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Impairment mitigation in superchannels with digital backpropagation and MLSD

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Abstract: We assess numerically the performance of single-carrier digital backpropagation (SC-DBP) and maximum-likelihood sequence detection (MLSD) for DP-QPSK and DP-16QAM superchannel transmission over dispersion uncompensated links for three different cases of spectral shaping: optical pre-filtering of RZ and NRZ spectra, and digital Nyquist filtering. We investigate the limits for carrier proximity of each spectral shaping technique and the correspondent performance behavior of each algorithm, for both modulation formats. For superchannels with carrier spacing close to the Nyquist limit, it is shown that the maximum performance improvement of 1.0 dB in $Q^2$-factor is provided by those algorithms. However, such gain can be highly reduced when the order of the modulation format increases.

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References and links

1. J.-X. Cai, Y. Sun, H. Zhang, H. G. Batshon, M. V. Mazurczyk, O. V. Sinkin, D. G. Foursa, and A. Pilipetskii, “49.3 Tb/s transmission over 9100 km using C+L EDFA and 54 Tb/s transmission over 9150 km using hybrid-Raman EDFA,” J. Lightwave Technol. 33(13), 2724–2734 (2015).

2. A. Ghazisaeidi, L. Schmalen, I. F. de Jauregui, P. Tran, C. Simonneau, P. Brindel, and G. Charlet, “52.9 Tb/s transmission over transoceanic distances using adaptive multi-rate FEC,” in Tech. Digest of European Conference on Optical Communication, paper PD.3.4 (2014).

3. G. Bosco, V. Curri, A. Carena, P. Poggio, and F. Forghieri, “On the performance of Nyquist-WDM terabit superchannels based on PM-BPSK, PM-QPSK, PM-8QAM or PM-16QAM subcarriers,” J. Lightwave Technol. 29(1), 53–61 (2011).

4. J. Wang, C. Xie, and Z. Pan, “Generation of spectrally efficient Nyquist-WDM QPSK signals using digital FIR or FDE filters at transmitters,” J. Lightwave Technol. 30(23), 3679–3686 (2012).

5. E. Porto da Silva, L. Carvalho, C. Franciscangelis, J. Diniz, J. Oliveira, and A. Bordonalli, “Spectrally-efficient 448-Gb/s dual-carrier PDM-16QAM channel in a 75-GHz grid,” in Tech. Digest of Optical Fiber Communication Conference, paper JTh2A.39 (2013).

6. L. H. H. Carvalho, C. Franciscangelis, G. E. R. Paiva, V. E. Parahyba, A. C. Bordonalli, J. R. F. Oliveira, E. P. da Silva, J. C. R. F. Oliveira, S. H. Linakis, and N. G. Gonzalez, “Transmission of a DAC-free 1.12-Tb/s superchannel with 6-b/s/Hz over 1000 km with hybrid Raman-EDFA amplification and 10 cascaded 175-GHz flexible ROADMs,” in Tech. Digest of European Conference on Optical Communication, paper P4.4 (2013).

7. L. H. H. Carvalho, C. Floridia, C. Franciscangelis, V. Parahyba, E. P. da Silva, N. G. Gonzalez, and J. Oliveira, “WDM transmission of 3x1,12-Tb/s PDM-16QAM superchannels with 6.5-b/s/Hz in a 162.5-GHz flexible-grid using only optical spectral shaping,” in Tech. Digest of Optical Fiber Communication Conference, paper M3C.3 (2014).

8. E. Ip, and J. M. Kahn, “Compensation of dispersion and nonlinear impairments using digital backpropagation,” J. Lightwave Technol. 26(20), 3416–3425 (2008).

9. Z. Tao, L. Dou, W. Yan, L. Li, T. Hoshida, and J. C. Rasmussen, “Multiplier-free intrachannel nonlinearity compensating algorithm operating at symbol rate,” J. Lightwave Technol. 29(17), 2570–2576 (2011).

