Distortion-aware 2D soft decision for VCSEL-MMF optical PAM interconnection

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Abstract: A distortion-aware 2D soft decision method of PAM signals have been proposed for VCSEL-MMF interconnection system. Improvements and application potential have been experimentally investigated on a 112-Gbps optical PAM-4/8 system using a multimode VCSEL.

1. Introduction

To address data traffic in the short-reach scenario, advanced data interconnection among data centers are urgently demanded for providing large through-output, high density and low power consumption. Typically for 100-m scaling interconnection, optical intensity modulation and direct detection (IM-DD) scheme is widely accepted as an efficient solution, due to its simplicity and energy efficiency that benefited from vertical-cavity and surface-emitting (VCSEL) and multimode fiber (MMF). VCSEL has general advantages of low price, high slope efficiency and small size, that making it quite suitable for mass production of optical interconnection module. Moreover, stimulated light of VCSEL can be easily coupled into MMF, ensuring a power-efficient detection at the receiver.

Optical interconnection based on VCSEL and MMF has its unique constraints for achieving a higher capacity. First of all, direct modulation using VCSEL will induce level nonlinearity due to its nonlinear amplitude response. Besides, noise of VCSEL-MMF is not strictly Gaussian type, but exhibiting dependency to signal power. Such a level-dependent noise is physically originated by relative intensity noise and shot noise. Furthermore, multi-mode lightwave propagation in MMF will induce much severer inter-symbol interference (ISI), than single-mode fiber link. Approaches to address ISI issue mainly focus on implementing equalizers at the transceiving sides. To combat level nonlinearity and level-dependent noise, several approaches have been proposed, including level pre-adaptation [1] and nonlinear equalizer [2]. In addition, we previously demonstrated a mitigation of level-denpendent noise and level nonlinearity at the decision process [3]. According to clustering results of k-means processing, improved estimation of log likelihood ratio (LLR) has been achieved with a more precise probability density function (PDF). But if severe ISI occurs, correlation between adjacent symbols make SD more difficult because PDF cannot be estimated precisely by using 1D Gaussian model. To solve that, an adaptive generation of soft-decision boundaries has beeen proposed for mitigating the symbol corelation, based on multi-variant Gassian mixture model trained with pilot sequences [4]. It relies on high sampling rate analog-to-digital converter (ADC) to perform data clustering. Moreover, assisted pilot sequence induce the reduction of net rate.

In this work, we proposed an intelligent SD method to mitigate level nonlinearity, level-dependent noise and ISI. After 2D mapping of time-slot symbols, Gaussian Mixture Modeling (GMM) clustering is performed directly on information data for characterizing above three distortions. Then, LLR can be better estimated thanks to learned matrixs of mean value and covariance. Its improvements have been experimentally investigated on a VCSEL-MMF optical PAM-4/8 link with data rate up to 112 Gbps. Because 2D PDF of received symbols can be well estimated even at a low sampling rate (down to 10 Gsa/s) according to mutual information analysis, proposed SD scheme exhibits convincing potential for practical use.

2. Intelligent 2D soft decision using Gaussian Mixture Modeling clusering of information data

Firstly, time-slot symbols require to be mapped on 2 dimensions, denoted as $\boldsymbol{r}_1$ and $\boldsymbol{r}_2$ respectively. Then, clustering is performed on 2D signal $[\boldsymbol{r}_1;\boldsymbol{r}_2]$. Here, we utilize GMM algorithm for clustering. That is because GMM performs better with elliptical clusters than other clustering methods like k-means [5]. The basic idea of GMM is to cluster data in the means of probability estimation. For 2D PAM-N clustering, the cluster number K of GMM amounts to N^2. Expectation-Maximization (EM) algorithm is to perform parameters estimation of Eq. 1,

$$p(\boldsymbol{x}|\boldsymbol{\pi},\boldsymbol{\mu},\boldsymbol{\Sigma}) = \sum_{k=1}^{N^2} \boldsymbol{\pi}_k \cdot \mathcal{N}(\boldsymbol{x}|\boldsymbol{\pi}_k,\boldsymbol{\mu}_k,\boldsymbol{\Sigma}_k), \tag{1}$$

