Nonlinear penalties in long-haul optical networks employing dynamic transponders

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Abstract: We report for the first time, the impact of cross phase modulation in WDM optical transport networks employing dynamic 28 Gbaud PM-mQAM transponders (m = 4, 16, 64, 256). We demonstrate that if the order of QAM is adjusted to maximize the capacity of a given route, there may be a significant degradation in the transmission performance of existing traffic for a given dynamic network architecture. We further report that such degradations are correlated to the accumulated peak-to-average power ratio of the added traffic along a given path, and that managing this ratio through pre-distortion reduces the impact of adjusting the constellation size of neighboring channels.

OCIS codes: (060.1660) Coherent communications; (060.4254) Networks, combinatorial network design; (060.4256) Networks, network optimization; (060.4370) Nonlinear optics, fibers.

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1. Introduction

The communication traffic volume handled by trunk optical transport networks has been increasing year by year [1]. The resultant change in traffic patterns not only requires a quantitative increase in total traffic volume, but also requires an increase in the speed of individual clients. This is particularly true for shorter links across the network, where the improved optical signal to noise ratio (OSNR) would allow the use of a higher capacity. One of the options to improve resource utilization in a static network is the deployment of spectrally efficient higher-order modulation formats enabled by digital coherent detection [2,3]. However, as attested by the rapid growth in reported constellation size [4–6], the optical hardware for a wide variety of coherently detected modulation formats is identical. This has led to the suggestion that a common transponder may be deployed and the format adjusted on a link by link basis to either maximize the link capacity given the achieved OSNR, or if lower, match the required client interface rate [7]. Such dynamic, potentially self adjusting, networks may be desirable to enable graceful capacity growth, ready resource allocation and transponder cost reductions. However many additional trade-offs and challenges associated with such networks are presented to system designers and network planners. One such challenge is associated with the nonlinear transmission impairments which strongly link the achievable channel reach for a given modulation format and symbol-rate [7,8]. Compensation of many of the linear and nonlinear fibre impairments can be achieved by employing electronic signal processing using digital back-propagation (DBP) [9–11]. Although the future potential of nonlinear impairment compensation using DBP in a dynamic optical network is unclear due to its significant computational burden and limited access to the full dense wave-division multiplexing band, simplification of nonlinear DBP algorithm using single-channel processing at the receiver has already commenced [12,13]

In such a dynamic network, there is a large range of options to provide the desired flexibility including symbol rate [14], sub-carrier multiplexing [15], network configuration [16] and signal constellation [3]. In this paper we focus on the signal constellation and report the impact of periodic addition of PM-mQAM (m = 4, 16, 64, 256) transmission schemes on existing PM-4QAM traffic in a 28 Gbaud WDM optical network with a maximum transparent optical path of 9,600 km. We demonstrate that the periodic addition of traffic at reconfigurable optical add-drop multiplexer (ROADM) sites degrades through traffic, and that this degradation increases with the constellation size of the added traffic. In particular, we demonstrate that undistorted PM-mQAM signals have the greatest impact on the through traffic, with the degradation strongly correlated to the total peak-to-average power ratio (PAPR) of the added traffic. Using this observation, we propose the use of linear pre-distorting of the added channels to reduce the impact of the cross-channel impairments.

2. Transmission model

Figure 1 illustrates the simulation setup. The optical link comprised nine WDM channels, employing 28 Gbaud PM-mQAM (m = 4, 16, 64, 256). The central channel was always 112 Gb/s PM-4QAM, and the immediate neighbours (left and right) were periodically selected to be PM-mQAM channels. All the transmitters were operated at a constant baud-rate of 28Gbaud with a channel spacing of 50 GHz. For all the carriers, both the polarization states were modulated independently using de-correlated 2^{15} and 2^{16} pseudo-random bit sequences

(PRBS) with different random number seeds, for x- and y-polarization states, respectively. Each PRBS was de-multiplexed separately into two multi-level output symbol streams which were used to modulate an in-phase and a quadrature phase carrier. The optical transmitters consisted of a continuous wave laser source, the central transmitter was operated at 1550 nm, followed by two nested Mach-Zehnder Modulator structures for x- and y-polarization states, and the two polarization states were combined using an ideal polarization beam combiner. The simulation conditions ensured 16 samples per symbol with 2^{13} total simulated symbols per polarization, corresponding to a total 32,768, 65,536, 98,304, and 131072 bits for PM-mQAM (m = 4, 16, 64, 256 respectively). All the channels had the same average power level and were combined using a multiplexer with a 30 GHz 3rd order Gaussian pass band. For simplicity we neglected polarization mode dispersion and laser line-width in this paper (for the worst-case scenario employing 256QAM, 80 kHz linewidth can be tolerated [17]).

