Novel Optical Field Reconstruction for IM/DD with Receiver Bandwidth Well Below Full Optical Signal Bandwidth

Qian Hu, Robert Borkowski, Mathieu Chagnon, Karsten Schuh, Fred Buchali, Henning Bülow
Nokia Bell Labs, Lorenzstr. 10, 70435 Stuttgart, Germany
qian.hu@nokia-bell-labs.com

Abstract: We propose a novel signal reception scheme for IM/DD enabling optical field reconstruction. We experimentally demonstrate 60-GBd PAM-4 transmission over 80-km without active and passive optical managements, with 33-GHz electrical bandwidth at transmitter and receiver. © 2020 The Author(s)

1. Introduction

Intensity modulation/direct detection (IM/DD) systems are characterized by their low cost and easy implementation. Nonetheless, the detrimental power fading effect severely limits their applicability in scenarios requiring high bandwidth-distance product [1], such as inter-data center interconnects (inter-DCIs), where hundreds of Gb/s need to be transported over distances ranging from 10 to 80 km. With conventional IM/DD systems, the transmission distance is limited to a few km at most for symbol rates on the order of 100 Gbaud [2], and even below 1 km at 180 Gbaud [3], assuming no optical chromatic dispersion (CD) compensation. The power fading induced penalty can be eliminated using coherent detection, albeit with a higher cost, footprint and power consumption. Alternatively, schemes based on single-sideband (SSB) modulation have been studied to enable optical field reconstruction via digital signal processing (DSP) while using a single-ended photodiode. The DD induced signal-signal beating interference (SSBI) can be mitigated through iterative SSBI estimation [4] or Kramers-Kronig (KK) relation [5]. However, generating an SSB signal is cumbersome. An IQ modulator can be used to generate an analytic SSB signal directly in the optical domain, which requires 2 digital-to-analog converters (DACs) and 2 driver amplifiers [6]. A transmitter based on a single DAC and a single-drive Mach-Zehnder modulator (MZM) can also be employed, followed by an optical filter to generate an SSB signal by suppressing one spectral side [7]. However, the need of a precise frequency alignment increases the system cost and wavelength sensitivity, making this solution impractical from a commercial standpoint. All techniques relying on SSB modulation and DD reported so far require a receiver bandwidth that is equal to, or larger than, the full optical bandwidth of the signal.

In this paper, we propose novel receiver DSP for IM/DD systems. It is the first DD-based optical field reconstruction scheme which allows to reduce the required receiver bandwidth to a value well below the full optical bandwidth of the signal. The proposed scheme benefits from the following properties: (1) only a single DAC is required at the transmitter, generating a real-value double-sideband (DSB) signal from an intensity modulator;

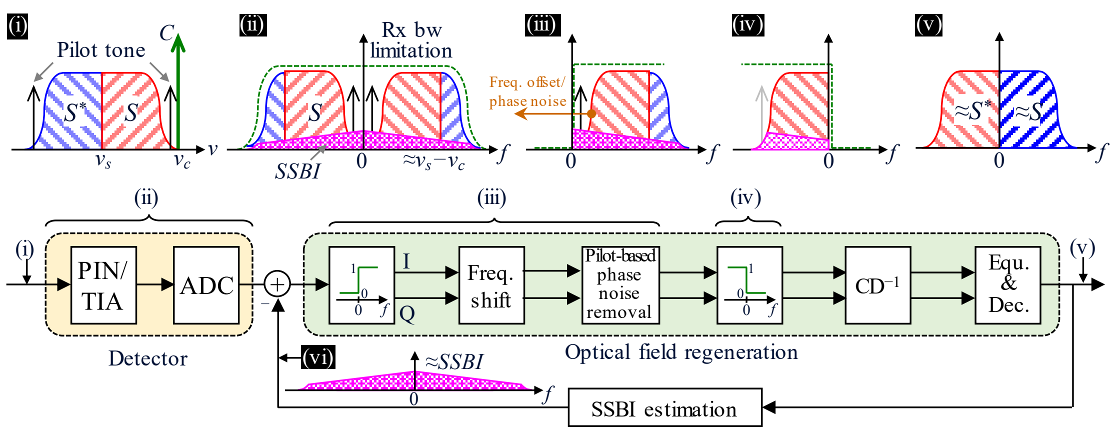

Fig. 1. Schematic diagram of the proposed scheme. (i) Optical spectrum of the transmitted signal. *S*: optical signal; *C*: optical carrier; ν_c: carrier optical frequency; ν_s: optical signal center frequency. (ii) Photocurrent spectrum at the input of the DSP chain. (iii) Spectrum of the analytic signal before frequency offset compensation and phase noise removal. (iv) Spectrum of the SSB baseband signal after upper sideband removal, subsequently used for CD compensation and equalization. (v) Spectrum of the signal after equalization and decision. (vi) Estimated SSBI subtracted from the received signal.