where, $\boldsymbol{x}$ is 2D data equaling to $[\boldsymbol{r}_1;\boldsymbol{r}_2]$, and $\mathcal{N}$ denotes 2D normal distribution. $\boldsymbol{\pi}_k$, $\boldsymbol{\mu}_k$ and $\boldsymbol{\Sigma}_k = [\sigma 1, \rho; \rho, \sigma 2]$ are mixture coefficient, mean value matrix[1] and covariance matrix respectively, which required to be interacted to certain values. Different to [4], GMM clustering is directly performed on information data based on k-means initialized centers, thus getting rid of pilot sequence. As a result, proposed 2D SD can overcome the requirement of high sampling rate ADC, by processing resampled sequences.

For VCSEL-MMF link, $\boldsymbol{\mu}_k$ are physically infected by level nonlinearity, $\sigma 1$ and $\sigma 2$ can describe level-dependent noise. Covariance ρ holds the physical meaning of ISI between adjacent symbols. Thus, GMM clustering can simultaneously extract the characteristics of above three distortions, improved LLR precision can thus be expected based on learned PDF,

$$\boldsymbol{LLR}_i = \log_2 \frac{\sum_{[\mu_1,\mu_2]_k \in \mathcal{S}_1^i} p(\boldsymbol{x}|\boldsymbol{\pi},\boldsymbol{\mu},\boldsymbol{\Sigma})}{\sum_{[\mu_1,\mu_2]_k \in \mathcal{S}_0^i} p(\boldsymbol{x}|\boldsymbol{\pi},\boldsymbol{\mu},\boldsymbol{\Sigma})}, \tag{2}$$

where, $\mathcal{S}_1^i$ and $\mathcal{S}_0^i$ denote the symbol sets whose i^{th} bit is '1' and '0', respectively. As a consequence, decision performance by judging LLR's sign can be improved.

3. Experimental results and discussions

Experimental evaluation of the proposed SD has been carried out on an IM-DD optical interconnection system using a commercially available VCSEL chip and OM3 MMF, as sketched in Fig. 1(a). Optical transmitter consists of a 25-GHz arbitrary waveform generator (AWG), a DC supply coupled into a bias-T and a commercial 850nm VCSEL chip with 20-GHz bandwidth. A 3-D alignment platform is used for VCSEL modulating and optically coupling. Signal receiver includes a 22-GHz PD and a digital storage oscilloscope (DSO). DSO with 160-Gsa/s sampling rate is working at the free-running state, to store 8000k-length symbols for offline processing. Measured frequency response of the optical link is plotted as the inserted picture in Fig. 1(a). 3-dB channel bandwidth is 12.4 GHz, which is mainly restricted by VCSEL performance.

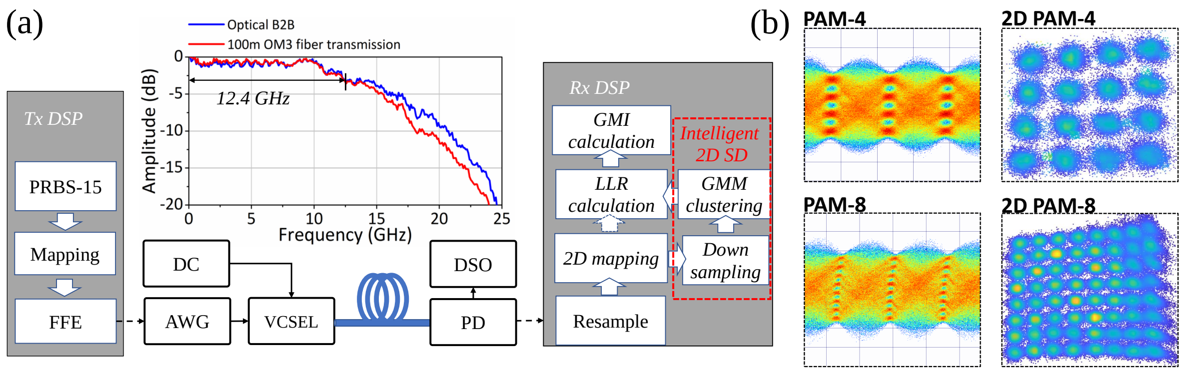

Fig. 1. (a) Experimental setup, (b) 100-Gbps eyes and 2D constellations in optical B2B case.

