Performance Improvement of Electronic Dispersion Post-Compensation in Direct Detection Systems Using DSP-Based Receiver Linearization

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Abstract: Significant improvements in the performance of electronic dispersion post-compensation enabled by beating interference compensation were experimentally demonstrated in a 112 Gb/s/λ WDM Nyquist-subcarrier modulation direct-detection system in transmission over distances up to 240 km.
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1. Introduction

Single-polarization direct-detection (DD) systems using cost-effective transceiver architectures may be favorable for metropolitan, back-haul, access and inter-data center applications. In such systems, single-sideband (SSB) QAM Nyquist-subcarrier modulation (Nyquist-SCM) has been shown to be an attractive signaling scheme to achieve high spectral efficiency (SE) (≥2 b/s/Hz) [1]. For cost reasons, it is preferable to compensate the accumulated chromatic dispersion along the fiber digitally, referred to as electronic dispersion compensation (EDC), rather than employing optical methods such as dispersion compensating fiber (DCF). Previously demonstrated DD SSB Nyquist-SCM systems utilized transmitter-based EDC (Tx-EDC) [1-3] because the nonlinearity due to square-law detection, known as signal-signal beating interference (SSBI), significantly impairs the effectiveness of receiver-based EDC (Rx-EDC). On the other hand, the drawback of Tx-EDC is that it requires prior knowledge of link dispersion at the transmitter, and therefore, requires feedback from the receiver. With the development of effective SSBI compensation techniques [4-6], the channel can be linearized, consequently improving the performance of Rx-EDC.

In this paper, we investigate, for the first time, the performance improvement of Rx-EDC in the presence of SSBI compensation. The experiments were performed on a WDM DD SSB 16-QAM Nyquist-SCM system, operating at 112 Gb/s per channel. Its performance was experimentally assessed over transmission distances of up to 240 km, and compared with that of Tx-EDC. Experimental results indicate that Rx-EDC can achieve similar performance compared to Tx-EDC if an effective SSBI compensation technique, such as our recently proposed two-stage linearization scheme described in [5], is performed prior to dispersion compensation at the receiver.

2. EDC Combined with SSBI Mitigation Technique in DD Systems

To assess the effectiveness of applying Rx-EDC combined with SSBI compensation, the two DD systems using Tx-EDC and Rx-EDC combined with SSBI cancellation technique were considered, as shown in Figs. 1(a) and 1(b).

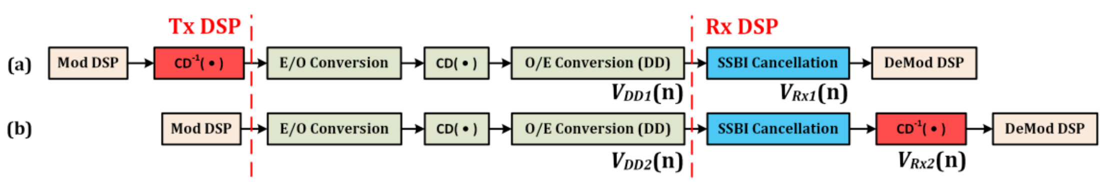


Fig. 1: DD system diagram with (a) Tx-EDC and (b) Rx-EDC combined with SSBI cancellation. Mod & Demod DSP: Modulation and demodulation DSP for SSB Nyquist-SCM signal.

For the first configuration, following the modulation DSP to generate the SSB QAM Nyquist-SCM signal $E_0(n)$, Tx-EDC is performed to mitigate the dispersion, as shown in Fig. 1(a). After transmission over the fiber followed by square-law detection, the detected signal $V_{DD1}(n)$ can be written as follows:

$$V_{DD1}(n) = \left|H_{CD}\left(E_{carrier} + H_{CD}^{-1}(E_0(n))\right)\right|^2 = E_{carrier}^2 + 2Re[E_{carrier} \cdot E_0(n)] + |E_0(n)|^2, \quad (1)$$

where $H_{CD}(\bullet)$ and $H_{CD}^{-1}(\bullet)$ are the operators representing the effects of dispersion and EDC, respectively, and $Re[x]$ signifies the real part of x. In the RHS of Eq. (1), the first term is simply the direct current (DC), the second term is the desired carrier-signal beating products (CSBP) and the third one is the SSBI. The third term can be removed by utilizing the SSBI mitigation scheme. Consequently, the signal before the demodulation DSP, $V_{Rx1}(n)$, which only includes the DC and desired CSBP terms, can be written as follows:

$$V_{Rx1}(n) \approx E_{carrier}^2 + 2Re[E_{carrier} \cdot E_0(n)]. \quad (2)$$

For the configuration shown in Fig. 1(b), if Tx-EDC is not performed, the detected signal $V_{DD2}(n)$ becomes:

