Mitigation of Transmitter Impairment with 4×2 WL MIMO Equalizer Embedding Preliminary CPR

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Abstract: Transmitter impairment mitigation for 58-GBaud PM-64QAM with 4×2 WL MIMO embedding preliminary CPR was demonstrated over 100 km SSMF. Q-penalties of 0.1 dB with 14 ps IQ skew and 10 degree phase error were achieved.

1. Introduction

Research on digital coherent transmission based metro and long-haul applications has been addressing the rapid increase in global traffic demand. To meet growing capacity requirements, higher symbol-rate and higher-order modulation used with constellation shaping techniques are promising technologies [1]. However, as symbol-rate increases, linear impairments originating to component bandwidth limit appear earlier and also as modulation format increases, the impact of various impairments on the signal quality becomes more significant. To deal with this issue, several digital signal processing (DSP) based device imperfection mitigation technics have been proposed, both for factory calibration [2] and adaptive equalization at the coherent receiver [3-7].

Compared with the device imperfection of receiver (Rx) side, that of transmitter (Tx) side is more challenging to equalize at the receiver DSP since it is mixed with transmission impairments; chromatic dispersion (CD), polarization mode dispersion (PMD), polarization rotation, and Rx devices characteristics. 2×1 widely-linear (WL) multiple-input-multiple-output (MIMO) equalizer has been proposed to compensate Tx impairment [5, 7], which is applied for the signal after carrier phase recovery (CPR). However, CPR was individually performed prior to Tx impairment compensation in this case. This induces in contamination of CPR, resulting performance degradation when Tx impairments are existed. The additional CPR after 2×1 WL MIMO might be improved performance [5], but it requires the extra computation resources.

In this paper, we propose 4×2 WL MIMO equalizer embedding preliminary CPR for Tx impairment mitigation. Differ from the conventional approach, we propose to first compensate carrier phase error, then to simultaneously compensate PMD, polarization rotation, and Tx impairments. The filter coefficients and carrier phase are jointly calculated by using output of MIMO equalizer in back propagating manner [7]. We experimentally demonstrate our method with 58-GBaud Polarization Mutiplexing-64 quadrature amplitude modulation (PM-64QAM), which effectively mitigates Tx impairments; IQ skew, IQ imbalance, IQ crosstalk, and quadrature phase error. Our method outperformed conventional Tx impairment compensation by using 2×1 WL MIMO after CPR in 100 km standard single mode fiber (SSMF) transmission for whole measurement conditions.

2. 4x2 WL MIMO equalizer embedding preliminary CPR

The concept of 4×2 WL MIMO embedding preliminary CPR is shown in Fig. 1. As a reference, the conventional DSP with Tx impairment compensation filter by using 2×1 WL MIMO after CPR is described on Fig. 1 (a). It applies filters in the following order: Rx impairment, CD, PMD and polarization rotation, carrier phase, Tx impairment. This sequence is based on its physical model [7]. Not shown on figure, Rx impairment and CD have been removed before polarization filter. The complex signal x_X and x_Y are fed into least mean square (LMS) based

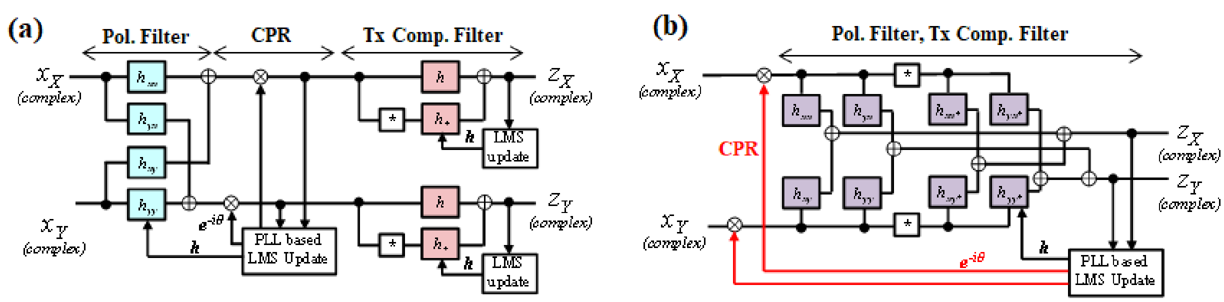

Fig. 1. Concept of 4×2 WL MIMO embedding CPR (a) Conventional method, (b) 4×2 WL MIMO embedding CPR