10. D. Marsella, M. Secondini, and E. Forestieri, “Maximum likelihood sequence detection for mitigating nonlinear effects,” J. Lightwave Technol. 32(5), 908–916 (2014).

11. T. Oyama, T. Hoshida, H. Nakashima, C. Ohshima, Z. Tao, and J. C. Rasmussen, “Impact of pulse shaping and transceiver electrical bandwidths on nonlinear compensated transmission,” in Tech. Digest of Optical Fiber Communication Conference, paper OTh3C.2 (2013).
12. G. Liga, T. Xu, L. Galdino, R. Killey, and P. Bayvel, “Digital back-propagation for high spectral-efficiency terabit/s superchannels,” in *Tech. Digest of Optical Fiber Communication Conference*, paper W2A.23 (2014).
13. E. P. da Silva, K. J. Larsen, and D. Zibar, “Mitigation of linear and nonlinear impairments in spectrally efficient superchannels,” in *Tech. Digest of Signal Processing in Photonic Communications*, paper SpS2C.3 (2015).
14. E. Ip and J. M. Kahn, “Power spectra of return-to-zero optical signals,” *J. Lightwave Technol.* 24(3), 1610–1618 (2006).
15. G. Agrawal. *Nonlinear Fiber Optics*, 3rd ed. (Academic Press, 2001).
16. R. Borkowski, D. Zibar, and I. T. Monroy, “Anatomy of a digital coherent receiver,” *IEICE Trans. Commun.* 97(8), 1528–1536 (2014).
17. M. Shtaif, R. Dar, A. Mecozzi, and M. Feder, “Nonlinear interference noise in WDM systems and approaches for its cancellation,” in *Tech. Digest of European Conference on Optical Communication*, paper We.1.3.1 (2014).
18. R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, “Inter-channel nonlinear interference noise in WDM systems: modeling and mitigation,” *J. Lightwave Technol.* 33(5), 1044–1053 (2015).
19. P. Poggiolini, G. Bosco, and A. Carena, “The GN-model of fiber non-linear propagation and its applications,” *J. Lightwave Technol.* 32(4), 694–721 (2014).
20. A. Mecozzi and R.-J. Essiambre, “Nonlinear Shannon limit in pseudolinear coherent systems,” *J. Lightwave Technol.* 30(12), 2011–2024 (2012).
21. R. Dar, M. Feder, A. Mecozzi, and M. Shtaif, “Properties of nonlinear noise in long, dispersion-uncompensated fiber links,” *Opt. Express* 21(22), 25685–25699 (2013).
22. C. Lin, S. Chandrasekhar, and P. J. Winzer, “Experimental study of the limits of digital nonlinearity compensation in DWDM systems,” in *Tech. Digest of Optical Fiber Communication Conference*, paper Th4D.4 (2015).
23. J.-X. Cai, C. R. Davidson, A. Lucero, H. Zhang, D. G. Foursa, O. V. Sinkin, W. W. Patterson, A. N. Pilipetskii, G. Mohs, and N. S. Bergano, “20 Tbit/s transmission over 6860 km with sub-Nyquist channel spacing,” *J. Lightwave Technol.* 30(4), 651–657 (2012).
24. M. Secondini, T. Foggi, F. Fresi, G. Meloni, F. Cavaliere, G. Colavolpe, E. Forestieri, L. Pot, R. Sabella, and G. Prati, “Optical timefrequency packing: principles, design, implementation, and experimental demonstration,” *J. Lightwave Technol.* 33(17), 3558–3570 (2015).