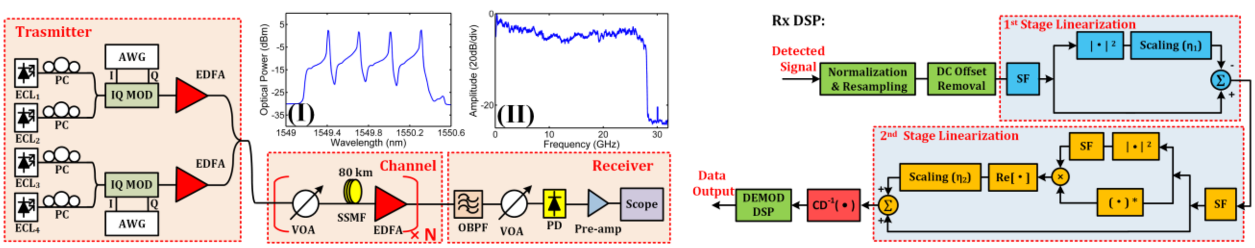
$$V_{DD2}(n) = E_{carrier}^2 + 2Re\left[E_{carrier} \cdot H_{CD}\left(E_0(n)\right)\right] + \left|H_{CD}\left(E_0(n)\right)\right|^2. \quad (3)$$

In contrast to Eq. (1), it can be seen that the second and third terms become the beating products between the dispersed signal with the optical carrier and with itself, respectively. If Rx-EDC is used without removing the beating interference, the extra distortion in the third term $H_{CD}^{-1}|H_{CD}(E_0(n))|^2$ prevents the EDC from recovering the undispersed signal waveform. Therefore, it reduces the performance of Rx-EDC compared to Tx-EDC. Assuming the third term can be removed almost completely by performing SSBI compensation followed by Rx-EDC, the signal before the demodulation DSP $V_{Rx2}(n)$ is written as:

$$V_{Rx2}(n) \approx H_{CD}^{-1}\left(E_{carrier}^2 + 2Re\left[E_{carrier} \cdot H_{CD}\left(E_0(n)\right)\right]\right) \approx E_{carrier}^2 + 2Re[E_{carrier} \cdot E_0(n)]. \quad (4)$$

The Rx-EDC can achieve similar performance with Tx-EDC, as can be seen by comparing Eq. (2) and Eq. (4). Therefore, it can be concluded that the performance of Rx-EDC depends on the effectiveness of the utilized beating interference compensation.

3. Experimental Setup



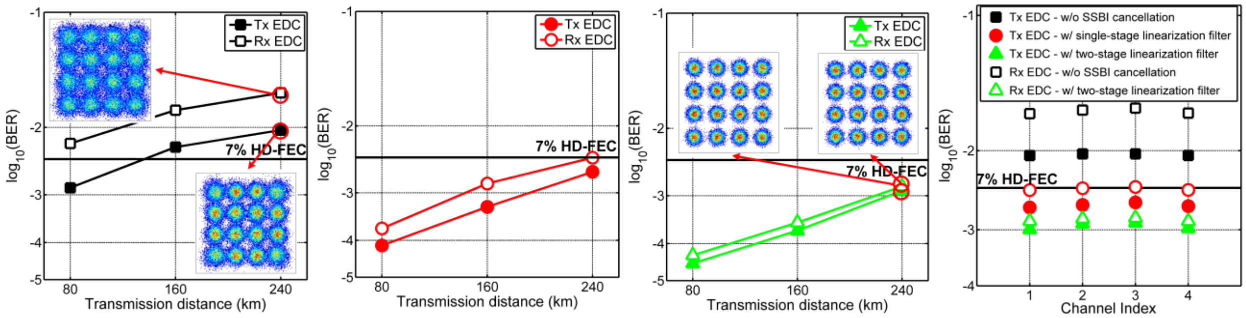
(a) (b)

Fig. 2: (a) Optical transmission experimental test-bed. Inset: (I) Experimental WDM and (II) detected digital spectra. ECL: External cavity laser. PC: Polarization controller. AWG: Arbitrary waveform generator. EDFA: Erbium-doped fiber amplifier. VOA: Variable optical attenuator. SSMF: Standard single-mode fiber. OBPF: Optical band-pass filter. PD: Photodiode. (b) Receiver DSP including two-stage linearization filter and Rx-EDC. MOD & DEMOD DSP: Conventional modulation and demodulation DSP for SSB Nyquist-SCM signal. SF: Sideband filter.

