Blind Radius Directed Equalizer with Likelihood-based Selection for Probabilistically Shaped and High Order QAM

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Abstract *We propose a novel equalization algorithm for high order and shaped M-QAM. Our blind RDE utilizes conditional filter updates based on the assignment likelihood of amplitude levels. Compared to traditional RDE we demonstrate a convergence rate of $> 99\%$ for up to 93% higher DGD.*

Introduction

The ever-increasing capacity demand in optical communication systems is promoting the use of high order complex-valued modulation formats, which provide increased spectral efficiency, and probabilistically shaped (PS) constellations, which perform superior over an additive white Gaussian noise (AWGN) channel and allow for increased transmission rate flexibility. These advantages come at the cost of a much higher complexity and lower reliability of standard digital signal processing (DSP) algorithms, which have been developed for low cardinality uniform quadrature amplitude modulation (QAM). A common solution is represented by the use of heavily data-aided DSP. These algorithms exploit known transmitted data sequences to provide high convergence rate and modulation format independence. These advantages make them widespread in current systems in particular to perform channel equalization (CE), frequency offset compensation (FOE) and carrier phase recovery (CPR) of high order or probabilistically shaped QAM signals.

Nevertheless, data-aided approaches come at the cost of reduced data rate. In particular, CE based on training sequences requires an overhead which grows with the channel impulse response length and the needed tracking speed[1]. To avoid this penalty improved blind algorithms that exploit the knowledge of the received signal statistics have been proposed for FOE[2], CPR[3] and CE[4]. Among these DSP stages CE is indisputably the most critical one. Blind time-domain solutions, based on the ubiquitous radius directed equalizer (RDE), provide in fact a low convergence rate in situations characterized by large amounts of polarization mode dispersion (PMD) and noise. This is mainly due to the low tolerance of the algorithm with respect to the wrong assignments of received symbols to their respective constellation amplitude levels.

In our work the state-of-the-art probabilistic-aware RDE[4] is improved by considering the likelihood of the correct blind signal amplitude assignments as a decision method for updating the adaptive filter taps. The idea to consider the symbol transmission probability in this context was already foreseen for unshaped 64-QAM[5] but by further considering the knowledge of the received signal amplitude statistics a more reliable equalizer can be obtained. Our implementation proves to provide increased convergence rate for both, high order and PS-QAM constellations in conditions characterized by large values of accumulated differential group delay (DGD). In particular, for 32 Gbaud 64-QAM we observe a convergence rate of $> 99\%$ for up to 14 ps additional DGD compared to the standard RDE.

Algorithm description

In the standard RDE the received signal amplitude A is blindly assigned to one of the constellation rings $R_k,\ k = 1, ..., N$ with N being the number of possible amplitudes of the modulation format in use. The decision is simply performed by taking the closest level in the transmitted constellation: $\min_k |A - R_k|$, an approach that is clearly sub-optimal[4]. This is particularly problematic for PS-QAM, as the transmission probabilities of the amplitude levels differ significantly among each other. For a AWGN channel, amplitude levels discrimination can be performed optimally by taking into account the AWGN noise variance σ^2. The likelihood of a received symbol with amplitude A to belong to the ring R_k follows a Rician distribution which can be written as:

$$p(A|R_k) = \frac{A}{\sigma^2} \exp\left[\frac{-(A^2 + R_k^2)}{2\sigma^2}\right] I_0\left(\frac{AR_k}{\sigma^2}\right), \tag{1}$$

where $I_0(\cdot)$ is the 0^{th} order modified Bessel function. By using this equation and the knowledge of the amplitude level transmission probability, we can optimize the decision thresholds and the expected values for R_k. They are found as the means of the Rician distributions which describe the elements in the different amplitude rings[4]. Nevertheless, in conditions characterized by strong AWGN or high DGD these optimized assignments do not reduce sufficiently the number of errors, what ultimately limits the convergence ability of the algorithm.

We propose to perform a conditional update of the filter taps using only symbols that provide a normalized likelihood higher than a given threshold α_{th}. This value represents the likelihood of a symbol to belong to the assigned amplitude level and can be calculated as:

$$\alpha(A) = \max_k \frac{p(R_k)p(A|R_k)}{\sum_{k=1}^{N} p(R_k)p(A|R_k)}. \qquad (2)$$

After having computed this quantity we only consider a received symbol with amplitude A for filter update if it satisfies $\alpha(A) > \alpha_{th}$. This operation is graphically shown in Fig. 1 for standard (64-QAM) and PS with target entropy 4 (64-QAM-PS4), together with the respective threshold and signal to noise ratio (SNR) used in this work. The amplitude levels falling in the highlighted areas are the ones that are used for the filter update. In the following we refer to our algorithm as the likelihood-based selection radius directed equalizer (LBS-RDE).