1. Introduction

The development of coherent detection with digital signal processing (DSP) techniques for optical receivers has enabled greater than 10 Tbit/s transmission capacity demonstrations over single mode optical fiber (SMF) systems [1,2]. Nevertheless, the increasing demand for network services keep pushing the development of optical communication, targeting optimal use of the physical layer resources. In this sense, transceivers are evolving to make efficient use of the available fiber channel spectrum. Under this perspective, multi-carrier transmission techniques allied with advanced modulation formats and pulse shaping, generally named “superchannels” have been extensively investigated. Due to the multi-carrier parallelism concept, superchannel architectures may become attractive by lowering the requirements on the speed of electronics necessary to increase transponder’s line rates, although its feasibility may also require highly integrated photonic devices. However, since the transmitted carriers are closely allocated within the superchannel bandwidth, impairments originated from linear crosstalk [3], non-linear Kerr effects and combinations of both may impose considerable performance penalties. From this perspective, in order to maximize performance of superchannels transmission, receiver’s DSP should be robust to both kind of impairments.

To minimize linear crosstalk penalties in multi-carrier transmissions, pulse shaping techniques to constraint modulated bandwidth have been explored, such as digital Nyquist filtering [4] and optical pre-filtering [5–7]. The benefits of those techniques have been experimentally assessed in long haul optical transmission systems. However, for superchannels close to the Nyquist limit, crosstalk can not be completely eliminated due to practical impossibility to obtain zero roll-off modulated spectra. Although it is well known that linear crosstalk can be compensated using multiple input multiple output (MIMO) based equalizers, for high bandwidth superchannels, joint carrier MIMO equalization techniques may require the receiver to operate with non-realistic sampling rates. Concurrently, nonlinear compensation (NLC) techniques based on DSP have been extensively investigated to improve robustness of the receivers.
against nonlinear impairments. In particular, digital backpropagation (DBP) [8], perturbation equalizers [9] and maximum likelihood sequence detection (MLSD) [10] have been explored. Previous works have investigated optimum performance bounds of DSP strategies, and transmitter/receiver architectures for different scenarios. In [11] perturbation based nonlinearity mitigation is numerically evaluated in WDM transmissions, with different pulse shaping and transmitter/receiver bandwidths, however not targeting superchannel scenarios. In [12], the optimum bandwidth for superchannel NLC using DBP was assessed, but without detailed analysis on impact of the linear impairments. MLSD strategies have been accessed in [10] for intra-channel NLC, without considering multi-carrier or superchannel scenarios.

In this work, we numerically investigate the combined performance of single carrier DBP (SC-DBP) based NLC, and MLSD in quasi-Nyquist superchannel transmission over standard dispersion uncompensated fiber links. We consider three distinct cases of carrier spectral shaping: small roll-off raised cosine and two optical pre-filtered transmitters. This paper is an extended version of the work published in [13]. We extend our previous results and discussions comparing DP-QPSK and DP-16QAM quasi-Nyquist superchannels, in order to evaluate the influence of the modulation format. In our analysis we assume that the receiver uses independent parallel processing for each subcarrier, without any MIMO processing or multi-carrier NLC.

2. Simulation setup

To investigate the performance of single channel DBP and MLSD for different superchannel configurations, we used a numerical simulation model illustrated in Fig. 1. The transmitted spectrum was composed of 5 phase-locked carriers modulated at 32 Gbaud. To quantify the impact of crosstalk for each pulse shaping, we simulated the transmission for different carriers frequency separation, varying from 45 to 32.5 GHz, with 2.5 GHz granularity.

The transmitter was configured to generate three different scenarios of narrow spectrally modulated carriers: pre-filtered non-return-to-zero (NRZ) (Fig. 1(b.1)), pre-filtered return-to-zero (RZ) with 50% duty cycle (Fig. 1(b.2)) and raised cosine (RC) with 1% of roll-off factor (Fig. 1(b.3)). NRZ pulses were generated with ideal rectangular shape, while RZ 50% pulse shape corresponds to the one described in [14]. The bit sequences used are decorrelated pieces of a pseudo-random bit sequence (PRBS, $2^{23} - 1$) with a fixed length of $2^{19}$ bits per carrier. The symbol sequences of different carriers were decorrelated randomly by at least 173 symbols. For all tested cases, the carriers were synchronized in time. After constellation mapping, the

