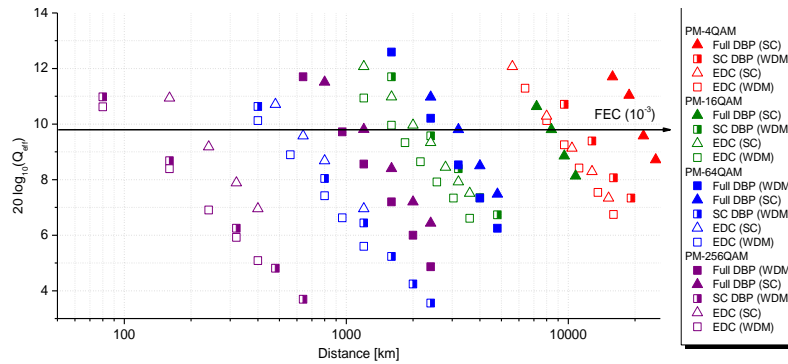


Fig. 4. Q_{eff} as a function of transmission distance for 112 Gbit/s PM-mQAM for single channel (triangles) and nine channel WDM (squares) transmission. $m = 4$ (red), 16(green), 64(blue), and 256(purple). EDC (open), SC DBP (half filled), and full band DBP (solid).

Figure 4 also shows the transmission regimes where performance above FEC threshold is possible with EDC and SC DBP alone. It can be seen that EDC clearly offer adequate performance for the majority of foreseeable transmission reaches (up to 10,000 km) for PM-4QAM. However, a strong dependence on the modulation order is observed, with the higher-order formats showing proportionately worse performance than would be expected from the linear required OSNR.

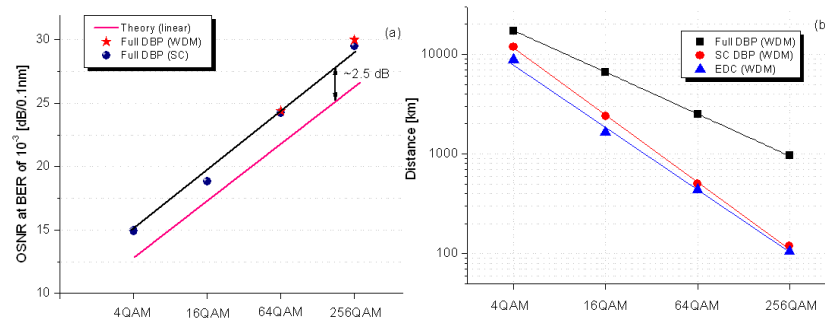


Fig. 5. a) Required OSNR at the NLT for maximum transmission reach achieving a BER of 10^{-3} , linear theory (pink line), data after full band DBP (red triangles: WDM, blue circles: single-channel), b) Maximum transmission distance at the NLT achieving a BER of 10^{-3} for a WDM system. EDC (triangle), SC DBP (circle), full band DBP (square)

This behavior is also illustrated in Fig. 5b, where observed variation in transmission reach with constellation size is reported for PM-mQAM, after EDC, SC DBP, and full band DBP. One can observe that for higher order formats the difference between full band DBP and EDC (and SC DBP) is significant, which can be attributed to higher peak-to-average power ratio and reduced dispersive effects for higher order formats owing to the lower baud rate. Together these features lead to stronger inter-channel nonlinear effects such as cross phase modulation, and higher-order formats are more sensitive to resultant uncompensated phase noise. For example the maximum reach of a PM-256QAM signal suffers a ~9-fold (~8-fold) degradation, whilst the PM-4QAM signal is only degraded by ~2 times (~1.5 times) after EDC (SC DBP), compared to the case with full band DBP. The small difference between EDC and SC DBP decreases with the order of modulation format, consistent with an increased XPM impact associated with reduced spacing.

The marked increase in effectiveness of DBP for higher order formats is also shown in Fig. 6 where the performance in terms of Q_{eff} (Fig. 6a) and NLT (Fig. 6b) is illustrated for EDC, SC DBP, and full band DBP for each format. The performance of a full band DBP system is evaluated with the NLT at a BER of 10^{-3} (Q_{eff} of 9.79 dB), and corresponding Q_{eff} and NLT are calculated for EDC and SC DBP systems for a given format at a fixed transmission distance (e.g. Figure 2). It can be seen that the Q_{eff} increases from ~3.5 dB to ~8 dB and ~2 dB to ~7.5 dB for EDC and SC DBP, respectively as the order of the modulation format is increased. Then again, similar behaviour is observed for improvement in the NLT across various formats, where a significant increase from 3 dB to 10 dB is observed. Consequently, DBP appears to have significantly greater impact for the higher-order modulation formats which will be required in order to continue increasing spectral efficiency.

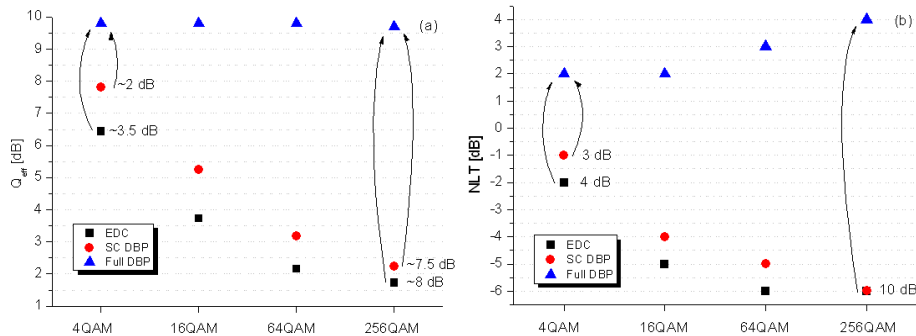


Fig. 6. Q_{eff} (a) and NLT (b), for EDC (circles), SC DBP (squares), and full band DBP (triangles) for PM-mQAM at transmission distances giving 9.79 dB Q_{eff} after full band DBP. (960 km (256QAM), 2,640 km (64QAM), 6,640 km (16QAM), and 17,200 km (4QAM)).

4. Conclusions

We have reported the impact of digital back-propagation on PM-mQAM formats up to 256QAM in a coherently-detected nine-channel 112 Gbit/s transmission system, demonstrating that the increased sensitivity of higher-order formats to nonlinear effects results in an increased penalty with respect to the back-to-back OSNR. However, when full band DBP is employed, the optimum peak performance for all modulation formats shows similar trend to back-to-back linear theory, with a ~2.5 dB offset. We also demonstrate that the transmission reach only reduces by a factor of ~2.5 for a 2 unit increase in capacity ($\log_2 m$) when full band DBP is employed. However, full-band DBP is only beneficial over a limited range of distances, bounded by relatively weak inter-channel degradation at short distances where it is not necessary, and by nondeterministic signal ASE interactions at longer distances.

Acknowledgments

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