In-Service Transmitter Calibration via Offloaded 4×2 WL MIMO Equalizer with Compensating IQ Imbalance

Masaki Sato[1], Hidemi Noguchi[1], Junichiro Matsui[2], Jun'ichi Abe[1], and Emmanuel Le Taillandier de Gabory[1]
[1] *Advanced Network Research Laboratories, NEC Corporation, 1753 Shimonumabe, Nakahara-Ku, Kawasaki, Kanagawa 211-8666, Japan*
[2] *Fiber Optic Devices Department, NEC Corporation, 1131 Hinode, Abiko, Chiba 270-1198, Japan*
m-satou-kj@nec.com

Abstract: In-service Tx-IQ imbalance calibration estimated with 4×2 MIMO equalizer for 96-Gbaud PM-PCS-64QAM was demonstrated over 120 km SMF. Q-penalties of 0.1 dB with 2 ps IQ skew and ±2.5 dB IQ peaking error were achieved. © 2024 The Author(s)

1. Introduction

Digital coherent transmission with higher symbol-rate and information rate (IR) is promising for meeting the growing traffic requirements [1]. As the symbol-rate and IR increase, frequency response deviations of electrical and optical devices significantly impact signal quality, especially IQ imbalance deviation can no longer be neglected. Several adaptive equalizers have been proposed to solve this issue [2-5], but these increase ASIC circuit resources and can be considered excessive, as real time adaption is not required for such slow deviations.

Coherent DSP typically features frequency domain equalizers (FDE) in the transmitter (Tx) and receiver (Rx) for Nyquist filtering and chromatic dispersion compensation (CDC) and the device calibration in the factory. We previously proposed an on-site calibration scheme via constrained adaptive multi-layer (ML) filters using weak Tx nonlinearity [6] that updates the filter coefficients of Tx and Rx FDE separately, including IQ common distortion in Tx/Rx. Generally, the filter convergence in ML filters becomes more complex as filter taps and layers increase and computation time is also longer, so alternatives must be considered for in-service calibration.

Besides the ML scheme, several multi-input-multi-output (MIMO) equalizers [2-4] can be used to derive FDE filter coefficients. However, it is not straightforward to utilize the filter coefficients since these MIMO equalizers also compensate IQ common distortions in Tx, Rx, and transmission line, including polarization mode dispersion (PMD) and polarization rotation, resulting in the estimation error for the calibration.

In this paper, we propose in-service Tx calibration of IQ imbalance estimated with offloaded 4×2 widely linear (WL) MIMO equalizer embedding preliminary carrier phase recovery (CPR) [2], where it compensates carrier phase error first, then PMD and Tx impairments are compensated simultaneously. Instead of using the filter coefficients directly, we propose to convert filter coefficients to compensate IQ differences only to avoid excess compensation for IQ common distortion. We experimentally demonstrate our method with 96-Gbaud polarization multiplexing-probabilistic constellation shaping-64 quadrature amplitude modulation (PM-PCS-64QAM), it effectively calibrates the frequency response of Tx devices and various IQ imbalances after 120 km single mode fiber (SMF) transmission.

2. In-service Tx IQ imbalance calibration via offloaded 4×2 WL MIMO equalizer embedding CPR

The concept of Tx imbalance calibration scheme is shown in Fig. 1. The block diagram of 4×2 WL MIMO equalizer embedding CPR located after the CDC filter on the offloaded Rx DSP is shown in Fig. 1 (a), which compensates for the whole remaining linear distortion of fiber transmission line and linear Tx impairments. Data-aided phase-locked loop (DA-PLL) using the pilot symbols is applied for CPR, and it is embedded for least mean square (LMS) method to update filter taps by using output complex signals of MIMO. Since MIMO equalizer relies on the standard coherent transceiver hardware and a pilot-based DSP, no dedicated hardware is required. Further, these filter configurations can be operated by software as these distortions are changing slowly for resource-efficient