2×2 strictly linear (SL) MIMO equalizer [7] for PMD compensation and de-multiplex polarization rotation. Then, data aided phase-locked loop (PLL) by using pilot symbols is applied for carrier phase recovery, and is embedded in LMS equalizer to update filter tap coefficients. After carrier recovery, 2×1 WL MIMO equalizer compensates Tx impairment for each polarization. Note that 2×1 WL MIMO is equivalent for 2×2 real I-Q MIMO [7], which used in ref [5] for Tx impairment compensation. The filter tap coefficients h and h_* are updated by data aided LMS algorithm. Even though WL 2×1 MIMO can mitigate some Tx impairments, excessive Tx impairment degrades previous equalizers, especially CPR performance [5].

Next, the proposed 4×2 WL MIMO embedding preliminary CPR is described on Fig. 1 (b). Similarly to LMS based 2×2 SL MIMO with data aided PLL, pilot symbols are used for carrier recovery, and updated filter tap coefficients by using output complex signals of MIMO, but the filter sequence is different. As joint update of filters enables us not to follow the physical model sequence for compensation, here, in contrast to previous works, we deliberately chose to first apply phase compensation for the complex signals before the 4×2 WL MIMO equalizer. Since carrier phase is updated by using the complex signals after MIMO equalizer, Tx impairment compensation filter, CPR is not contaminated by Tx impairments. Moreover, polarization filter and Tx compensation filter are consolidated into a single 4×2 WL MIMO equalizer; it handles precise Tx impairment compensation and high PMD compensation, as both requires long impulse response MIMO equalizer. This consolidation of filters may keep the circuit resources in the reasonable scale.

The output samples z of the proposed MIMO are described as

$$y_j[k] = e^{-i\theta_j} x_j[k] \qquad (1)$$

$$z_i[k] = \sum_{j,m}\left(h_{ij}[m]y_j[k-m] + h_{ij*}[m]y_j^*[k-m]\right) \qquad (2)$$

where x is the input samples, θ is compensated phases, j is input vector, i is output vector, m is number of the tap, and k is the sample time. The filter tap coefficients h_{xx}, h_{yx}, h_{xy}, h_{yy}, h_{xx*}, h_{yx*}, h_{xy*}, h_{yy*} are updated as

$$h_{ij} \rightarrow h_{ij} + 2\mu l_i y_j^*[k], \qquad h_{ij*} \rightarrow h_{ij*} + 2\mu l_i y_j[k] \qquad (3)$$

where μ is the step size, l is the error between pilot symbol p and the output sample z

$$l_i = p_i[k] - z_i[k] \qquad (4)$$

3. Experimental setup for evaluation of Tx impairment mitigation

Fig. 2 shows the experimental setup and offline DSP for 58-GBaud-root raised cosine filtering (RRC)-PM-64QAM transmission. The roll-off factor of 0.05 was used. External cavity lasers (ECL) with a 10 kHz linewidth were used for both signal source and local oscillator (LO) set at 1550.1 nm. On the Tx side, the electrical signal was modulated with a PM-IQ modulator and four 120-GSa/s DAC. Forward error correction (FEC) of low-density parity-check code for DVBS-2 with a frame length of 64,800 and a code rate of 4/5 was used. Eight FEC frames were generated for each polarization by loading random bits to their payload and were then mapped to PM-64QAM with gray mapping. In this experiment, a pilot sequence was inserted for each polarization to perform a pilot-based DSP [8]. One pilot symbol of QPSK was inserted every 25 symbols, and an overhead of 2^{10} QPSK symbols was also inserted for pre-convergence of MIMO filter. Tx IQ skew, Tx IQ imbalance, Tx IQ crosstalk were digitally emulated for X polarization, and quadrature phase was manually shifted for X polarization to verify the proposed method. For the transmission line, we used one 100 km span of SSMF after polarization scrambling at a rate of 100 rad/s with EDFA amplification. The fiber launch power was set to -2 dBm to reduce the penalties due to the fiber nonlinearity, resulting in a received OSNR of 30.8 dB/0.1nm. Passing through the optical bandpass filter (OBPF), the optical signal was captured by the coherent receiver and following four 128-GSa/s ADC converted it to the electrical domain.