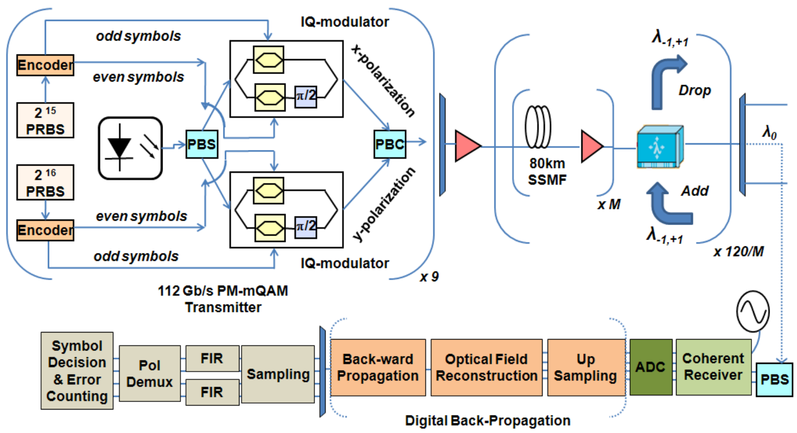

Fig. 1. Simulation setup for 28 Gbaud PM-mQAM transmission. *M*: Number of spans between ROADM nodes.

The signal was propagated over standard single mode fibre (SSMF) transmission link with 80 km spans, no inline dispersion compensation and single-stage erbium doped fibre amplifiers (EDFAs). The fibre had attenuation of 0.2 dB/km, dispersion of 20 ps/nm/km, and a nonlinearity coefficient (γ) of 1.5/W/km. Each amplifier stage was modelled with a 4.5 dB noise figure and the total amplification gain was set to be equal to the total loss in each span. Note that the total optical path was fixed to be 9,600 km and after every *M* spans, a ROADM stage was employed and the channels to the left and right of the central channel were dropped and new channels were added. The dropped channels were coherently detected after first ROADM and the central channel after the last ROADM link.

At the coherent receiver the signals were pre-amplified (constant power of 0 dBm), filtered with a 50 GHz 3rd order Gaussian de-multiplexing filter, coherently-detected using four balanced detectors to give the baseband electrical signal and sampled at 2 samples/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 via single-channel DBP (SC-DBP), which was numerically implemented by up-sampling the received signal to 16 samples/symbol and reconstructing the optical field from the in-phase and quadrature samples, followed by split-step Fourier method based solution of nonlinear Schrödinger equation. The upper bound on the step-size was set to be 1 km and the step length was chosen adaptively during the integration along the fibre based on the condition that in each step the nonlinear effects must change the phase of the optical field by no more than 0.05 degrees. Polarization de-multiplexing and residual dispersion compensation was then performed using FIR filters. Finally, the symbol decisions were made, and the performance assessed by direct error counting (converted into an effective Q-factor (Q_{eff})). All the numerical simulations were carried out using VPItransmissionMaker® v8.5, and the digital signal processing was performed in MATLAB® v7.10.

3. Results and discussions

The maximum performance of the central PM-4QAM channel after the maximum optical path (9,600 km) occurred for a launch power of −1 dBm. The launch power of all the added channels was also fixed at −1 dBm, such that all channels had equal launch powers. Figure 2 illustrates the performance of the central test channel (1550 nm) after the last node (solid), along with the performance of two co-propagating channels (1550 ± 0.4 nm) employing various modulation formats after the first ROADM node (half-solid), at a fixed total transmission distance of 9,600 km for a number of ROADM spacing's, using both SC-DBP (Fig. 2a) and EDC (Fig. 2b). It can be seen that SC-DBP offers a Qeff improvement of ~1.5 dB compared to EDC based system. This performance improvement is strongly constrained by inter-channel nonlinearities, such that intra channel effects are not dominant.. Moreover, the figure shows that as the number of ROADM nodes are increased, or distance between ROADMs decreases, the performance of higher-order neighboring channels improves significantly due to the improved OSNR. However, even when the add drop traffic is PM-4QAM, the performance of the through channel degrades as the number of ROADM nodes is increased, despite the reduction in peak-to-average power ratio (PAPR). The PAPR evolutions for the various formats are shown in Fig. 3. The asymptotic values are reached after approximately 30 km, and reach a slightly higher value for $m \geq 16$. Significantly, the PAPR is reduced at the ROADM site, particularly so for PM-4QAM. Figure 3 implies that harmful increases in the instantaneous amplitude of the interfering channels are not the cause of the penalty experienced by the through channel; we can therefore only conclude that this results from interplay between channel walk off and nonlinear effects. Given that walk-off is known to induce short and medium range correlation in crosstalk between subsequent bits [18], effectively low pass filtering the crosstalk [19]. We thus believe that the most likely cause of the penalty experienced by the through channel is the randomization of the crosstalk by the periodic replacement of the interfering data pattern, and that this effect dominates over the slight reduction in PAPR observed.