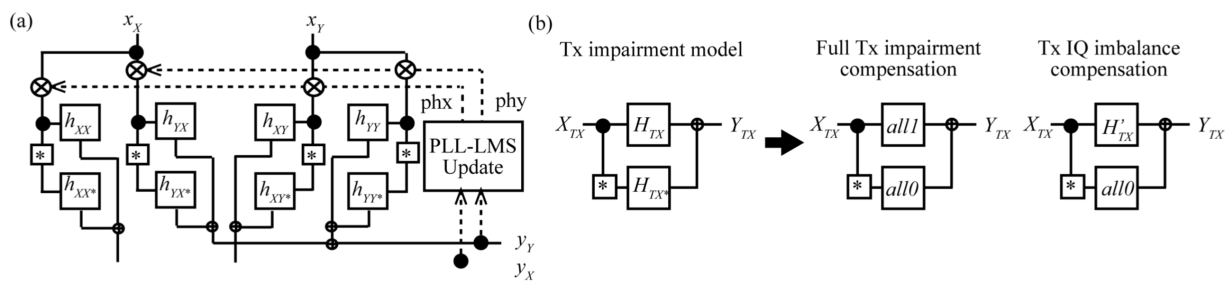

Fig. 1. Concept of Tx IQ imbalance calibration (a) The block diagram of 4×2 WL MIMO equalizer embedding CPR, (b) Tx linear impairment model with WL expression for the complex signal of the single polarization

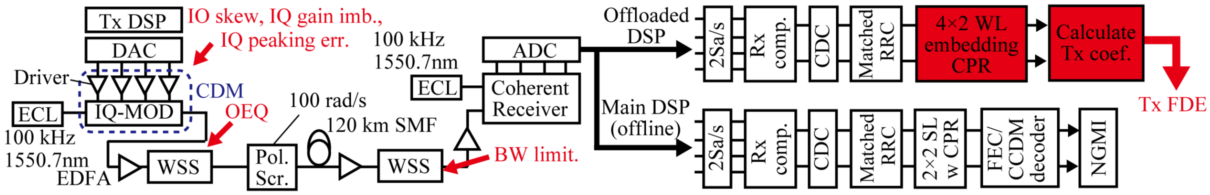

Fig. 2. Experimental setup and offline DSP

implementation and the control of the equalizer does not need to be real time.

4×2 WL MIMO filter coefficients ideally contain inverse characteristics of Tx impairments. As our target is frequency response variation rather than full calibration for in-service calibration, we derive IQ imbalance from these coefficients, the residual IQ common distortion can be handled with a 2×2 MIMO equalizer in the main DSP. Fig. 1 (b) shows Tx impairment model with WL expression for the complex signal of the single polarization. In the frequency domain, output signals Y_{TX} are described as

$$Y_{TX}(\omega) = H_{TX}(\omega)X_{TX}(\omega) + H_{TX*}(\omega)X^*_{TX}(-\omega) \tag{1}$$

Where X_{TX}, ω, H_{TX} and H_{TX*} are, respectively, the input signals, the angular frequency, the frequency response for input signals, and that for complex conjugate of input signals. $H_{TX}(\omega)=1$ and $H_{TX*}(\omega)=0$ should be satisfied to fully compensate Tx impairments. In contrast, IQ imbalance compensation requires $H_{TX*}(\omega)=0$ without IQ common distortion compensation. The filter coefficients h_{xx}, h_{xx*}, are expressed in the frequency domain as H_{xx} and H_{xx*}. To achieve full Tx impairment compensation in X polarization, H_{xx} and H_{xx*} can be applied to the original signals $X_{TX'}$,

$$X_{TX}(\omega) = H_{xx}(\omega)X_{TX'}(\omega) + H_{xx*}(\omega)X^*_{TX'}(\omega) \tag{2}$$

