Inline Optical Compensation of Group Delay Ripple for Long-haul Transmission Using Offloaded 2×2 MIMO Filter

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Abstract: We demonstrated inline optical compensation of group delay ripple estimated with offloaded 2×2 MIMO filter for 84-GBaud PM-PCS-16QAM over 10,200 km SMF. We showed 38 % reduction of MIMO taps, compared to the conventional method. © 2022 The Author(s)

1. Introduction

High symbol rate digital coherent transmission is promising for meeting the growing traffic requirements [1]. As the symbol rate increases, the impact of linear impairments in the transmission line such as chromatic dispersion (CD), CD slope, and bandwidth degradation of the optical devices become more significant. Especially at high baud rates, the group delay characteristic cannot be neglected any longer and it needs to be compensated for some distortion, e.g., CD slope. In a general manner, impairments can be compensated by digital signal processing (DSP) for digital coherent transmission. On a typical receiver (Rx) DSP, CD is compensated by fixed frequency domain equalizer (FDE), and residual linear impairments are compensated by following adaptive time domain multiple-input-multiple-output (MIMO) equalizer as well as polarization de-multiplexing. Obviously, the required number of taps of finite impulse response (FIR) filter, *i.e.* the required circuit resource, is increased in proportion to the length of impulse response of impairments. As circuit resource issues are key to realize high-capacity digital coherent processor, alternatives need to be considered.

Programmable optical filter (POF) with gain and phase capabilities have been reported [2]; they are a candidate for alternative compensation of linear impairment. So far, POF is often used for gain adjustment, gain flattening of optical devices [3] and gain emphasis of transmitter (Tx) devices [4]. Still, the phase capability has been utilized to a limited extend, like variable CD compensation [5] and others.

In this paper, we propose inline optical compensation of group delay ripple (GDR) for high baud rate signals with POF based on estimation by offloaded 2×2 MIMO filter. We demonstrate the phase capability of POF, to compensate the ripple part of group delay, which reduces the signal quality of high baud rate signals. Concretely, we first estimate GDR with a large 2×2 MIMO equalizer, which we offload from main real-time signal DSP; then we compensate GDR by POF accordingly, reducing the required MIMO taps in the main DSP. We demonstrate experimentally the compensation of GDR in the transmission over 10,200km of single mode fiber (SMF) of 84-GBaud Polarization Mutiplexing-16 quadrature amplitude modulation based probabilistic constellation shaped signal (PM-PCS-16QAM). We show a resulting reduction by 38 % of the required MIMO taps in the main DSP, compared to conventional MIMO only case.

2. Inline optical compensation of group delay ripple estimated with offloaded 2×2 MIMO filter

The concept of inline optical compensation of GDR estimated with offloaded 2×2 MIMO filter is shown in Fig. 1. On the conventional main Rx DSP, incoming signal is digitized by analog-to-digital convertor (ADC), fixed FDE compensates CD first, the following adaptive 2×2 MIMO equalizer compensates whole remaining linear distortion of fiber transmission line, MIMO tap length limits the performance accordingly. Although our experimental

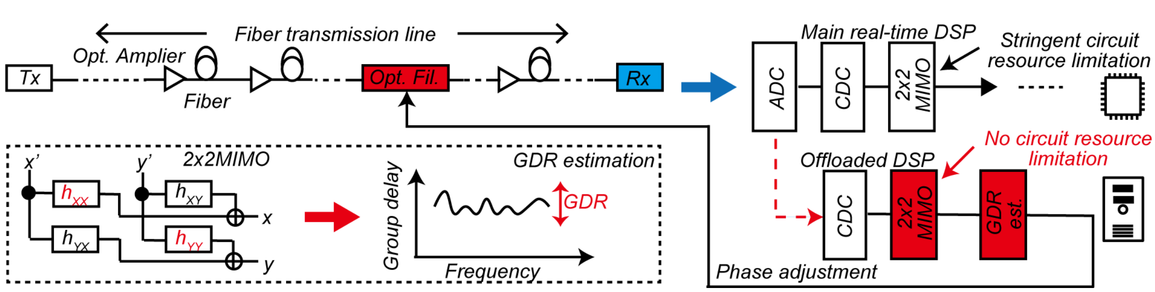

Fig. 1. Concept of inline optical compensation of group delay ripple estimated with offloaded 2×2 MIMO filter. Inset: Proposed GDR estimation flow in offloaded DSP.

investigations use offline processing, main DSP in telecommunication systems require real-time processing such as with ASIC with severe circuit resource constraints.

