Adaptive Multi-Layer Filters for Compensating for Impairments in Transmitters and Receivers for SDM Transmission

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Abstract *An extended adaptive multi-layer filter architecture that compensates for transmitter/receiver impairments in SDM transmission is presented. Simultaneous compensation and monitoring of receiver IQ skew was experimentally demonstrated for -10 to +10 ps in WDM/SDM transmission of 32-Gbaud PDM-64QAM signals over 102-km coupled 4-core fiber. ©2022 The Author(s)*

Introduction

Coupled space-division multiplexing (SDM) transmission systems, in which coupling between spatial modes is compensated for by receiver (Rx)-side multi-input multi-output (MIMO) processing, are attractive for providing high spatial density [1,2]. Several transmission experiments using coupled multi-core fibers, which are suited for long-haul transmission [3,4], have been demonstrated [5–10].

SDM systems usually require multiple transmitters (Txs) and Rxs. Impairments occurring in Tx/Rx devices, such as IQ skew and IQ amplitude imbalance, are becoming non-negligible as a higher-order modulation format and a higher symbol rate are used [11,12]. The number of electrical channels increases in SDM systems, though integration of them has been investigated [13]. Thus, it becomes harder to ensure the uniformity of channel characteristics or to calibrate them especially for SDM systems.

For compensation of IQ impairments in a Tx/Rx for single-mode fiber (SMF) transmission, adaptive filters on the Rx-side have been investigated [14–19]. Tx/Rx impairments are not mutually commutative with other impairments that may occur in the transmission line, including chromatic dispersion (CD). Thus, Rx impairment compensation is performed by adopting independent CD compensation on I and Q components and a subsequent widely-linear (WL) MIMO filter [14,17–19]. As for SDM systems, mode coupling and modal dispersion as well must be dealt with. In a recent demonstration of SDM transmission over coupled 4-core fiber (C4CF), a real-valued MIMO filter on IQ signals was used [8]; however, this is not sufficient to fully compensate for Tx/Rx IQ impairments due to mutual commutativity. Moreover, straightforward extension of adaptive WL MIMO filter approaches to SDM systems results in an inefficiently large adaptive filter having redundant cross terms among IQ components of multiple spatial modes.

We previously proposed a multi-layer (ML) filter architecture to compensate for Tx/Rx IQ impairments as well as other impairments in a transmission system [20]. With this architecture, layers can be designed to have minimum cross terms and temporal spread to compensate for specific impairments efficiently, while considering the mutual commutativity of impairments. The coefficients are adaptively controlled by gradient calculation with back propagation from the last layer and stochastic gradient descent (SGD).

In this study, we have extended the adaptive ML filter architecture to coupled SDM transmission systems. We demonstrated that the adaptive ML filters including an 8×8 strictly-linear (SL) MIMO filter compensated for IQ skews in multiple Rxs simultaneously in WDM/SDM transmission of 32-Gbaud PDM-64QAM signals over 104 km of C4CF. It also demonstrated that IQ skew in Rxs can be monitored through the adaptive filter coefficients.

Adaptive ML filters including 8×8 MIMO filter

Figure 1 shows the proposed adaptive ML filter architecture that compensates for Tx/Rx impairments in SDM transmission over C4CF. There are five layers. Each layer contains various types of half-symbol-spaced finite impulse response filters to compensate for specific

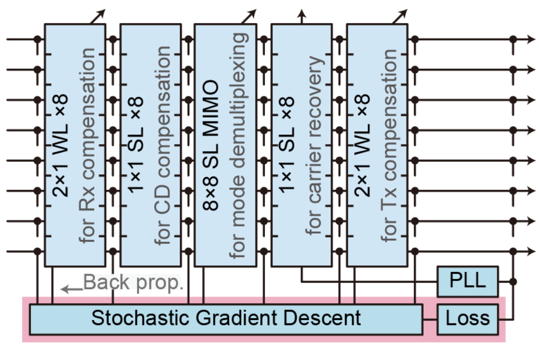

Fig. 1: Adaptive multi-layer filters including 8×8 MIMO filter.

impairments in the reverse order in which they occur when any two of them are not mutually commutative.

Complex-valued response filters with complex-valued input and output in the phasor representation cannot provide IQ impairment compensation since they cannot provide IQ independent responses. In this sense, these filters are referred to as SL. Real-valued response MIMO filters for IQ components are required to compensate for Tx/Rx impairments [14]. These filters are equivalent to complex-valued response filters for which the inputs are a signal and its complex conjugate [15]. They are referred to as WL.