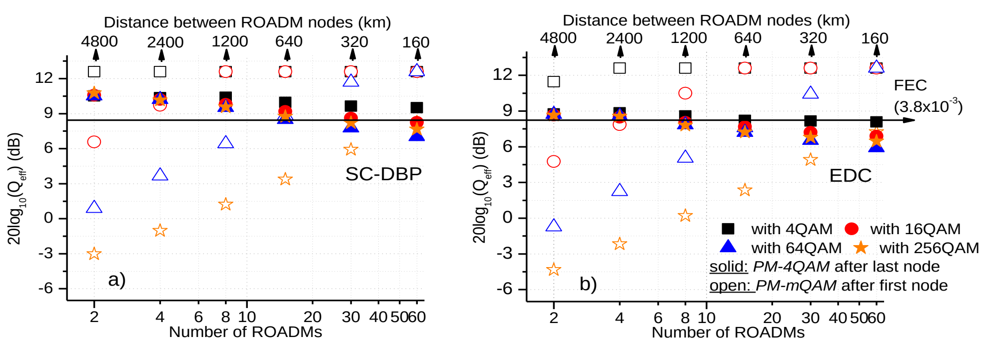

Fig. 2. Q_{eff} as a function of number of ROADMs (and distance between ROADM nodes) for 28 Gbaud PM-mQAM showing performance of central PM-4QAM (solid), and neighbouring PM-mQAM (open). a) with single-channel DBP, b) with EDC. Square: 4QAM, circle: 16QAM, up triangle: 64QAM, star: 256QAM. Up arrows indicate that no errors were detected, implying that the Q_{eff} was likely to be above 13 dB.

It can also be seen from Fig. 2 that added channels with higher-order formats induce greater degradation of the through channel. In particular if there are 30 ROADM sites (320 km ROADM spacing) allocated to transmit PM-64QAM according to an OSNR analysis taking into account the inevitable 2.5 dB required OSNR penalty [3], whilst this traffic operates with significant margin, the through traffic falls below the FEC threshold (BER of

$3.8x10^{-3}$). This increased penalty is due to the increased nonlinear degradation encountered in the first span after the ROADM node, where higher order formats induce greater XPM than PM-4QAM by virtue of their increased PAPR.

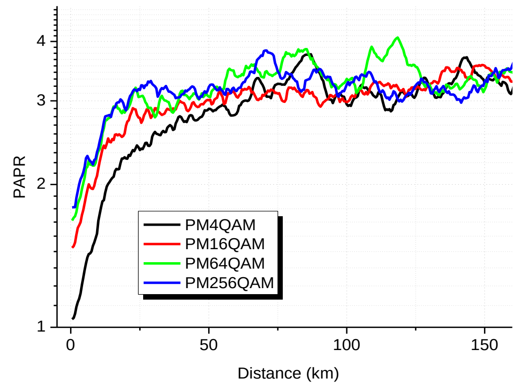

Fig. 3. Variation in PAPR, for 4QAM (black), 16QAM (red), 64QAM (green) and 256QAM (blue) for a loss-less linear fibre with 20 ps/nm/km dispersion.

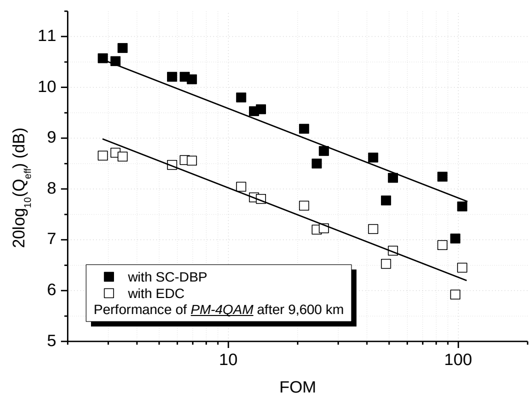

Fig. 4. Q_{eff} of the PM-4QAM through channel for 28 Gbaud PM-mQAM add/drop traffic after 9,600 km as a function of a figure of merit (FOM) defined in the text for various add drop configurations. Solid: with single-channel DBP, open: with EDC.