In the offline DSP, the received signal was resampled to 2-Sa/sym. and filtered to compensate Rx frontend imperfections; CD was compensated in the frequency domain for each polarization. The frame synchronization was performed by correlation to the known overhead [8] after constant modulus algorithm based blind polarization de-multiplexing and frequency offset (FO) compensation based on the fourth power of the signal. Once the location of

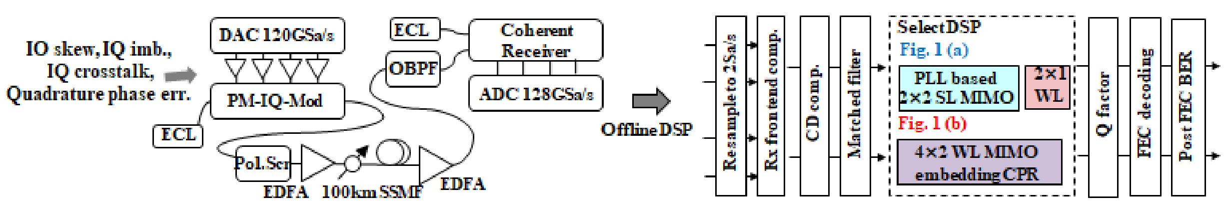

Fig. 2. Experimental setup and offline DSP

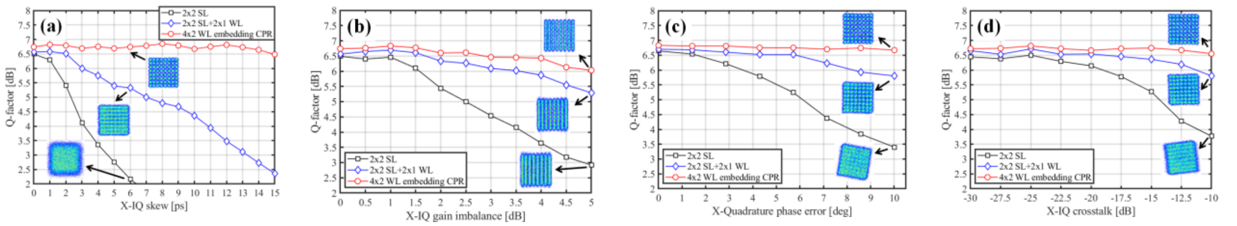

Fig. 3. Experimental results with Tx impairments, (a) X-IQ skew, (b) X-IQ gain imbalance, (c) X-Quadrature phase error, (d) X-IQ crosstalk

overhead was detected, matched RRC filtering was applied for the output of CD compensation block, then two MIMO configurations were evaluated; (1) T/2-spaced data aided PLL based 2×2 SL MIMO equalizer with T-spaced 2×1 WL MIMO after CPR, which we described on Fig. 1 (a), and (2) the proposed 4×2 WL MIMO embedding preliminary CPR, detailed on Fig. 1(b). In addition, 2×2 SL MIMO only was applied for the benchmark of Tx impairments. For all configuration, the filter coefficient update was carried out using the symbols of the QPSK pilot with data-aided LMS as described earlier. The tap lengths of the filters were 29 taps for T/2-spaced MIMO, and 15 taps for T–spaced MIMO. Once the signals were demodulated removal of the pilot and the overhead, Q-factor, same as the pre FEC bit error (BER), was calculated, and the post FEC BER was calculated after FEC decoding.