The performance of Rx-EDC was experimentally evaluated using the optical test-bed, shown in Fig. 2(a). Odd and even channels were generated using two IQ-modulators, which were driven by two arbitrary waveform generators (AWGs), operating at 92 GSa/s sampling rate and 33 GHz 3-dB bandwidth. In the transmitter DSP performed using Matlab, 28 GBaud (112 Gb/s) SSB 16-QAM Nyquist-SCM signals were generated using a subcarrier frequency of 14.28 GHz (0.51 × symbol rate) and Nyquist pulse-shaping (root-raised-cosine) filters with a roll-off factor of 0.01. Four WDM channels were transmitted, with the channel spacing set to 37.5 GHz, giving a net information spectral density of 2.8 b/s/Hz, assuming a 7% FEC overhead. The optical carrier-to-signal power ratio (CSPR) value was optimized at each value of optical signal-to-noise ratio (OSNR) to achieve the optimum system performance.

Transmission experiments were performed employing a straight-line multiple span fiber link with 80 km span length using standard single-mode fiber (SSMF) and erbium-doped fiber amplifiers (EDFAs) with 5 dB noise figure. At the receiver, the channel of interest was demultiplexed using an optical band-pass filter with a 3-dB bandwidth of 31 GHz, and subsequently, detected using a single-ended PIN photodiode followed by a single ADC, operating at 80 GSa/s. Before performing the Rx-EDC, the beating interference compensation technique utilizing a two-stage linearization filter [5] was applied. It consists of two stages: The first stage is the same as the single-stage linearization filter [4]. The second stage removes the majority of the unwanted beating interference introduced by the first stage, and consequently, further improves the compensation performance, making the technique effective and relatively simple. The performance of the Rx-EDC was compared with Tx-EDC in the cases of performing no SSBI compensation, and when applying the single-stage filter [4] and the two-stage linearization filter [5].

4. Experimental Results



(a) (b) (c) (d)

Fig. 3: BER vs transmission distance with Tx-EDC and Rx-EDC (a) without beating interference mitigation, (b) with single-stage linearization filter, and (c) with two-stage linearization filter. Fig. 3(a) insets: Received constellations with Rx-EDC (EVM = 23.0%) and Tx-EDC (EVM = 21.0%)). Fig. 3(c) insets: Received constellations with Rx-EDC (EVM = 15.7%) and Tx-EDC (EVM = 15.4%)). (d) BERs for each channel after 240 km transmission.

The system performance is shown through plots of the BER at the optimum launch power versus transmission distance (Fig. 3), for the cases without beating interference mitigation (a), with the single-stage linearization filter (b) and with the two-stage linearization filter (c). The CSPR value was swept from 9 dB to 12 dB, and adjusted at each transmission distance to achieve the optimum system performance. Without SSBI compensation, significant performance differences can be observed between the Rx-EDC and Tx-EDC (Fig. 3(a)). From 80 km to 240 km transmission, the BER increased from 6.3×10^{-3} to 2.4×10^{-2} for Rx-EDC whereas a much lower BER was obtained for Tx-EDC (from 1.3×10^{-3} to 9.3×10^{-3}). With the single-stage linearization filter applied, the BERs were reduced and also the performance difference between Rx-EDC and Tx-EDC was reduced. From 80km to 240 km, the BER increased from 1.9×10^{-4} to 4.0×10^{-3} for Rx-EDC and from 7.5×10^{-5} to 2.1×10^{-3} for Tx-EDC, in which the BERs were approximately halved. In the case of the two-stage linearization filter, further improvement of BERs can be achieved and Rx-EDC and Tx-EDC showed very similar performance. From 80 km to 240 km, the BER reduced from 4.8×10^{-5} to 1.5×10^{-3} for Rx-EDC and from 3.4×10^{-5} to 1.2×10^{-3} for Tx-EDC, which is marginally lower. The slight difference in BERs shown in Fig. 3(c) is mainly due to the residual uncompensated beating terms introduced by the second-stage. Similar performance improvements shown in Fig. 3(a-c) were observed for all the WDM channels over a transmission distance of 240 km, as shown in Fig. 3(d), at the net SE is 2.8 b/s/Hz.

5. Conclusions

We reported the performance improvement of receiver-based electronic dispersion compensation using two low-complexity signal-signal beating interference compensation techniques in direct-detection links. The performance of Rx-EDC was experimentally assessed in a 4×112 Gb/s WDM SSB 16-QAM Nyquist-SCM DD system over up to 240 km transmission with a 2.8 b/s/Hz net SE. Rx-EDC performance was compared with the performance of Tx-EDC in the cases without and with different beating interference compensation techniques. With effective two-stage linearization filter, the two EDC schemes offered very similar performance. To the best of our knowledge, this is the first experimental implementation of Rx-EDC combined with digital SSBI compensation in DD SSB Nyquist-SCM system, which simplifies the system since knowledge of link dispersion is not required at the transmitter. Due to the reduction in complexity, the proposed solution increases the suitability of WDM DD SSB Nyquist-SCM signaling for applications such as metro networks, back-haul, access and inter-data center links.

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6. References

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