This is further confirmed in Fig. 4 which plots the Q_{eff} of PM-4QAM after last node, for both EDC and SC-DBP, in terms of a figure of merit (FOM) related to the increased amplitude modulation experienced by the test channel in the spans immediately following the ROADM node, defined as,

$$FOM_{PM-mQAM}(m) = (ROADM_N) \times \left[I_{\max}(m) / \overline{I_{all}(m)} \right] \quad (1)$$

where m represents the modulation order, $ROADM_N$ represents number of add-drop nodes, I_{max} and I_{all} are the maximum and total intensity of the given modulation format. A strong correlation between the penalty and change in PAPR is observed. For instance, for a high number of ROADMs the system would be mostly influenced by relatively un-dispersed signals and the difference between peak-to-average fluctuations for multi-order QAM varies significantly. This leads to higher-order modulation formats impinging worse cross-channel effects on existing traffic for shorter routes.

Having observed that the nonlinear penalty is determined by the reduction in the correlation of nonlinear phase shift between bits arising from changing bit patterns, and to changes in PAPR arising from undistorted signals, it is possible to design a mitigation strategy to minimize these penalties. Figure 5 illustrates, for both EDC and SC-DBP systems, that if the co-propagating higher-order QAM channels are linearly pre-distorted, the performance of the PM-4QAM through traffic can be improved. The figure shows that when positive pre-distortion is applied, such that the neighboring channel constellation is never, along its entire inter node transmission length, restored to a well-formed shape, the impact of cross-channel impairments on existing traffic is reduced significantly.

On the other hand, when negative pre-distortion (dispersion pre-compensation) of less than the node-length (distance per node) is employed, the central test channel is initially degraded further. This behavior can be attributed to the increased impact of the PAPR of the undispersed constellation which is restored in the middle of the link. However, if negative pre-distortion of more than the node-length is employed, the penalty is reduced due to lower PAPR induced XPM, and the performance saturates for higher values of pre-distortion, similar to the case of positive pre-distortion. This behavior is consistent with the postulate that ROADM nodes destroy the inter bit XPM correlation typically encountered in a point to point link [18] which enables a degree of compensation of WDM crosstalk, and that this effect is increased if there is a significant difference in the PAPR of the signal. Note that the performance is never restored to the point to point, homogenous PM-4QAM system owing to a combination of slightly increased PAPR for the higher order formats, and the reduction in data correlation associated with the data exchange at the ROADM sites.

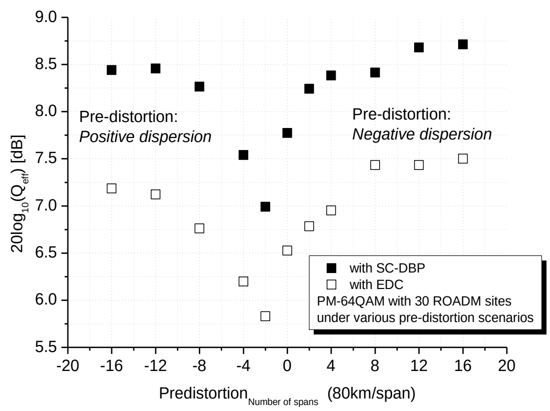

Fig. 5. Q_{eff} of the PM-4QAM through channel with 30 ROADM sites, when the neighbouring PM-64QAM channel is linearly pre-distorted (dispersion only). Solid: with single-channel DBP, open: with EDC.

4. Conclusions

We have reported that cross-channel nonlinear impairments strongly constrain the transmission performance of a 28 Gbaud PM-4QAM through channel in the presence of heterogeneous PM-mQAM neighbors (m = 4, 16, 64, 256) for a WDM dynamic optical network. It has been shown that increasing the network capacity by introducing higher-order formats incur a significant penalty on the existing traffic due to strong XPM effects. Such penalties are shown to be correlated to the total variation in peak-to-average power ratio of the higher-order channel along the path of the through channel and it has been demonstrated that such effects can be reduced given higher-order channels are linearly pre-distorted.

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