Independent Component Analysis Equalizer for Direct Detection in Presence of Modal and Temporal Crosstalk

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Abstract: A novel adaptation of independent component analysis controls both cross-polarization and inter-symbol interference in a direct-detection link using Stokes vector modulation. 30-Gb/s experiments confirm polarization de-rotation and near-error-free transmission.

1. Introduction: Rapidly growing throughput within data centers has driven a search for new, multi-dimensional modulation formats that offer low cost and high faceplate density. In particular, Stokes vector modulation (SVM) has been shown to enable multi-dimensional signaling without the high cost, size, and power dissipation of a high-coherence local oscillator laser [1-4]. In SVM, symbol states are defined by Stokes vector components S1, S2, and S3, creating a 3-dimensional constellation in Stokes space. Fiber birefringence rotates the constellation as it propagates, requiring de-rotation at the receiver. Non-idealities in the transmitter and/or the receiver can lead to both distortion of the constellation shape and scatter around each constellation point. For example, such impairments might arise from imbalanced modulator biases or drive amplitudes, or from imperfect alignment of receiver polarization branches. The impairments are usually more severe at high symbol rates, which stress the bandwidth of electrical components. Many of these effects can be described in terms of crosstalk among Stokes vector components and among timeslots, and they can be mitigated by use of an equalizer that operates across both temporal and modal dimensions.

Independent component analysis (ICA) [5] has previously been applied to polarization de-rotation in a coherent receiver [6]. In this work, we develop and demonstrate a novel 6D adaptation of ICA for a direct detection receiver that simultaneously de-rotates the SVM constellation, corrects distortion of constellation shape, and mitigates inter-symbol interference (ISI) at high symbol rates. The algorithm is shown to effectively improve the BER performance of 8-state cubic SVM in laboratory experiments operating at data rates up to 30 Gb/s (i.e., 10 Gsym/s).

2. Independent Component Analysis: ICA is a method of resolving mixed components of multidimensional stochastic data into separate un-mixed components that are both statistically independent and uncorrelated. Since uncorrelated components can be still dependent on each other, independence is a much stronger **property.** In order to adapt ICA to our SVM optical channel, we treat each Stokes component, along with L time-delayed instances of it, as components of our receiver signal vector. That is, ICA is performed on the observed random vector:

$$S_{out}(n)= [s1(n), s2(n),s3(n),s1(n-1),s2(n-1),s3(n-1)\ldots,s1(n-L),s2(n-L),s3(n-L)] \qquad (1)$$

The goal here is to find the mixing and unmixing matrices (W and A) without any prior knowledge of S_{in} except that its components are uncorrelated and each component carries independent information from the others.

$$S_{out} = WS_{in} \qquad , \; S_{in} = AS_{out} \qquad (2)$$

This can be achieved by performing pre-whitening on the data through covariance matrix eigen decomposition and then iteratively seeking an orthogonal rotation of the pre-whitened data that maximizes the non-Gaussianity of the rotated components. Non-Gaussianity is a measure of independence that addresses higher order statistics, guaranteeing that the reconstructed components share no information about each other. We assume that all channels

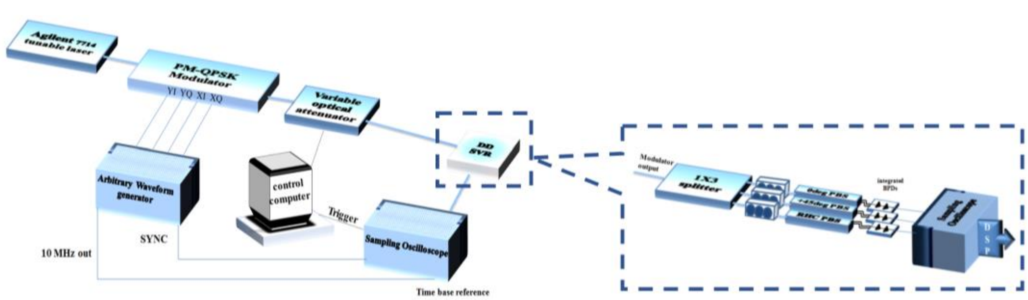

Fig. 1. Experimental setup for transmitting and receiving 8-state SVM

have equal variance of unity, and we project each restored independent component to the nearest class of vectors in the subspace S_{out} to restore the original order of components.