By adjusting the baud rate of AWG, 100-Gbps and 112-Gbps PAM-4 and PAM-8 signals have been recorded at the receiver. Then, 2D constellation can be obtained by 2-symbol mapping. At the symbol rate of 50 Gbaud, eye-diagrams and 2D constellations are plotted in Fig. 1(b). Constellations are not in perfect rectangular shape, indicating severe nonlinear distortions. Under this circumstance, large amount errors may occur when using conventional SD with assuming all symbols consistently distributed. Our previously proposed 1D SD can deal with this issue by extracting such level nonlinearity [3] by k-means clustering. However, individual symbols are still not ideally Gaussian distributed, indicated by the non-circular clusters of 2D constellations in Fig. 1(b).

3.1. *Intelligent 2D soft decision of PAM-4/8 signals*

The proposed 2D SD is performed through processing 2D signals. For obtaining initialized center $\boldsymbol{\mu}_k$ of the k^{th} cluster, 10-times replicated k-means process is performed on 1D signals on each dimension. Initializing states of $\boldsymbol{\Sigma}_k$ and $\boldsymbol{\pi}_k$ are all zeros. Then, EM algorithm is performed based on Eq. 1, to extract $\boldsymbol{\mu}_k$, $\boldsymbol{\Sigma}_k$ and $\boldsymbol{\pi}_k$. By setting the threshold of 10^{-15}, the 2D-PDF based on interacted $\boldsymbol{\mu}_k$, $\boldsymbol{\Sigma}_k$ and $\boldsymbol{\pi}_k$ are plotted in Fig. 2.

As for PAM-4 signaling, the maximum probabilities of individual clusters differ much, indicated by 2D view of PDF in Fig. 2(a). Moreover, level nonlinearity and level-dependent noise can be observed from the top view. Although PAM-8 exhibits reduced signal bandwidth, compared to PAM-4, it also suffers ISI due to channel's rolling-down frequency response and time skewing, refered to Fig. 1(b). The results of PAM-8 signaling are given as Fig. 2(b). Covariance is not zero thus leading oval distribution, which is more approaching to the real occurance.

[1] $\boldsymbol{\mu}_k$ is a two-elements vector, which can be used for labeling 2D PAM symbols.

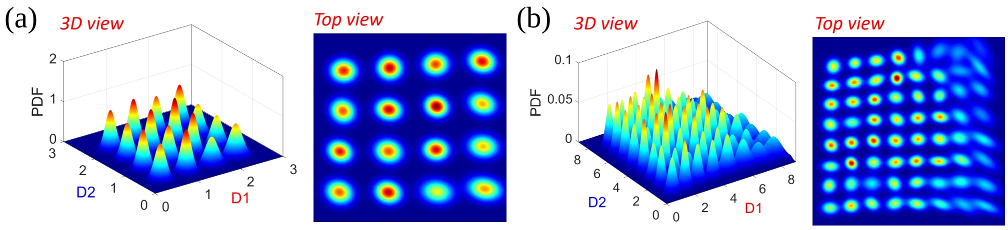

Fig. 2. Estimated 2D PDFs using proposed 2D SD: (a) 100-Gbps PAM-4, (b) 100-Gbps PAM-8.

3.2. Improvement and application potential of the proposed 2D SD

In order to quantitatively evaluate the improvement of 2D SD compared to conventional SD, GMI values has been calculated for experimental data. Assuming optimal 20%-OH FEC assistance, the lowest GMI values achieving error-free signaling are 1.667 and 2.5 bits/symbol for PAM-4 and PAM-8, respectively [6]. As indicated by Fig. 3(a), proposed 2D SD offers 0.28-dB power budget advantage than conventional SD, for 100-Gbps and 100-m PAM-4 signaling. Moreover, error-free can be obtained by 2D SD, even at the data rate of 112Gbps. As for PAM-8, proposed 2D SD provides over 0.59-bits/symbol GMI gain that supporting 20%-OH FEC error free.

