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Nonlinear Impairment Compensation Using Expectation Maximization for PDM 16-QAM Systems

Darko Zibar(1), Ole Winther(2), Niccolo Franceschi(1,2), Robert Borkowski(1), Antonio Caballero(1), Valeria Arlunno(1), Mikkel N. Schmidt(2), Neil Guerrero Gonzales(3), Bangning Mao(3), Knud J. Larsen(1) and Idelfonso Tafur Monroy(1)

(1) DTU Fotonik, Technical University of Denmark, Build. 343, DK-2800, dazi@fotonik.dtu.dk
(2) DTU Informatics, Technical University of Denmark, Build. 343, DK-2800
(3) Huawei Technologies Dusseldorf GmbH, ERC, Riesstrasse 25, Munich, Germany

Abstract *We show experimentally that by using non-linear signal processing based algorithm, expectation maximization, nonlinear system tolerance can be increased by 2 dB. Expectation maximization is also effective in combating I/Q modulator nonlinearities and laser linewidth.*

Introduction

Currently, there is a lot of ongoing research on DSP based algorithms for optical fibre channel impairment compensation. Linear signal processing algorithms can be effectively used to compensate for linear fibre channel impairments and have been demonstrated very successfully for higher order QAM signaling[1]. However, for long-haul systems employing higher order QAM nonlinear optical fibre impairments can severely limit the transmission distance as well as the achievable total capacity[1-6]. It has been shown that nonlinear fibre impairments can be compensated by various techniques: digital backpropagation, maximum-likelihood sequence estimation, nonlinear polarization crosstalk cancelation, nonlinear pre- and post-compensation, RF-pilot, etc, and references therein[2-6]. Some of the above mentioned methods suffer from complexity and, additionally, the achievable gain in the nonlinear tolerance is dependent on particular transmission scenarios. Therefore, DSP algorithms for nonlinearity compensation are still open for research.

In this paper, we show, for the first time, that by using Expectation Maximization (EM) algorithm, system tolerance towards nonlinearities can be increased. First, we show, by numerical simulations, an improvement in nonlinear system tolerance for optically dispersion managed PDM 16-QAM signaling. As a proof of concept, an experimental set up employing PDM 16-QAM at 14 Gbaud is constructed and an improvement in the nonlinear system tolerance of up to 2 dB is demonstrated. Additionally, we show that expectation maximization algorithm is efficient in combating I/Q modulator nonlinearity and phase noise.

Principle set-up and the EM algorithm

The set-up used for the numerical investigations and on which we also base our experimental set-up is shown in Fig. 1. The transmitter laser is at 1550 nm and has a linewidth of 100 kHz. The output of the laser is passed through an optical I/Q modulator which is driven by a four level 4 PAM electrical signals in order to generate the optical 16-QAM signal. The output of the I/Q modulator is then passed through a polarization multiplexing stage, and the output is then amplified and launched into the fibre span for the transmission. The fibre span consists of a different number of stages where each stage consists of 80 km of SMF and 17 km of a DCF. EDFA amplification is employed after the SMF and the DCF, respectively, as shown in Fig. 1. After transmission, the incoming PDM 16-QAM data signal is coherently detected, sampled and passed to the DSP demodulation module. The DSP module consists of an I/Q imbalance compensation, clock recovery (2 samples/sym), joint polarization demultiplexing and carrier

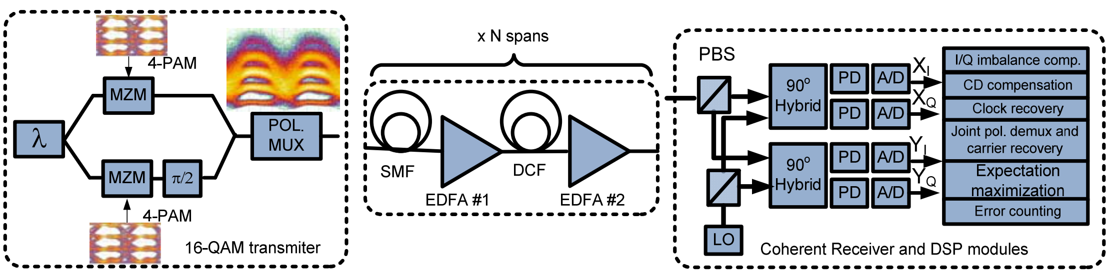

Fig. 1: Schematic diagram of a set-up used for simulations and experiment. PD: photodiode, PBS: polarization beam splitter, A/D: analog-to-digital converter, LO: local oscillator