3. Experiments: The transmitter and receiver are shown in Fig. 1. A cubic 8-SVM constellation is produced by an OIF-standard PM-QPSK modulator, using relatively simple bias points and data drives on just 3 of its 4 data ports [7]. For the experiments conducted here, we set the X branch biases to null points with a 90° phase shift between XQ and XI. The Y branches are biased to maximum for YI and minimum for YQ, with zero phase shift. DC-balanced quaternary signals for XI_{data} and XQ_{data} are equal to $\pm 0.7637V_\pi$ or $\pm 0.3204V_\pi$, while the DC-balanced binary signal for YQ_{data} is equal to $\pm 0.2059V_\pi$, and no data signal is applied to YQ_{data} .

The receiver splits incoming light into 3 equal branches, each comprising a polarization transformer that aligns its balanced photodiode with one of the three principal axes: S1, S2, or S3. Thus the output of each receiver branch directly measures one Stokes parameter, while the intensity S0 is recovered from $S0 = \sqrt{S1^2 + S2^2 + S3^2}$; the receiver recovers all 4 Stokes parameters using direct detection.

4. Results: The received Stokes vectors at 30Gb/s before any DSP are visualized on the Poincare sphere in Fig. 2. The cubic geometry of the 8-SVM signal is recognizable, but both rotation and pattern-dependence caused by ISI are quite severe, degrading the bit-error rate (BER). However, after applying ICA with lag of L=1, rotation of the cube is eliminated and ISI is significantly reduced.

The resulting enhancement of BER at 30 Gb/s is plotted in Fig. 3. ICA with L=0 is slightly better than the best rigid de-rotation, because distortion of the cube shape is also corrected. Further improvement of the BER is obtained with L=1, because linear crosstalk between adjacent symbols is now corrected. Fig. 4 presents the BER with L=1 over a range of data speeds, compared the theoretical prediction for ideal transmission limited only by the circuit noise of our receivers. The BER at 7.5 Gb/s and 15Gb/s fall within ~1 dB of the theory, while the shallower slope of the experimental curve at 30 Gb/s suggests that ICA with L=1 may not be able to correct all impairments at higher speeds.

6. Conclusion & Acknowledgement:

We have experimentally demonstrated ICA-based equalization of cubic 8-SVM constellations, with a transmitter based on an integrated PM-QPSK modulator and a direct-detection receiver. Both constellation plots and BER curves confirm that 6-dimensional ICA correctly de-rotates the Stokes vectors and greatly reduces the ISI present at 30 Gb/s. This work was supported in part by the USA National Science Foundation (NSF) under award 1609389.

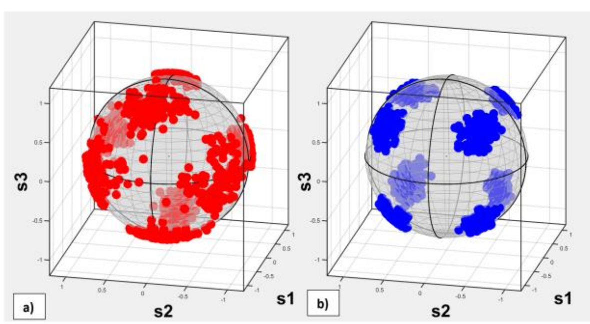

Fig. 2. Recovered Stokes vectors at 30 Gb/s a) before ICA; b) after ICA with L=1.

7. References

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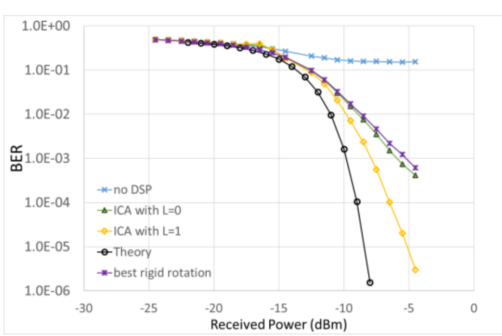

Fig. 3. Bit error rate vs. received optical power, for cube constellation 8-SVM at 30 Gb/s.

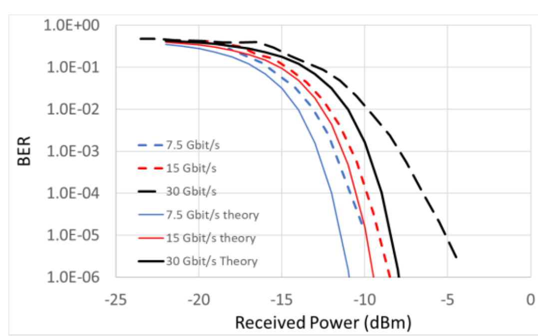

Fig. 4. Bit error rate vs. received optical power, for cube constellation 8-SVM at various data rates.