In fact, GMM clustering does not require to be performed on real-time data. Thus, we reduce the sampling rate by down sampling for investigating its performance. As indicated by Fig. 3(c), postive GMI gain of 112-Gbps data can be obtained even at 10-Gsa/s sampling rate. Consequently, proposed intelligent SD method exhibits potential of real-time implementation based on commercial-product-level ADC.

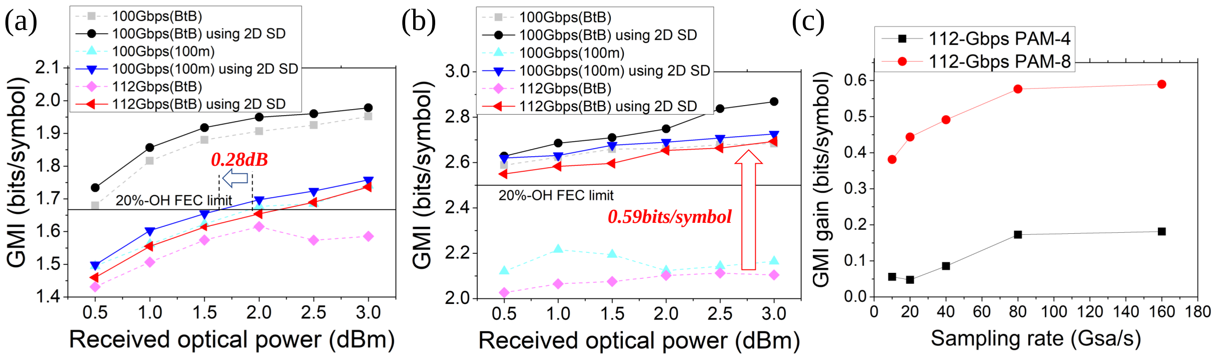

Fig. 3. GMI curves for (a) PAM-4, (b) PAM-8, and (c) SD performance at different sampling rate.

4. Conclusion

We experimentally demonstrated an intelligent 2D SD on a VCSEL-MMF based optical PAM system with data rate up to 112 Gbps. Results indicate that the proposed method can improve signaling performance cost-efficiently.

5. Acknowledgement

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References

1. Y. You, W. Zhang, L. Sun, J. Du, C. Liang, F. Yang, and Z. He, "Time skewing and amplitude nonlinearity mitigation by feedback equalization for 56Gbps VCSEL-based PAM-4 links," Opt. Commun. **410**, 909–915 (2018).
2. N. Stojanovic, F. Karinou, Z. Qiang, and C. Prodaniuc, "Volterra and Wiener equalizers for short-reach 100G PAM-4 applications," J. Light. Technol. **35**, 4583–4594 (2017).
3. L. Sun, J. Du, K. Xu, B. Liu, and Z. He, "k-means assisted soft decision of PAM4 to mitigate level non-linearity and level-dependent noise for VCSEL-based 100-Gbps 100-m MMF optical interconnection," in *Optical Fiber Communication Conference,* (2019), pp. M1F–5.
4. F. Lu, P. Peng, S. Liu, M. Xu, S. Shen, and G. Chang, "Integration of multivariate gaussian mixture model for enhanced pam-4 decoding employing basis expansion," in *Optical Fiber Communication Conference,* (2018), pp. M2F–1.
5. J. D. Banfield and A. E. Raftery, "Model-based Gaussian and non-Gaussian clustering," Biometrics pp. 803–821 (1993).
6. J. Cho, L. Schmalen, and P. J. Winzer, "Normalized generalized mutual information as a forward error correction threshold for probabilistically shaped QAM," in *European Conference on Optical Communication,* (2017), pp. 1–3.