Optical Intensity Reshaping for Enhanced Vertical Resolution in Coherent Optical Receivers

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***Abstract*—We propose an optoelectronic technique to enhance the effective vertical resolution of coherent receivers and assess its resilience against device and transmission impairments. A Q-factor improvement of 3-6dB is obtained for 1024-QAM over DCI distance.**

Keywords — coherent detection, effective number of bits, data-center interconnects

I. Introduction

To accommodate the ever-increasing demand for transmission capacity, optical transmission systems have adopted multilevel quadrature amplitude modulation (*M*-QAM) formats and high symbol rate interfaces [1]. The spectral efficiency increases with the constellation cardinality but one of its limiting factors is the vertical resolution of digital-to-analog converters (DACs) and analog-to-digital converters (ADCs) [2]. Such devices usually reach noise floors around 5 effective number of bits (ENoB) for sampling rates above 100 GSa/s[3]. The nonconstant signal envelope of high-order *M*-QAM leads to significant peak-to-average power ratio (PAPR) further reducing the effective dynamic range of ADC/DAC and so the achievable signal-to-noise ratio (SNR) [4]. Besides the linear SNR penalty, ADC ENoB also limits nonlinear mitigation techniques such as digital backpropagation (DBP) [4]. In this work, we propose a technique to enhance the effective vertical resolution of coherent receivers by reducing the PAPR of the signals before detection. Instead of additional electronic processing, this is done through optical signal processing using optoelectronic modulator – potentially with energy efficiency gains [5]. The novel approach is dubbed here as optical intensity reshaping (OIR). Improvements to receiver sensitivity and DBP performance are shown when using OIR. A Q-factor improvement of 3-6dB is demonstrated over data center interconnect (DCI) distances. Also, the resilience of the proposed technique to devices (e.g., ADC/DAC, laser) and channel impairments is investigated

II. Optical Intensity Reshaping (OIR)

A relationship between ENoB and PAPR is drawn in [6] assuming that, to 1st order, signal distortion (e.g. harmonics) impact in the signal-to-noise-plus-distortion ratio (SNDR) of ADCs is proportional to the signal power. And, for the case of multifrequency signals, SNDR is then given as a function of PAPR by [6]: $\text{SNDR[dB]} = 10\log_{10}(\alpha\cdot S/(N+\alpha\cdot D))$, $\alpha = 2/\text{PAPR}$, where S is the power of the undistorted signal, and N and D are, respectively, the power of the noise and signal distortion. From here it follows that, the larger the PAPR, the lower the achievable signal quality – as confirmed by experiments in [6]. Here, the PAPR for a given signal x is defined as $\text{PAPR[dB]}=10\log_{10}(\max(|x|^2)/\text{E}\{|x|^2\})$, where $\text{E}\{\cdot\}$ refers to the expectation operator.

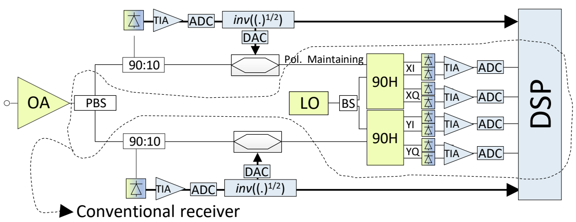

Fig. 1. Implementation of Optical intensity reshaping (OIR), with the optical tap polarizations detected and processed separately.

The technique OIR operates on the intensity envelope of the incoming optical signal trying to remove from it as much intensity information as possible and reduce the PAPR of the signals before detection. Fig. 1 illustrates its implementation. Two intensity modulators are driven by the reciprocal (i.e. multiplicative inverse $1/x$) waveform that is obtained from an optical tap using direct detection. This tap can be taken before the polarization beam splitter (PBS) (using a single tap), or after it as in Fig. 1. These cases are dubbed here OIR and OIR plus optical polarization splitting (OPS), respectively.

The required signal inversion in OIR can be performed in the analog domain using log and anti-log amplifiers, or through digital signal processing (DSP) in between an ADC-DAC pair. Here, the latter option is chosen. After reducing the PAPR, the ADCs are only required to deal with residual fluctuations of the intensity in both quadrature components of the received signal. Before any other typical DSP stage is applied (see Fig. 2), the digitized optical tap signals are used in the receiver DSP for reconstruction of the detected field.

III. Simulation Setup

Fig. 2 shows the simulation setup considering a WDM system with 5 channels on a 29-GHz-spaced grid, each modulated with 28-Gbaud dual-polarization (DP) 1024-QAM. DP-IQ modulators (DP-IQMs) driven by signals shaped with 0.01-roll-off root raised cosine (RRC) filters. The frames consisted of 2^{16} symbols, with CAZAC training sequences (TS) of 2^{11} symbols. The signals were launched into 2 spans of 60 km of standard single-mode fiber (SMF) with an attenuation of 0.2 dB/km, a polarization mode dispersion (PMD) of 0.04 ps/√km, and a dispersion of 17 ps/(nm·km). EDFAs with 3dB noise figure were used at the end of each span to fully compensate for the fiber attenuation. Propagation was implemented using the split-

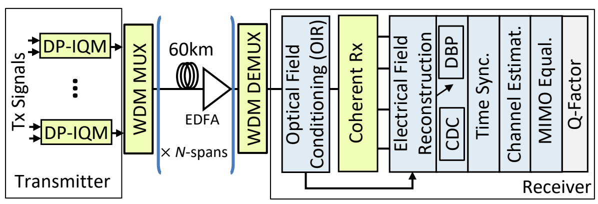

Fig. 2. Transmission simulation setup including OIR and DSP blocks.