4. Results and Discussion

We investigated Tx impairment mitigation performance of 4×2 WL MIMO embedding preliminary CPR, and compared it with the conventional 2×1 WL MIMO after CPR for the reference of this work. Overall, even without the additional impairment, Tx mitigation technics compensated for residual impairments, improving Q-factor by 0.15 dB for 2×1 WL and up to 0.3 dB for the proposed 4×2 WL. In Fig. 3 (a), the Q-factor is plotted as a function of X-IQ skew. Note that Q-factor was averaged over two polarization signals. Clearly, the proposed method outperformed other methods. Indeed 2×2 SL MIMO only suffered from IQ crosstalk due to the skew imbalance between IQ signals, the Q-factor was linearly degraded by skew value. 2×1 WL mitigated IQ skew but the Q-penalty was gradually increased as skew increases above 3ps due to the degradation for previous equalizers described the above. For the proposed scheme, a Q-penalty of 0.1 dB appeared only at 14 ps, *i.e.* 0.8 UI, which is far larger than the specification of available frontend components, whereas 2×1 WL resulted a Q-penalty of 3.8 dB.

In Fig. 3 (b), the Q-factor is plotted as a function of X-IQ gain imbalance. Again, the proposed 4×2 WL showed the best performance. However, the Q-factor was gradually degreased as gain imbalance was increased since the gain imbalance introduce polarization dependent loss. Even so, for 2 dB gain imbalance, 2×1 WL showed 0.2 dB Q-penalty, whereas the proposed method showed only 0.1 dB penalty. In Fig. 3 (c), the Q-factor is plotted as a function of quadrature phase error of X polarization. Similarly to the skew evaluation, 4x2 WL outperformed other methods and only 0.1 dB Q-penalty was observed up to 10 degree meanwhile 2×1 WL showed 1.1 dB Q-penalty. Finally, IQ crosstalk tolerance was evaluated. The crosstalk used this experiment was calculated as the inverse of magnitude response of 5^{th} order Bessel filter, defined by the crosstalk level at the symbol-rate, 58-GHz. In Fig. 3 (d), the Q-factor is plotted as a function of X-IQ crosstalk. Similarly to other experiments, 4×2 WL showed the best results and only 0.1 dB Q-penalties were observed up to -10 dB meanwhile 2×1 WL showed 0.8 dB Q-penalty. Furthermore, we confirmed that no bit error after FEC was observed in the case with 4×2 WL for all measurement conditions.

5. Conclusion

We propose 4×2 WL MIMO equalizer embedding preliminary CPR for Tx impairment mitigation, it compensates carrier phase error first, then simultaneously compensate PMD, polarization rotation, and Tx impairments. We experimentally evaluated our method with 58-GBaud PM-64QAM after 100 km SSMF transmission, by adding Tx X-IQ skew, Tx X-IQ gain imbalance, quadrature error and Tx X-IQ crosstalk, and compared with the conventional 2×1 WL MIMO after CPR. Our method outperformed the conventional method for whole cases, and showed negligible 0.1 dB Q-pearlites with 14 ps skew, 2 dB gain imbalance, 10 degree phase error, and -10dB crosstalk.

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Reference

[1] P. Winzer et al., Opt. Exp., vol. 26, no. 18, 24190-24239 (2018)
[2] A. Matsushita et al., JLT, vol. 37, no. 2, 470-476 (2019).
[3] R. Rios-Müller, et al., JLT, vol. 33, no. 7, 1315-1318 (2015).
[4] E. P. da Silva, D. Zibar, JLT, vol. 34, no. 15, 3577-3586 (2016).
[5] C. Fludger, T. Kupfer, ECOC 2016, Tu.2.A.2 (2016).
[6] T. Kobayashi et al., OFC 2019, Th4B.2 (2019).
[7] M. Arikawa et al., Opt. Exp., vol. 28, no.16, pp23478-23494 (2020).
[8] M. Mazur et al., Opt. Exp., vol. 27, no. 17, pp24654–24669 (2019).