The computation of the thresholds as here described requires calculations that are not suitable for real-time implementation. Instead, a viable strategy would be to pre-compute these values and store them in a look-up table (LUT), similarly to what has been already proposed in related works[3],[4]. The algorithm also requires an estimation of the SNR which at this stage of the DSP chain can be either obtained by OSNR monitoring or from an iterative search until convergence[4].

Simulation setup

The algorithm is tested on data generated in VPIphotonics Design Suite 11.0. For each simulation 2^{15} 32 Gbaud symbols are modulated as 64-QAM unshaped or PS with target entropy of 4 and 5 following a Maxwell-Boltzmann probability mass function. At the transmitter pulse shaping is performed by using a raised-cosine filter with roll-off factor 0.2.

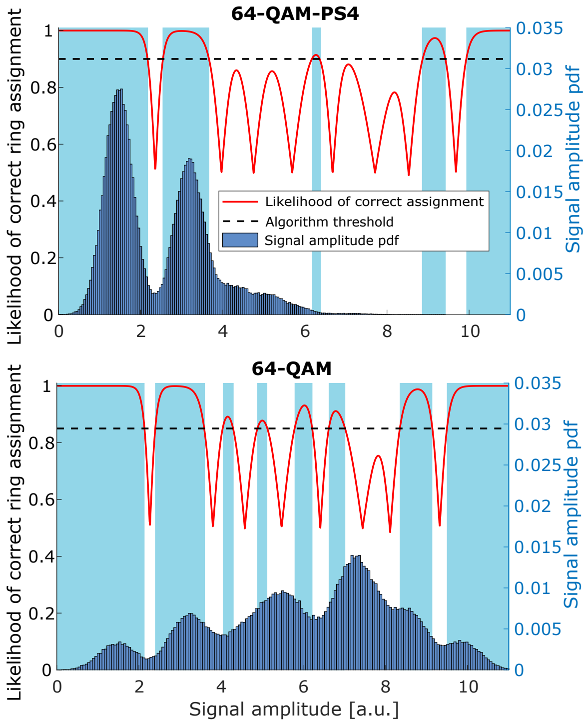

Fig. 1: Signal amplitude probability density function and relative likelihood of the ring assignment versus received amplitude. (Top) 64-QAM-PS4 with SNR $= 14$ dB, $\alpha_{th} = 0.9$. (Bottom) 64-QAM with SNR $= 22$ dB, $\alpha_{th} = 0.85$.

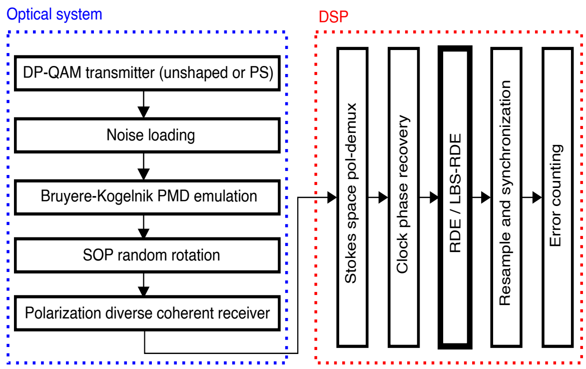

Fig. 2: Simulation setup.

The signal is then impaired by AWGN such that after successful equalization a bit error rate (BER) $\approx 3.8 \times 10^{-3}$ is obtained. A deterministic PMD emulator based on the Bruyere-Kogelnik model[6] is used to produce first- and second-order PMD effects. Random polarization rotation is imposed before the receiver, where the signal is passed through a low-pass filter with 32 GHz bandwidth. Finally, sampling at 2 Sa/sym is performed and the resulting digitized signal is passed to the DSP chain. It consists of clock phase recovery, Stokes space polarization demultiplexing and either RDE or our proposed LBS-RDE. For the Stokes space polarization demultiplexing the conventional implementation[7] is used for 64-QAM while the PS-aware solution[4] is considered for shaped signals. Both equalizers utilize 25 taps; their update coefficients are separately opti-