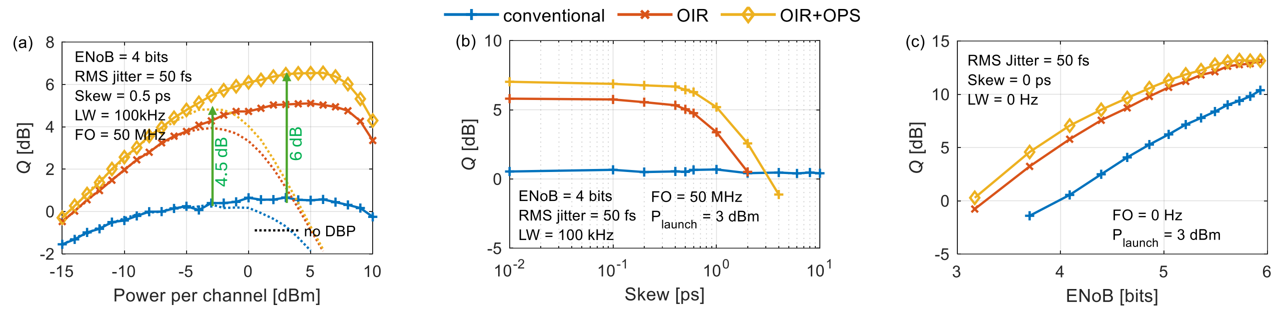

Fig. 3. Q-factor, after 2 x 60 km, versus (a) launch power with and without DBP, (b) skew (c) $ENoB_{DC}$. – results averaged over 40 realizations.

step Fourier method (SSFM) including PMD, with a step bounded by the local error method below 10^{-5} [7]. After coherent detection, the signals were sampled at 2 Sa/symbol and processed with the DSP stages in Fig. 2. Linear and nonlinear compensation were considered. For the linear case, chromatic dispersion compensation (CDC) was implemented in the frequency domain. Nonlinear compensation was performed by full-band DBP after simultaneously demultiplexing and detecting a WDM super-channel (with a bandwidth of 5×29 GHz). DBP was implemented using SSFM, but with fixed steps of 100 m and characteristics of opposite-sign values of those in the transmission channel [7], except for PMD that was not included in backpropagation. Subsequently, channel equalization, carrier frequency offset (FO) and phase recovery compensation (with pilots inserted at a rate of 1/32) were performed. Finally, the Q-factor was estimated through error counting [8]. A net data rate of 2.2 Tb/s was achieved, given 20% FEC and 3% TS overheads.

The ADCs were modelled as proposed in [9]. The frequency dependent ENoB is described as [9] $ENoB(f) = ENoB_{DC} + \log_2|H(f)| - 0.5\log_2(1+6(2^{ENoB_{DC}}\pi f\sigma)^2)$, where $H(f)$ is the ADC filter profile, modeled using a 10^{th} order Gaussian filter with half the symbol rate (or a multiple for super-channel detection), σ is the root-mean-square (RMS) jitter assumed to be 50 fs, and $ENoB_{DC}$ represents the hardware bit architecture reduced by distortions [9]. If not stated otherwise $ENoB_{DC}$ = 4 bits. All the photodiodes were modelled with a 10^{th} order Gaussian filter with a bandwidth of half the symbol rate (or a multiple in the case of super-channel detection), except for that in the optical tap needed for OIR, which consisted of a raised-cosine (RC)-shaped filter with a bandwidth of $0.2\times$ the symbol rate. This was done to remove fast power fluctuations.

IV. Results and Discussions

Fig. 3 presents the analysis of the technique OIR assuming transmission over 2 spans of 60 km considering impairments from lasers and DACs/ADCs as well as fiber impairments. Fig. 3(a) shows, for $ENoB_{DC} = 4$ bits, the Q-factor of the central channel versus its launch power with (full lines) and without (dashed lines) full-band DBP. The focus is not on DBP computational efficiency but on the gains provided by OIR. These results were obtained at the presence of 50-MHz FO and phase noise from transmitter and LO lasers. For the non-DBP case, OIR (or OIR+OPS) provided a Q-factor improvement of 3.5 dB (or 4.5dB) over the conventional receiver at the optimum launch power of -3 dBm. The extra gain of OIR+OPS comes from acting separately on the two polarizations. Comparing the scenarios with DBP, a significant mitigation of the nonlinearities translated into a 4.5 dB (or 6 dB) gain for OIR (or OIR +OPS) over the conventional receiver at the optimum launch power of 3 dBm. In Fig. 3 (b), the skew requirements of OIR are assessed. This is the time misalignment between the inverted optical tap signal and the optical signal passing through the intensity modulators. The OIR performance starts degrading for a skew larger than 1ps, a skew tolerance in line with the specifications of commercial receivers [10]. Fig. 3 (c) shows the Q-factor as a function of $ENoB_{DC}$. The gains provided by OIR are larger for $ENoB_{DC}$ between 3 and 5 bits, reducing for $ENoB_{DC} > 5$ bits given the fiber link OSNR limits, beyond which quantization noise is no longer dominant.

V. Conclusions

The technique OIR is shown to enable Q-factor improvements in the range of 3-6 dB for DCI distances. This performance is shown to be resilience against impairments present on DACs/ADCs, conventional receivers as well as in optical fibers. The ENoB boost can be used to increase spectral efficiency or to relax ADC ENoB requirements and operate at a larger electrical bandwidth. OIR is well suited to take advantage of maturing photonic integrated circuits. The additional loss added by OIR can be overcome by the pre-amplifier as well as by on chip amplification with small degradation to the overall noise figure for DCI distances.

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