To satisfy the conditions of full Tx compensation for $Y_{TX}(\omega)$ regarding $X_{TX'}(\omega)$, H_{TX} and H_{TX*} are transformed as

$$H_{TX}(\omega) = \frac{H^*_{xx}(-\omega)}{H^*_{xx}(-\omega)H_{xx}(\omega) - H_{xx*}(\omega)H^*_{xx*}(-\omega)}, H_{TX*}(\omega) = \frac{-H_{xx*}(\omega)}{H^*_{xx}(-\omega)H_{xx}(\omega) - H_{xx*}(\omega)H^*_{xx*}(-\omega)} \tag{3}$$

With Eq. (3), the filter coefficients for Tx IQ imbalance compensation are described as

$$X_{TX}(\omega) = X_{TX'}(\omega) - \frac{H_{TX*}(\omega)}{H_{TX}(\omega)}X^*_{TX'}(-\omega),\ where\ \frac{H_{TX*}(\omega)}{H_{TX}(\omega)} = \frac{-H_{xx*}(\omega)}{H^*_{xx}(-\omega)} \tag{4}$$

To substitute Eq. (4) into Eq. (1), $Y_{TX}(\omega)$ are described as

$$Y_{TX}(\omega) = \left(H_{TX}(\omega) - \frac{H_{TX*}(\omega)H^*_{TX*}(-\omega)}{H^*_{TX}(-\omega)}\right)X_{TX'}(\omega) = H'_{TX}(\omega)X_{TX'}(\omega) \tag{5}$$

The complex conjugate of X_{TX} disappears, and IQ imbalance can be compensated even IQ common distortion H'_{TX} remains. The same applies to Y polarization with h_{yy}, h_{yy*}. Also, polarization cross-terms h_{xy}, h_{xy*}, h_{yx} and h_{yx*} can be used as an alternative, depending on the polarization condition in the transmission line. In this case, the intensity of the filter coefficients can simply be summed to determine which coefficients to use. The obtained filter coefficients of 2×1 WL filter are converted to 2×2 real-valued IQ MIMO coefficients for each polarization [6], which is used for fixed Tx compensation by FDE in the main Rx DSP.

3. Experimental Setup for evaluation of Tx impairment calibration

Fig. 2 shows the experimental setup for 800 Gbps 96-Gbaud PM-PCS-64QAM signal with an IR of 4.4 b/sbl/pol. The roll-off factor of 0.05 was used for root raised cosine (RRC) filtering. We used external cavity lasers (ECL) for both signal source and local oscillator (LO) with 1 GHz offset. Tx optical carrier was modulated with a coherent driver modulator (CDM) [7] and four 120-GSa/s DAC. Forward error correction (FEC) of low-density parity-check code for DVBS2 with a frame length of 64,800 and a code rate 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-PCS-64QAM with PCS and constant composition distribution matching (CCDM). The optical equalization was applied to coarsely compensate Tx IQ common distortion by wavelength selective switch (WSS). A pilot sequence was inserted 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. X-IQ skew and X-IQ gain imbalance were digitally emulated, and X-IQ peaking of drivers inside CDM [7] was adjusted for frequency dependent IQ imbalance.

We used 120-km SMF for the transmission line, the fiber launch power was -2 dBm to avoid fiber nonlinearity. At the Rx side, another WSS is used to emulate bandwidth (BW) limitation in the transmission line. The received OSNR was 30.5 dB/0.1nm. The optical signal was received coherently and digitalized with four 256-GSa/s ADC.