![Fig. 1. Schematic of the simulation setup. (a) Block diagram of the transmitter, fiber channel and coherent receiver. (b) Spectra used for comparison: (b.1) PF-NRZ, (b.2) PF-RZ 50%, (b.3) RC (roll-off = 0.01). (c) Modulated carriers’ spectrum (RC pulse shaping).](image-url)
data was oversampled to 16 samples per symbol. Following pulse shaping and optical modulation, narrow pre-filtering of RZ and NRZ spectra was performed by a passband optical filter modeled with a Gaussian attenuation profile (according to the WaveShaper filter models) and 3 dB bandwidth of 25 GHz, located after the dual polarization in-phase/quadrature (DP-IQ) modulator. This filter was bypassed in the RC pulse shaping configuration. The optical multiplexing stage (MUX) was considered ideal, imposing no extra filtering to the carriers. The carriers were transmitted over 3600 km (45 × 80 km) for the DP-QPSK modulation, and the over 800 km (10 × 80 km) when modulated with DP-16QAM. Both cases simulated dispersion uncompensated links with lumped Erbium doped fiber amplifiers (EDFAs). The fiber spans were modelled with the following typical parameters: \(\gamma = 1.3 \text{ W}^{-1}\text{km}^{-1}\) (nonlinear coefficient), \(\alpha = 0.2 \text{ dB/km}\) (fiber attenuation), \(D = 16.6 \text{ ps/nm/km}\) (chromatic dispersion), \(L = 80 \text{ km}\) (span length), \(G_{\text{EDFA}} = 16 \text{ dB}\) (EDFA gain), \(N_{\text{F}_{\text{EDFA}}} = 4.5 \text{ dB}\) (EDFA noise figure). All results presented refer to the central carrier performance. The optical field propagation within the fiber was simulated applying standard Split Step Fourier (SSF) method to solve numerically the vectorial coupled-mode form of the nonlinear Schrödinger equation (NLSE), as it is described in [15]. Polarization mode dispersion (PMD) effects were disregarded. SC-DBP was performed with a fixed step size of \(\Delta z = 20 \text{ km}\) (4 steps/span). The equivalent lowpass frequency response of the optical demultiplexer (DEMUX) and optical coherent receiver frontend was simulated with Gaussian shaped frequency response with a 3 dB bandwidth of 24 GHz, for all cases. This value was chosen to match the specifications of standard commercial devices. A set of DSP algorithms [16] was applied to compensate for channel impairments and estimate the transmitted data: decimation to 2 samples/symbol, frequency domain chromatic dispersion equalization or DBP, adaptive equalization with the constant modulus algorithm (CMA, 21 taps) for DP-QPSK, and multi-modulus algorithm (MMA, 21 taps) for DP-16QAM, carrier recovery (digital PLL), maximum likelihood sequence detection (MLSD), digital demodulation and error counting. The adaptive equalizer was used to approximate the matched filter at the receiver for each tested configuration. MLSD was performed per polarization at 1 sample per symbol, based on a minimum Euclidean distance metric. Each sequence of received symbols was compared with estimated means of channel states stored in a lookup table. The means were calculated using histograms of training sequences in order to account for true channel statistics.

3. Results

The results obtained by numerical simulations are presented in this section. The chosen figure of merit for performance assessment is the \(Q^2\)-factor, in dB, which is calculated from the bit error rate (BER) according to \(Q^2_{\text{dB}} = 20\log_{10}\left[\sqrt{2}\text{erfcinv}(2\text{BER})\right]\).

