Photonic Blind Source Separation for Multimode Optical Fiber Interconnects

Dongliang Wang[1], **Benshan Wang**[1], **Weipeng Zhang**[2], **Thomas Ferreira de Lima**[2], **Bhavin J. Shastri**[2,3], **Paul R. Prucnal**[2], **Chaoran Huang**[1*]

[1] *Department of Electronic Engineering, the Chinese University of Hong Kong, Shatin, Hong Kong*
[2] *Department of Electrical and Computer Engineering, Princeton University, Princeton, NJ, 08540*
[3] *Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, ON KL7 3N6, Canada*
[*] *crhuang@ee.cuhk.edu.hk*

Abstract: We propose combining blind source separation (BSS) algorithm with photonic matrix processor to solve dynamic modal crosstalk in multimode fiber interconnects. The approach can solve DSP constraints and enable high-capacity and low-power data-center interconnects.

1. Introduction

Mode-division multiplexing (MDM) is a widely used technique to improve data-carrying capacities in optical communication systems, which promises to overcome nonlinear Shannon limit encountered in single-mode fibers [1]. However, MDM is always accompanied by modal crosstalk and other deleterious effects in transmission channels [2]. Despite the existence of many mature algorithms to retrieve transmitted data from channel impairment, their hardware implementations remain a challenging problem since conventional digital electronics always face harsh tradeoffs between the number of addressable spatial channels, energy consumption, and bandwidth.

In this work, we propose and demonstrate a photonic-electronic processor consisting a photonic front-end matrix processor with a novel blind source separation (BSS) algorithm, to undo modal crosstalk in a short-reach MDM optical fiber interconnect for intra-data-center communications. The proposed system inherits the advantages of photonic matrix processor [3] and the "blindness" of BSS [4–6], leading to superior energy and cost efficiency and reduced latency, while offering unmatched agility in signal format, data rate, and content of transmissions. The feasibility of using photonic processors for mode crosstalk equalization has been recently demonstrated [7,8], assisted with training sequences. Our approach, photonic BSS, in contrast, can tackle the more difficult problem of making the receiver transparent to any data rate and modulation format, and workable with slow and cost-effective electronics. We demonstrate that our approach can unscramble random modal crosstalk varying with millisecond-timescale in a short-reach MDM fiber link, and recover 50 Gbaud/s per channel pulse amplitude modulation 4-level (PAM4) data streams using a sub-Nyquist sampling rate of only 2 Gsample/s in a free-running mode. The approach can solve DSP constraints and enable high capacity, low-power data-center interconnects.

2. Algorithms and Hardware Implementations

Within the distance of intra-data-center links, chromatic and modal dispersion can be neglected. Modal crosstalk can be modeled as an complex-valued N$\times$N matrix, where N is the number of spatial modes. The matrix randomly drifts with the perturbations along the fiber at millisecond timescale [2]. At the receiver, the signals are demultiplexed and then processed by our proposed photonic BSS photonic-electronic processor to equalize transmission channel induced distortions, as well as the residual crosstalk in the mode demultiplexer, as shown in Figure 1(a).

The proposed photonic BSS photonic-electronic processor consists of a Mach-Zehnder interferometers (MZI) meshes which can perform unitary matrix operations all optically on the mature silicon photonic platform and monolithically integrate with the multi-mode receivers [9]. The subsequent electronic system learns the channel matrix based on the BSS algorithm, which separates mixed signals by maximizing the relative distance from the Gaussian distribution of each independent channel. Therefore, the BSS algorithm only needs to measure signals' statistic properties, rather than the full waveform. For this reason, unlike most used MIMO algorithms, BSS allows ADCs to sample at a far slower frequency than the Nyquist frequency, and the sampling does not need to synchronize with the signal, both resulting in significantly lower power consumption and cost.

In our demonstration, mixed 50 GBaud/s PAM4 data streams after the MZI meshes are digitized at a sub-Nyquist sampling rate of 2 Gsample/s in a free-running mode. BSS learns the channel matrix by iterative searching for principal component analysis (PCA) to obtain whitening matrix, and independent component analysis (ICA) to obtain the inverse of channel matrix sequentially using the Nelder-Mead method [5]. The estimated matrix is converted into the driving voltages to control the photonic matrix processor. The photonic matrix processor would compute an updated channel matrix from the optical domain "on-the-fly" until convergence.