The first layer in the ML architecture (Fig. 1) consists of 2×1 WL filters for eight spatial modes for Rx impairment compensation. The second layer consists of eight 1×1 SL filters for CD compensation. The third layer consists of an 8×8 SL MIMO filter for mode demultiplexing, i.e., compensation for mode coupling and modal dispersion. The fourth layer consists of eight 1-tap 1×1 SL filters for carrier recovery (CR). The fifth layer consists of eight 2×1 WL filters for Tx impairment compensation. Each layer is designed to minimize cross terms to compensate for the corresponding impairments.

The filter coefficients in each layer are adaptively controlled by gradient calculation with back propagation and SGD to minimize the loss, which is composed of the last layer's output. Forward and back propagation of SL/WL filters in the adaptive ML filter architecture as provided in our previous work [20] can be used with the 8×8 MIMO filter as well. The coefficients of the first, third, and fifth layers are controlled by SGD. The coefficients of the second layer are given by the physical CD model and dealt with as static. CR in the fourth layer is controlled by a phase locked-loop using the last layer's outputs.

Use of this adaptive ML filter architecture sufficiently compensates for Tx/Rx impairments as well as mode coupling and modal dispersion in coupled SDM transmission. Moreover, the impairments can be monitored through the coefficients in the corresponding layer after adaptive control. Tx/Rx IQ impairments can be monitored through the coefficients of the fifth and first layers, respectively, as for SMF [21].

Experimental setup

We evaluated the performance of the proposed ML filter architecture in the SDM/WDM transmission experiment over C4CFs. We focused on compensation of Rx impairments, especially Rx IQ skew, which are relatively hard to compensate for since they occur after mode coupling and modal dispersion.

The experimental setup is shown in Fig. 2. On the Tx-side, 16-channel 32-Gbaud PDM-64QAM signals at frequencies from 192.90 to 193.30 THz in a 50-GHz grid were generated. The signal at 193.30 THz was used for evaluation. It was generated by a laser-diode (LD) source and a four-channel digital-to-analog converter (DAC) at a sampling rate of 92 GS/s. The transmitted data were 16 low-density parity-check FEC frames for DVB-S2 with a frame length of 64,800 and a code rate of 0.8 with random bits included in the payload. They were mapped to PDM-64QAM, and a root raised cosine filter with a roll-off factor of 0.1 was applied. The remaining 15 channels were generated by a modulator (MOD) and a 64-GS/s DAC. After equalization of their powers and low-speed polarization scrambling (PS), the optical signal was split into four and decorrelated to emulate SDM signals.

The transmission line consisted of two spans of 52-km C4CF, 104 km in total. The span losses were compensated for by parallel single-core EDFAs. The span input power was set to 0 dBm/ch/core. After transmission, the SDM signals under evaluation were demultiplexed by optical bandpass filters (OBPFs) and received by four polarization-diversity coherent Rxs. The outputs of the Rxs were sampled with a 16-channel oscilloscope at a sampling rate of 50 GS/s as an analog-to-digital converter (ADC). The Rx IQ skew was emulated in the digital domain. The DSP was performed offline.

In the DSP, the signals were normalized and resampled to two-fold oversampling. Then, the adaptive ML filters shown in Fig. 1 were applied. The tap lengths were 5 for the first and fifth layers, 61 for the second layer, and 41 for the third layer. The loss function for adaptive filter control was first based on data-aided LMS. Since SDM emulation was performed in this experiment, the decorrelated transmitted symbols were used as the training pattern. After convergence, the loss

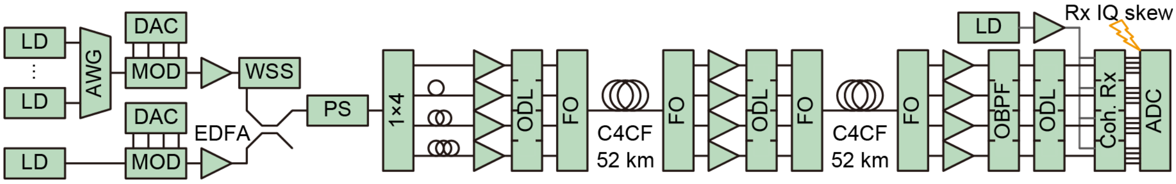

Fig. 2: Experimental setup for WDM/SDM transmission of 32-Gbaud PDM-64QAM signals over 104 km of C4CF. AWG: arrayed waveguide grating, WSS: wavelength selective switch, ODL: optical delay line, FO: fanout.