3.1. 5 × 32 GBaud DP-QPSK Superchannel

Figure 2 depicts in contour plots the \(Q^2\)-factor gain with respect to electronic chromatic dispersion compensation (EDC) only, obtained with SC-DBP as function of carrier separation and fiber input power for DP-QPSK superchannel transmission. These results illustrate how the performance of SC-DBP is affected by inter-carrier interference for each transmitter configuration. For coarse inter-carrier spacing (≥ 40 GHz), SC-DBP results in similar performance improvement values in the nonlinear transmission regime for all three configurations. However, as carrier frequency spacing decreases towards quasi-Nyquist superchannel, the \(Q^2\)-factor improvement provided by SC-DBP per input power is less affected in the low roll-off RC configuration. This can be explained considering that a higher level of crosstalk increases the impact of inter-carrier nonlinear effects, which should reduce the single carrier NLC performance.
Fig. 2. $Q^2$-factor improvement after SC-DBP as function of carrier spacing and fiber input power for the DP-QPSK superchannel after 3600 km transmission.

Fig. 3. $Q^2$-factor improvement of MLSD compared with SbS decisions as function of fiber input power per carrier with 32.5 GHz carrier spacing for the DP-QPSK superchannel after 3600 km transmission.
Comparing all three superchannel configurations, the results show that modulated carriers with low roll-off Nyquist spectra provide performance robustness for SC-DBP in quasi-Nyquist superchannels, additionally to minimization of linear crosstalk interference.

We then investigate the performance of MLSD. Under low crosstalk conditions (i.e., for coarse carrier frequency spacings) negligible performance improvement is obtained by MLSD compared with symbol-by-symbol (SbS) decisions. However, approaching quasi-Nyquist carrier spacing (i.e., increasing crosstalk), MLSD and SbS strategies show distinct performances. Figure 3 shows the $Q^2$-factor gain obtained with 16, 256 and 4096 MLSD states (2, 4 and 6 taps, respectively) for 32.5 GHz frequency spacing, with and without NLC by SC-DBP. A $Q^2$-factor improvement of 0.5 dB over SbS decisions is obtained by MLSD at optimum fiber input power, for systems with pre-filtering. This gain is attributed to linear crosstalk mitigation rather than intra-carrier NLC, since it is approximately constant for both linear regime and nonlinear regime after DBP.

The benefit by MLSD decreases faster in the nonlinear regime as the transmitted power increases if SC-DBP is not previously applied, due to the increasing weight of the nonlinear impairment in the overall noise. Additionally, no improvement is obtained using MLSD with RC configuration (Fig. 3(c)). It is shown (Fig. 3(a) and 3(b)) that the performance gain provided by MLSD saturates when more than 4 memory taps are considered, which indicates the time window limit for linear crosstalk effects that can be mitigated. In absence of linear crosstalk, MLSD is not able to improve the performance over SbS decisions, and it may penalize it in some cases, due to error propagation of wrong symbol decisions, as the negative $Q^2$-factor gain values of Fig. 3 indicate.

Figure 4 shows the $Q^2$-factor versus input power per carrier for the quasi-Nyquist superchan-
nel configuration. In this results, MLSD was configured with 4 memory taps. For pre-filtered transmitters (Fig. 4(a) and 4(b)), at the optimal input power (-2 dBm) the $Q^2$-factor improvement of combined SC-DBP and MLSD is 1.0 dB.

In the nonlinear transmission regime with crosstalk, the gain of MLSD is degraded and the performance curve tends to converge to the same obtained by SbS decisions. However, the combination of DBP and MLSD still improves the $Q^2$-factor by around 2.0 dB in the nonlinear transmission regime, compared with EDC and SbS detection. When the carriers experience low levels of crosstalk (Fig. 4(c)), SC-DBP provides the same 1.0 dB margin of improvement at the optimal input power, which is the expected value for single-carrier NLC [17, 18] in multicarrier transmission scenarios. Finally, as depicted in (Fig. 4(c)), MLSD and SbS decisions have the same performance if the transmitter is configured with RC pulse shaping, either using DBP, or not. This can explained by the Gaussian characteristic of the nonlinear impairments in long haul dispersion uncompensated links [19]. In this case, as the nonlinear impairment approximately behaves as uncorrelated additive Gaussian noise, its statistics also average out when the receiver search for the probabilities distributions to be used in the MLSD stage.