The proposed scheme consists of two parts, the offloaded DSP, and POF located in fiber transmission line. The offloaded DSP is used for GDR estimation, it is implemented in software, outside of main real-time DSP; thus, it is not limited by the circuit resource of the main real-time DSP. Moreover, it is not real-time since the compensated GDR is slow evolving phenomena, depending on temperature and ageing of devices. The estimation of GDR involves signal processing similar to the main DSP, using the large 2×2 MIMO equalizer adaptively compensating GDR. After convergence, we select arbitrarily the filter coefficient h_{xx} for GDR estimation since our target GDR, *e.g.,* CD slope, is common for both polarizations. The complex frequency response of H_{xx} is described as

$$H_{xx}(\omega) = |H_{xx}(\omega)|e^{j\theta(\omega)},\ \theta(\omega) = tan^{-1}\left(\frac{Im(H_{xx}(\omega))}{Re(H_{xx}(\omega))}\right) \quad (1)$$

where ω, $|H_{xx}(\omega)|$ and $\theta(\omega)$ are respectively the angular frequency, the amplitude response, and the phase response. GDR $\tau_r(\omega)$ is described as

$$\tau_r(\omega) = \tau(\omega) - \langle\tau\rangle,\ \tau(\omega) = -\frac{d\theta(\omega)}{\theta(\omega)} \quad (2)$$

where $\tau(\omega)$ is the estimated group delay, $\langle\tau\rangle$ is an offset parameter. GDR is reconverted to phase response $\theta_c(\omega)$.

$$\theta_c(\omega) = -\int_{\omega_0}^{\omega} \tau_r(\omega_c)d\omega_c \quad (3)$$

Averaging and removal of out of band noise is applied for $\tau_r(\omega)$ to improve the compensation accuracy. Finally, the phase response $\theta_c(\omega)$ is applied to the POF. As we perform optical GDR compensation, we can reduce the number of taps for adaptive MIMO equalizer without the penalty due to the GDR in the fiber transmission line. Note that it is possible to alternatively incorporate GDR compensation into the fixed FDE of the main DSP but with some additional expense in the circuit resource.

3. Experimental Setup for evaluation of inline optical compensation of group delay ripple

Fig. 2 shows the experimental wavelength division multiplexing (WDM) transmission setup with nine 100 GHz spaced channels modulated with 84-Gbaud PM-PCS-16QAM signal with an information rate (IR) of 2.8 b/sbl/pol. We used external cavity lasers (ECL) with a 100 kHz linewidth. On the Tx side, the optical carrier was modulated with a PM-IQ modulator and four 120-GSa/s digital-to-analog convertors (DAC). Forward error correction (FEC) of low-density parity-check code for DVBS2 with a frame length of 64,800 and a code rate of 4/5 was used. Four FEC frames were generated for each polarization by loading random bits to their payload and were then mapped to PM-PCS-16QAM with probabilistic amplitude shaping [6] and constant composition distribution matching (CCDM) [7]. 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. The roll-off factor of 0.05 was used for root raised cosine filtering. The surrounding eight channels were generated with four DAC. For the transmission line, we used a recirculating loop, consisting of five spans of 60-km SMF. The fiber launch power was set to +1 dBm for the optimum value. A wavelength selective switch (WSS) used as POF for gain flattering and the proposed optical compensation of GDR. The WSS has a frequency resolution of 1 GHz and a group delay control range of ±25 ps. The received OSNR was 20.7 dB/0.1nm after 10,200 km. The optical signal was received coherently and digitalized with four 256-GSa/s ADC.

The main Rx DSP was performed offline. The received signals were resampled to 2-Sa/sym. and CD was compensated by FDE. After frame synchronization, matched RRC filtering was applied to the output of the FDE. T/2-spaced data aided phase-lock-loop based 2×2 MIMO equalizer was performed with carrier recovery. The filter coefficient update was carried out using the pilot symbol with data-aided leas-mean-square. After demodulation, Q-factor were calculated from the bit error rate (BER) before and after FEC and CCDM decoding, and the normalized generalized mutual information (NGMI) averaged over two polarizations were evaluated.

The offloaded DSP was also performed offline. Phase setting of WSS inside the recirculating loop was initialized

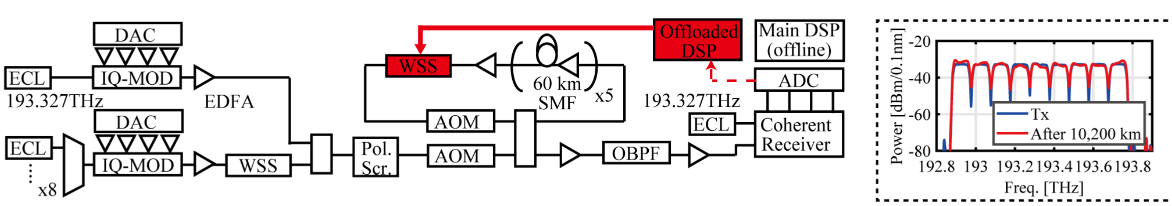

Fig. 2. Experimental setup. Inset: Optical signal spectrum. EDFA: erbium-doped fiber amplifier; AOM: acousto-optic modulator; OBPF: optical bandpass filter.