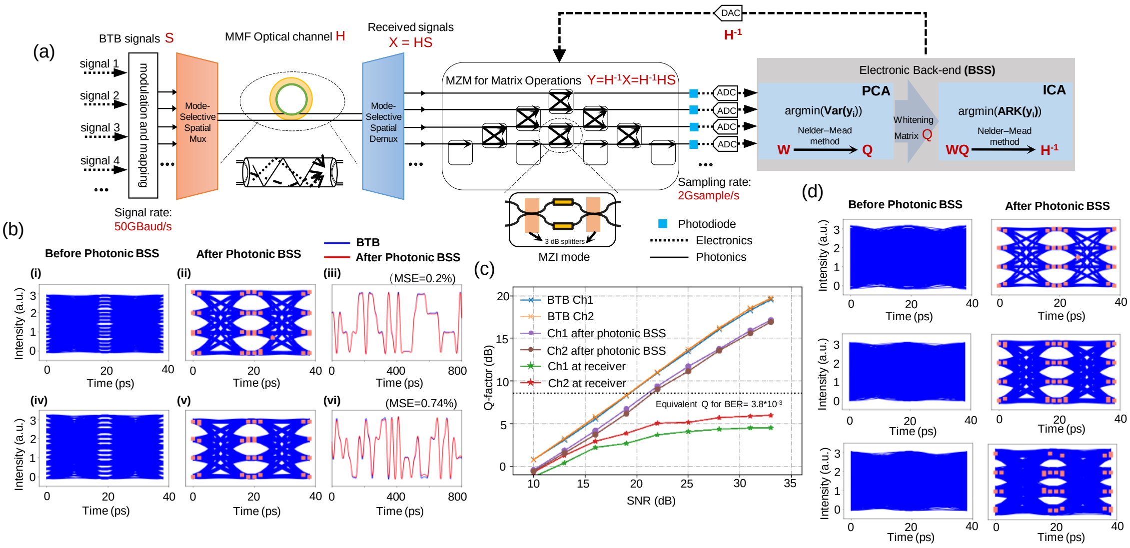

Fig. 1. (a) MDM fiber link with photonic BSS; (b) Eye diagrams and signal waveforms of 2-channel processing. (c) Q-factors at different SNRs. (d) Eye diagram of 3-channel processing.

3. Results

We emulate the MDM fiber link as a complex-valued matrix with the modal crosstalk at -5 dB and with its values fluctuating ±1 dB at a time scale of a few milliseconds due to the environmental fluctuations [10]. We use the photonic BSS to undo the modal crosstalk and recover 50 GBaud/s PAM4 data streams. No training sequences are inserted in the transmission data. As shown in Figure 1(b), BSS fully recovers the signals from the modal crosstalk, resulting in clearly opened eye diagrams for two spatial channels. We then evaluate the accuracy of BSS by comparing the recovered signal waveforms with back-to-back signals and the average mean square error (MSE) of the two signals is 0.20% and 0.74%, respectively. We next evaluate the photonic BSS under additive white Gaussian noise. The signal qualtity factor under a wide range of signal-to-noise ratios (SNRs) are assessed as shown in Figure 1(c). After BSS, the system can achieve the forward error correction threshold (BER $= 3.8 \times 10^{-3}$) with 3 dB SNR penalty compared to the back-to-back signals. Photonic BSS is also applied to a three-mode MDM fiber link. The eye diagrams before and after the photonic BSS is shown in Figure 1(d). We observe the signal quality is degradation as we move to higher modes. The main source of scaling limitation comes from the sequential learning in our photonic BSS approach, in which a higher-order component is obtained after the lower-order component. In this case, the errors generated in the lower-order ICs will cascade to the higher-order ones. Our future work will investigate improved algorithms that can reduce the error transfer from lower-order to higher-order components.

4. Conclusion

In this work, we propose and demonstrate a novel photonic front-end processor to address the modal crosstalk in short-reach MDM optical fiber interconnects. The proposed system has distinct benefits in power consumption and latency at high data rates and large channel numbers compared with DSP. The findings indicate that photonics can solve growing constraints in DSP and pave ways for future high-speed, low-energy communication systems.

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