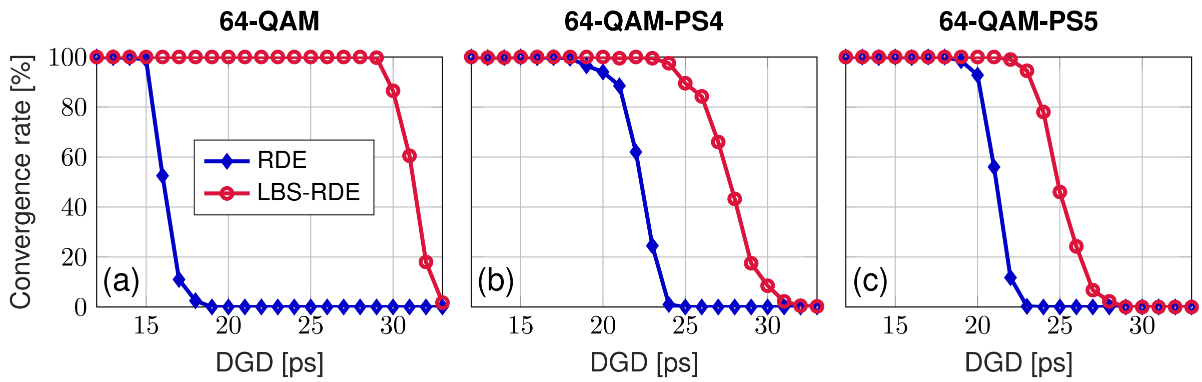

Fig. 3: Convergence rate of the standard RDE and our proposed LBS-RDE versus DGD for (a) 64-QAM unshaped, (b) 64-QAM-PS with entropy 4 and (c) 64-QAM-PS with entropy 5.

Tab. 1: Equalizer parameters

Modulation format	64-QAM -PS4	64-QAM -PS5	64-QAM
N taps	25	25	25
SNR [dB]	14	17.5	22
α_{th}	0.9	0.95	0.85

mized. For the LBS-RDE α_{th} is optimized for each tested modulation format. The values set for the simulations are summarized in Tab. 1. A graphic representation of the setup is shown in Fig 2.

Performance evaluation

The DGD is swept from 12 to 33 ps. For each point the setup is run 200 times with different symbol sequences subject to random PMD realizations and state of polarization rotations. This operation is performed in order to gather accurate statistics of the equalizer performance. In Fig. 3 the convergence rate of the standard RDE and our proposed LBS-RDE versus DGD are shown. For 64-QAM (Fig. 3a) the LBS-RDE shows an exceptional increase in PMD tolerance, with a convergence rate $> 99\%$ for up to DGD $= 29$ ps. The standard RDE is able to provide this performance only for DGD ≤ 15 ps and rapidly deteriorates for larger values. Also for PS-QAM the LBS-RDE demonstrates superior performance. With 5 ps (64-QAM-PS4) and 4 ps (64-QAM-PS5) of additional DGD that is tolerated, however, the improvement is smaller compared to the 64-QAM case. This can be explained by Fig. 1. For PS-QAM most symbols reside on the innermost rings and are used almost identically in both equalization approaches. For 64-QAM, on the contrary, we observe highly populated regions with low likelihood that are discarded by the LBS-RDE. Thus, a more significant number of assignment errors is eliminated, leading to a larger improvement.

Conclusions

We presented a novel blind algorithm for channel equalization that improves the standard RDE by exploiting likelihood information of correct amplitude ring assignments to perform decisions on the adaptive filter taps updates. We showed that our solution provides strongly improved tolerance to impairments caused by PMD for 32 Gbaud 64-QAM and 64-QAM-PS constellations. In particular, our algorithm demonstrated in the unshaped case an exceptional increase of the maximum allowed DGD for achieving a 99% convergence rate of the equalizer: the 29 ps of tolerated DGD represent a value that is 93% higher than the one observed using the standard RDE.

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References

[1] M. Kuschnerov, M. Chouayakh, K. Piyawanno, B. Spinnler, E. De Man, P. Kainzmaier, M. S. Alfiad, A. Napoli, and B. Lankl, “Data-aided versus blind single-carrier coherent receivers”, *IEEE Photonics Journal*, vol. 2, no. 3, pp. 387–403, 2010.

[2] Q. Yan, L. Liu, and X. Hong, “Blind carrier frequency offset estimation in coherent optical communication systems with probabilistically shaped m-qam”, *Journal of Lightwave Technology*, vol. 37, no. 23, pp. 5856–5866, 2019.

[3] G. Di Rosa and A. Richter, “Low complexity blind carrier phase recovery for probabilistically shaped qam”, *IEEE Photonics Technology Letters*, 2020.

[4] S. Dris, S. Alreesh, and A. Richter, “Blind polarization demultiplexing and equalization of probabilistically shaped qam”, in *Optical Fiber Communication Conference*, Optical Society of America, 2019, W1D–2.

[5] D. Lavery, M. Paskov, R. Maher, S. J. Savory, and P. Bayvel, "Modified radius directed equaliser for high order qam", in *2015 European Conference on Optical Communication (ECOC)*, 2015, pp. 1–3.

[6] H. Kogelnik, L. Nelson, J. Gordon, and R. Jopson, "Jones matrix for second-order polarization mode dispersion", *Optics Letters*, vol. 25, no. 1, pp. 19–21, 2000.

[7] B. Szafraniec, B. Nebendahl, and T. Marshall, "Polarization demultiplexing in stokes space", *Optics express*, vol. 18, no. 17, pp. 17 928–17 939, 2010.