recovery stage. We apply expectation maximization algorithm[7] for nonlinearity compensation after joint polarization demux and carrier recovery. The main idea behind the EM algorithm is that the signal in x/y-polarization can be considered as a Gaussian mixture consisting of a number of components where each of the components can be described by a 2-D Gaussian distribution. For the particular case of 16-QAM, we have 16 components due to 16 constellation points in 2D. The EM then evaluates in the maximum likelihood sense the most likely parameters that generated the Gaussian mixture model in terms of means, variances and mixture components. In general terms, all information imprinted in the constellation originating from nonlinear as well linear impairments is used by the EM to find the most likely model that generated the data. This information is then used to compensate for system nonlinear impairments by finding optimum (quadratic) decision boundaries for signal detection. In general, the EM algorithm can be used to combat any nonlinear impairments that are imprinted in a constellation.

Simulation results

First, we investigate how the EM algorithm can be used to combat I/Q modulator nonlinearites and laser linewidth. For all simulation results, the baud rate is kept at 28 Gbaud.

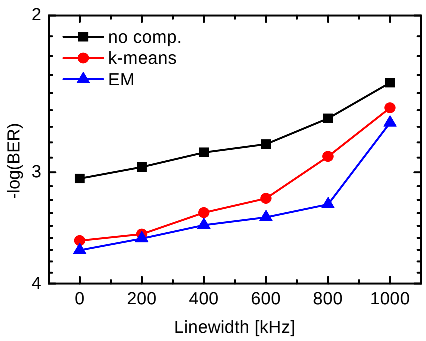

Fig. 2: *Simulation:* BER as a function of combined laser linewidth.

We deliberately drive the I/Q modulator with high enough peak-to-peak amplitude of the electrical 4-PAM signal such that the constellation diagram of the 16 QAM signal is distorted. In Fig. 2, the BER is plotted as function of the combined laser linewidth for the back-to-back case. The laser linewidth will also have an impact on the shape of the constellation points and this effect can be caught by the EM algorithm. In order to determine the effectiveness of the EM algorithm, we also plot in the same figure the BER when k-means algorithm is used and when no compensation is used. The k-means algorithm, is relatively simple, another widely used clustering algorithm in nonlinear signal processing[7]. It computes the means of the clusters and information can be used to perform minimum distance signal detection. Fig. 2 shows that compared to the case when no compensation is used, the k-means and the EM are very efficient in combating the I/Q modulators nonlinearities associated and the laser linewidth. For laser linewidth values exceeding 400 kHz, the EM algorithm outperforms the k-means.

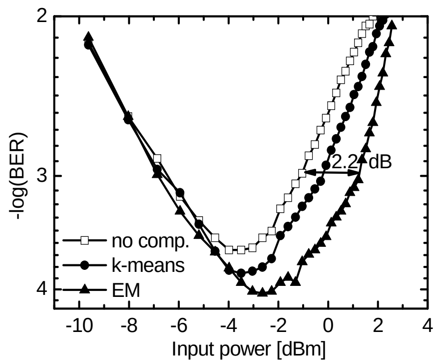

Fig. 3: *Simulation:* BER as a function of input signal power. The length of the transmission distance is 1200 km

Next, we consider a transmission link. However, we assume that the dispersion is negligible and that the dominant nonlinear impairment is the nonlinear phase noise. In Fig. 3, the BER is plotted as a function of the input signal power to the transmission span. In general, there is a relatively large improvement in the nonlinear system tolerance when using the EM algorithm. Fig. 3 shows that by only using the k-means algorithm the system tolerance can be increased by approximately 1 dB for –log(BER) of 3, while by using the EM, the system tolerance can be increased by ~2.2 dB compared to the case when neither the EM nor k-means is used.