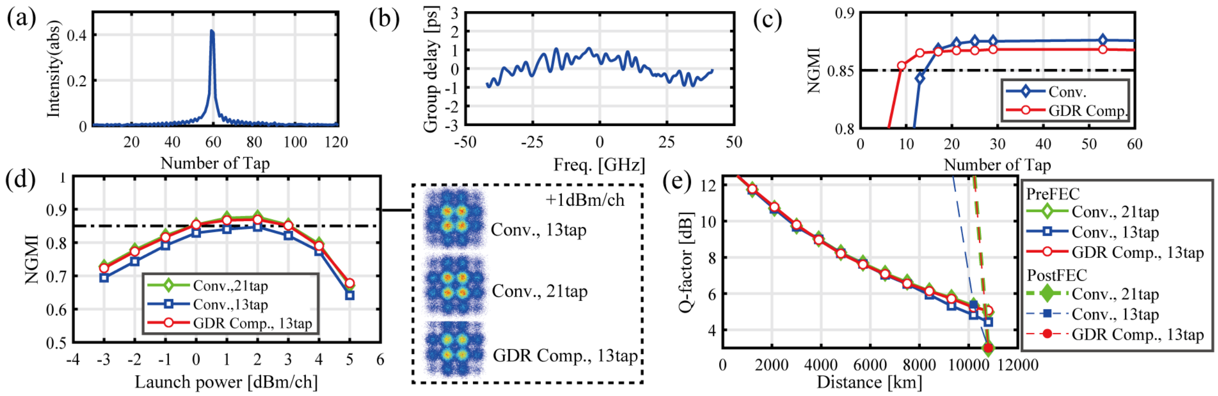

Fig. 3. Experimental results (a) Filter coefficient h_{xx} of offloaded DSP at 300 km distance, (b) Estimated GDR at 300 km distance, (c) NGMI as a function of number of tap at 10,200 km distance, (d) NGMI as a function of launch power at 10,200 km distance, (e) Q-factor as a function of transmission distance with +1 dBm/ch.

to zero, and the tap length of the offloaded MIMO filters was set to 121. GDR estimation was carried out with filter coefficient h_{xx}, and the phase response $\theta_c(\omega)$ was set to the WSS.

4. Results and Discussion

First, we evaluated the proposed GDR estimation after a single loop lap of 300 km, passing once through the WSS. The fiber launch power was set to +1 dBm/ch. The filter coefficient h_{xx} of the offloaded 2×2 MIMO filter and the estimated GDR are plotted in Fig. 3 (a) and (b). We observed less than 1 ps of GDR for one lap, resulting in more than 30 ps after 10,200 km transmission. We attribute it to the CD slope of the SMF.

Second, we evaluated the proposed inline GDR compensation, compared it with conventional 2×2 MIMO implemented in the main DSP only case, where phase setting of the WSS is initialized to zero. In Fig. 3 (c), NGMIs are plotted as a function of number of taps after 10,200 km transmission at optimum launch power. Whereas the conventional case of 2×2 MIMO inside the main DSP required 21 taps to achieve saturated NGMI, the proposed scheme significantly reduced by 38 % the required tap length of 2×2 MIMO inside the main DSP, to reach saturated NGMI, with only 13 taps. This confirms the effectiveness of estimation and resulting inline optical compensation of GDR. Next, NGMI values are plotted as a function of the launch power in Fig. 3 (d). Regardless of launch power in this experiment, the proposed scheme with 13 taps achieved almost same NGMI as the conventional case with 21 taps in the main DSP. Finally, the Q-factors are plotted as a function of transmission distance for three cases in Fig.3 (e). No performance difference was observed up to 8,000 km since accumulated GDR was not a dominant impairment. However, after 8,000 km transmission, an extra pre FEC Q-penalty of 0.4 dB occurred for the conventional case with 13 taps, and post FEC errors were observed at 10,200 km. In contrast, the proposed scheme with 13 taps showed almost the same performance as the conventional case with 21 taps up to 10,800 km, and no post FEC error was observed up to 10,200km.

5. Conclusion

We have proposed inline optical compensation of GDR using offloaded 2×2 MIMO filter, where the offloaded DSP first estimates GDR with a large 2×2 MIMO equalizer, and where we compensate GDR by POF in the transmission line, reducing number of the taps of MIMO equalizer in the main DSP. We demonstrated our method with a 10,200 km WDM transmission experiment using 84-GBaud PM-PCS-16QAM with 2.8 b/sbl/pol signals, showing that the proposed scheme enabled a 38 % reduction of the number of taps for 2×2 MIMO of the main DSP, compared with the conventional main DSP only case. Namely, we realized 10,200 km transmission with only 13 taps for 2×2 MIMO equalizer in the main DSP.

Acknowledgements

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