3.2. 5 $\times$ 32 GBaud DP-16QAM Superchannel

Figure 5 shows the gain in $Q^2$-factor provided by SC-DBP as function of carrier frequency separation and fiber input power for the DP-16QAM superchannel transmission. It can be noticed that, as the carrier spacing decreases, the area with DBP gain greater than 1 dB is reduced, when compared to the DP-QPSK case (Fig. 2). These results indicate that the impact of inter-carrier crosstalk on SC-DBP performance depends on the modulation format, as also pointed out in [20, 21].

Fig. 5. $Q^2$-factor improvement of SC-DBP as function of carrier spacing and fiber input power for the DP-16QAM superchannel after 800 km transmission.
Figure 6 shows the maximum $Q^2$-factor value obtained at the optimum input power as a function of the carrier spacing for DP-16QAM superchannel transmission. For coarse carrier spacing, SC-DBP provides a $Q^2$-factor improvement of 1.0 dB for all cases. This gain tends to vanish when the carriers move to the quasi-Nyquist superchannel configuration. For pre-filtered transmitters (Fig. 6(a) and 6(b)), the minimum allowed frequency spacing with $Q^2$-factor above the forward error correction (FEC) limit is 35 GHz. The crosstalk penalty is higher for the pre-filtered RZ 50% case than for the pre-filtered NRZ, due to the broader spectrum of the former. Among all tested cases, only the RC pulse-shaping case is robust enough to provide acceptable pre-FEC performance at 32.5 GHz of carrier spacing. However, $Q^2$-factor improvement due to SC-DBP reduces to 0.2 dB, in agreement with similar experimental results shown in [22]. Using 2 memory taps ($16^2 = 256$ states), no improvement is provided by MLSD. Further increment to 4 memory taps MLSD ($16^4 = 665536$ states!) was not considered due to complexity constraints to run the algorithm.

3.3. On the MLSD crosstalk mitigation performance

Although no detailed analysis on the mechanisms that allow MLSD mitigate linear crosstalk penalties was targeted in this work, we can conjecture based on [23, 24]. Qualitatively, we can indicate that, given the DSP configuration set in receiver, the training rule to adapt the equalizer taps may indirectly choose a narrow bandwidth filter structures that suppress crosstalk from neighbor carriers. In other words, it may “translate” linear crosstalk penalty in linear
intersymbol interference (ISI) penalty, which then can be mitigated with MLSD.

The negligible gain of MLSD in the DP-16QAM case can be attributed to two reasons: large number of channel states which are not well separated in the Euclidean space, and insufficient signal-to-noise ratio at the receiver. Further investigation would be required to define the limits of MLSD performance for each modulation format.

4. Conclusion

Combined performance of single-carrier digital backpropagation and maximum likelihood sequence detection has been investigated for mitigation of linear and nonlinear impairments in optical DP-QPSK and DP-16QAM superchannels generated with three distinct spectral shaping techniques: optical pre-filtering of RZ and NRZ spectra, and digital Nyquist filtering. We evaluate the impact of superchannel carrier spacing on the performance of each algorithm. Numerical results indicate that the use of both algorithms can complementary provide, at the nonlinear threshold, up to 1.0 dB of $Q^2$-factor improvement, over standard chromatic dispersion compensation in the digital domain. However, we showed that MLSD is only advantageous for transmitters using optical spectral shaping, in configurations where linear inter-carrier crosstalk is present. Comparing DP-QPSK with DP-16QAM results, it can be noticed that the impact of the impairments scale with the order of the modulation format, indicating that for dense superchannels transmitted over dispersion long haul uncompensated links, the combination of both techniques is only effective for low-order modulation formats.

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