Next, we consider the nonlinear phase noise as well as the dispersion in the link. For the considered case the dispersion is compensated optically by the DCF, i.e. dispersion managed system, see Fig. 1. The total transmission distance is 1500 km. The results of the BER as a function of the input signal power are shown in Fig 4. It is observed from Fig. 4 that by employing the EM system tolerance towards nonlinearities can be increased. It is observed from Fig. 4, that the improvement in the nonlinear system tolerance is approximately 1.2 dB for the –log(BER) of 3.

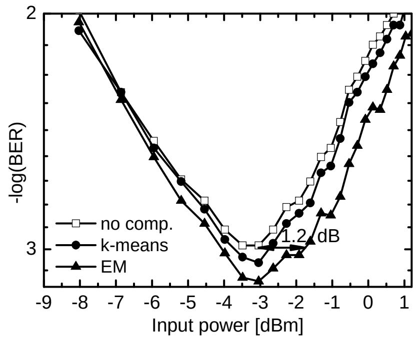

Fig. 4: *Simulation:* BER as a function of input power for dispersion managed system (1500km)

Experimental results

The baud rate for the experiment is kept at 14 Gbaud. Fig. 5, shows a constellation diagram of a signal impaired by the nonlinear phase noise. We plot the recovered constellation diagram of the x and y-polarization after carrier recovery.

It is observed from Fig. 5, that due to the nonlinear impairments, especially the outer constellation points are distorted and thereby elliptical. Some of the clusters are elliptical in horizontal and some of them in vertical direction. The inner constellation points are less affected due to lower power, however, they do experience a slight nonlinear phase shift.

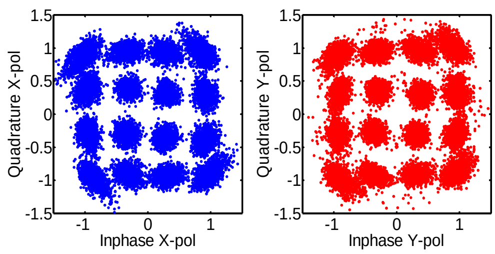

Fig. 5: *Experiment:* Recovered constellation diagram impaired by the nonlinear phase noise.

In the case, when neither k-means nor EM algorithm is used the corresponding –log(BER) is 2.63 and 2.7, respectively. On the other hand when the EM algorithm is used after the carrier recovery, the -log(BER) can be pushed down to 3.02. This shows that the EM can be used to compensate for generally rather distorted constellations. Next, we move to the optically dispersion compensated transmission system, shown in Fig. 1. The total transmission distance is 800 km. In Fig. 6, we plot the BER as a function of the input signal power for the dispersion managed system employing PDM 16-QAM at 14 Gbaud. In general, there is an improvement in the nonlinear system tolerance by employing the expectation maximization algorithm which is in accordance with simulation results. We observe up to 3 dB of improvement in nonlinear tolerance compared to case when no compensation is used.

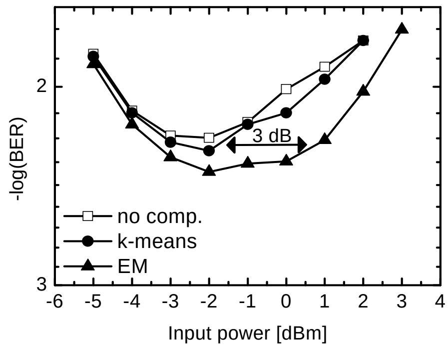

Fig. 6: *Experiment:* BER as a function of input signal power for dispersion managed system

The reason why we get more improvement for the experimental data may be due to the fact that the EM is also effective in compensating residual distortion associated with I/Q nonlinearities. It is observed from the figure that only very little improvement can be obtained by using the k-means algorithm, and this is also in good agreement with the simulation results.

Conclusion

We have shown that the expectation maximization algorithm is a powerful tool in combating system impairments, (fibre nonlinearities, I/Q nonlinearities and laser linewidth), which significantly distort the signal constellation. Additionally, we have demonstrated, numerically and experimentally that by using expectation maximization, up to 2 dB of improvement in nonlinear system tolerance can be obtained for PDM 16-QAM.

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