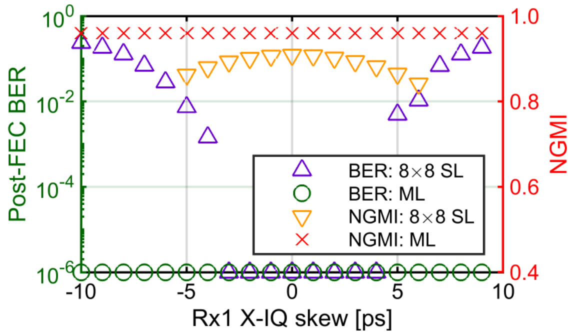

Fig. 3: Post-FEC BER and NGMI with the reference 8×8 SL and proposed ML configurations after 104-km transmission over C4CF with emulated individual Rx IQ skew.

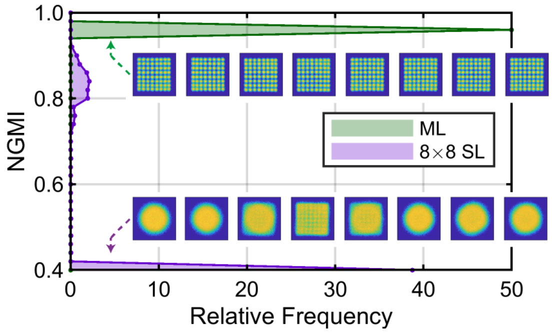

Fig. 4: Histogram of NGMI after 104-km transmission with emulated simultaneous Rx IQ skews for all eight spatial modes in random 1000 realizations.

was switched to decision-directed LMS. The normalized generalized mutual information (NGMI) [22] and post-FEC BER were evaluated. For reference, we used a conventional DSP with CD compensation and an adaptive 8×8 MIMO filter with CR, which was controlled by data-aided and decision-directed LMS as well. This reference configuration is hereinafter referred to as 8×8 SL after its adaptive filter structure.

Experimental results

We first evaluated the case in which IQ skew was emulated in an Rx individually. Figure 3 shows the post-FEC BER and NGMI obtained with the 8×8 SL and ML configurations after 104-km transmission while Rx IQ skew was emulated in one polarization. With the 8×8 SL configuration, error-free transmission was achieved only within Rx IQ skew from −3 to +4 ps. In contrast, error-free transmission was achieved from −10 to +10 ps with the proposed ML configuration. Even when the emulated Rx IQ skew was zero, the ML configuration provided better NGMI since it compensates for slight Rx/Tx IQ impairments remained in the experimental setup. Similar results were obtained when emulating IQ skew in another Rx.

We then evaluated the case in which there were simultaneous Rx IQ skews in eight spatial modes. Random IQ skews were sampled from a Gaussian distribution with a zero mean and a

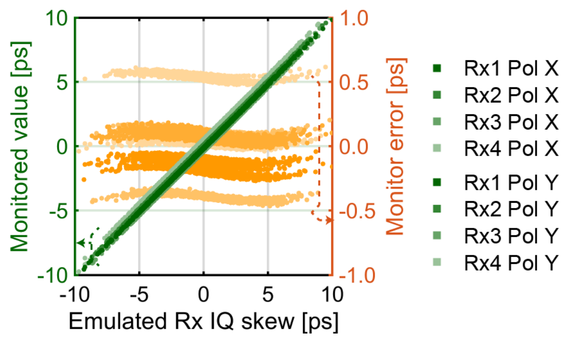

Fig. 5: Monitored values (green) and errors (yellow) of Rx IQ skew through filter coefficients of the adaptive ML filters after 104-km transmission over C4CF with emulated simultaneous Rx IQ skews in random 1000 realizations.

standard deviation of 3 ps; 100 realizations for 10 acquisitions of received signals, 1000 in total, were evaluated. Figure 4 shows a histogram of the NGMI after 104-km transmission with emulated simultaneous Rx IQ skews. With the 8×8 SL configuration, the obtained NGMI spread to a lower value. Adaptive control sometimes failed to achieve convergence, resulting in a peak below an NGMI of 0.4. With the ML configuration, a steady and higher NGMI (~0.96) was achieved. This demonstrates that the proposed ML architecture compensated for simultaneous Rx IQ skews in SDM transmission over C4CF.

Finally, we evaluated the monitoring of Rx IQ skews through the coefficients of the first layer of the ML filters [21]. Figure 5 shows the monitored results and errors in Rx IQ skews after 104-km transmission with emulating random 1000 simultaneous Rx IQ skews as described above. The monitored and emulated values are well matched, with an error less than 0.6 ps. The slight offsets were due to remaining skews in the setup.

Conclusions

Our extended adaptive ML filter architecture including an 8×8 MIMO filter for Tx/Rx impairment compensation in coupled SDM was shown to compensate for Rx IQ skews simultaneously in WDM/SDM transmission of 32-Gbaud PDM-64QAM signals over 104 km of C4CF. The Rx IQ skews could also be monitored through the adaptive filter coefficients for IQ skew of -10 to +10 ps with an error less than 0.6 ps.

Acknowledgements

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