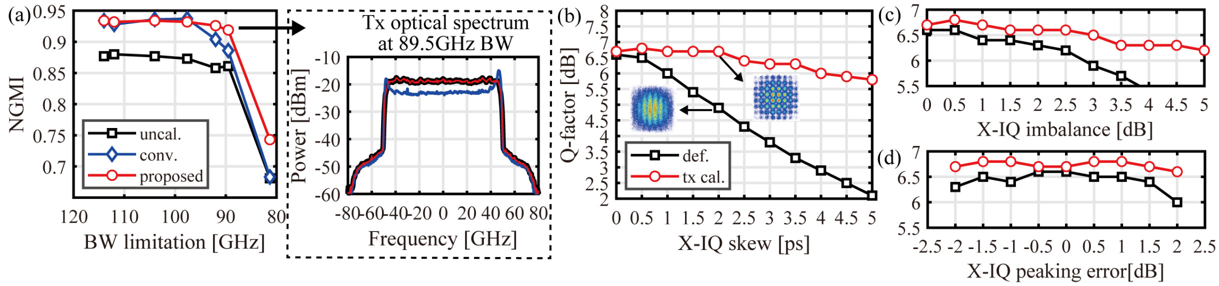

Fig. 3. Experimental results (a) BW limitation (Inset: Tx optical signal spectrum with 500MHz resolution), (b) X-IQ skew, (c) X-IQ gain imbalance, (d) X - IQ peaking error of drivers inside CDM

The validation consists of calibration by deriving the Tx FDE filter coefficients and then by signal evaluation using Tx FDE-based compensation. The received signals were resampled to 2-Sa/sym. CD was compensated by FDE with Rx front-end compensation, and matched RRC filtering was applied to the output of the FDE. The signal after RRC filtering was fed to the 4×2 WL MIMO equalizer embedding CPR for the proposed calibration scheme. 101 tap was selected to compensate for Tx impairments. The filter coefficient update was carried out using the pilot symbol with DA-LMS. The obtained 2×2 real-valued MIMO filter coefficients were set Tx FDE. In the main DSP, Tx FDE-based compensation was applied. PLL-based 2×2 SL filter with 65 taps was performed with CPR. After demodulation, the Q-factors were calculated from the bit error rate before and after FEC and CCDM decoding, and the normalized generalized mutual information (NGMI) averaged over two polarizations were evaluated.

4. Results and discussion

First, we compared the proposed scheme with the conventional case, where the obtained MIMO filter coefficients are directly applied to Tx FDE. In Fig. 3. (a), NGMI is plotted as a function of BW limitation in the transmission line. The uncalibrated case was used as a benchmark. Both calibration schemes successfully calibrated residual IQ delay and the device frequency response down to 98 GHz. In the conventional case, NGMI decreased rapidly due to pre-emphasis when the BW was narrower than 96 GHz, as shown in the optical spectrum after Tx WSS, since BW limitation is also compensated at Tx with this method. In contrast, the proposed method showed marginal degrease with BW limitation, and the optical spectrum was almost the same as the uncalibrated case where the proposed method compensated Tx IQ imbalance only.

Next, we evaluated several IQ imbalances for the proposed scheme. Rx WSS was set to 115 GHz BW, and Tx calibration was carried out using the proposed method in advance. Overall, the proposed method outperformed the default case, with no calibration for each impairment. The Q-factor is plotted as a function of X-IQ skew in Fig. 3 (b). A Q-penalty of 0.1 dB appeared at 2 ps. The penalty was gradually increased to 0.9 dB at 5ps; the excessive IQ imbalance may cause this penalty, but it is sufficient for in-service calibration. In Fig. 3 (c), the Q-factor is plotted as a function of X-IQ gain imbalance; a Q-penalty of 0.1 dB appeared at 2.5 dB gain imbalance. The Q-factor was gradually decreased with the gain imbalance increase since it introduced polarization dependent loss. Finally, the Q-factor is plotted as a function of X-IQ peaking error in Fig. 3 (d). Even though the peaking might induced some nonlinear effect, negligible penalties below 0.1 dB were observed within ±2.5 dB peaking error.

5. Conclusion

We have proposed in-service Tx IQ imbalance-only compensation via offloaded 4×2 WL MIMO equalizer embedding CPR. Our method was experimentally demonstrated with 800 Gbps 96-GBaud PM-PCS-64QAM 120km transmission, it showed robust frequency-dependent IQ imbalance compensation under the severe BW limitation, whereas the conventional scheme was deteriorated by excessive compensation. Also, the proposed scheme showed negligible 0.1 dB Q-penalties for in-service operation with 2 ps skew, 2.5 dB imbalance, and ±2.5 dB peaking error.

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