(2) no optical filter is required to alter the optical signal before the detection; (3) a receiver bandwidth only slightly larger than half of the full optical bandwidth is required. Based on the proposed scheme, we demonstrate 60 GBd PAM-4 transmission over 80 km fiber using a transmitter and receiver of only 33 GHz electrical bandwidth. Neither optical filtering, optical amplification, nor optical CD compensation is applied in the system.

2. Proposed Scheme

The proposed scheme is illustrated in Fig. 1. An optical carrier from a free-running laser is added next to the optical signal coming out of an intensity modulator fed with a real-valued signal, exhibiting spectral Hermitian symmetry. A schematic of the transmitted optical signal is depicted in Fig. 1(i). A pilot tone is added to the transmitted signal to assist subsequent frequency offset compensation and phase noise mitigation stages in receiver DSP. At the receiver, the signal is detected with a single-ended photodetector followed by an ADC. A receiver of 3-dB bandwidth slightly larger than that of the transmitter is used. During the signal reception, a portion of the signal spectrum is filtered out by the receiver bandwidth, leaving only a vestigial part of the signal spectrum, as shown in Fig. 1(ii). The required receiver bandwidth is roughly a factor of 2 smaller than that for KK-based DSP. To reconstruct the transmitted optical field, a sequence of DSP steps is applied. First, a complex-valued representation of the received signal is obtained by adding to the received signal its Hilbert transform as the imaginary part, to suppress negative frequency components. The resulting transfer function is represented by the green dashed line in Fig. 1(iii). This analytic signal is then spectrally shifted by the optical frequency difference between the two free-running lasers. The phase noise is mitigated using the pilot tone. Next, another Hilbert transform is applied, this time suppressing positive frequency components, as depicted by the green dashed transfer function in Fig. 1(iv). CD compensation and equalization are applied on the resulting analytic signal, which is polluted by SSBI. An estimation of the transmitted signal in baseband is given by taking the real part of the equalized signal, as demonstrated in Fig. 1(v). The SSBI can be mitigated iteratively through a feedback loop as follows. CD from the fiber link is added to the estimation of the transmitted signal, from which SSBI is computed and filtered to mimic the low-pass filtering of the receiver analog front-end, as in Fig. 1(vi). The resulting signal is subtracted from the received signal. Finally, all DSP steps outlined above, applied to the initial received signal, are repeated for the new signal with less SSBI.

3. Experiment

The proposed scheme is demonstrated using the experimental setup shown in Fig. 2. At the transmitter, two independent laser sources are used for the optical signal and carrier respectively. Raised-cosine-shaped (roll-off 0.05) PAM-4 signal at 60 GBd is generated using an 88 GS/s digital-to-analog converter. A 31 GHz sine wave is added to the signal digitally as a pilot tone to assist the frequency and phase recovery. The generated electrical signal is amplified by a driver amplifier and fed into an MZM biased at null. The modulated optical signal is then combined with the optical carrier originating from the other free-running laser source via an optical coupler. The carrier wavelength is tuned to the vicinity of the pilot tone, as shown in Fig. 2(i). After transmission over different lengths of standard single mode fiber (SSMF), the optical signal is detected using a p-i-n photodiode integrated with an AC-coupled transimpedance amplifier (PIN-TIA). The detected signal is then real-time sampled by an ADC at 80 GS/s for offline DSP. Due to the bandwidth limitation of the ADC, the spectrum of the received signal is cut sharply at 33 GHz, as shown in Fig. 2(ii), blocking the information from one sideband of the transmitted signal. The transmitted signal is recovered following the DSP stack detailed in the previous section, which is operated at 2 samples per symbol (120 GSamples/s). Only one iteration of SSBI estimation is implemented to avoid a high complexity of DSP.

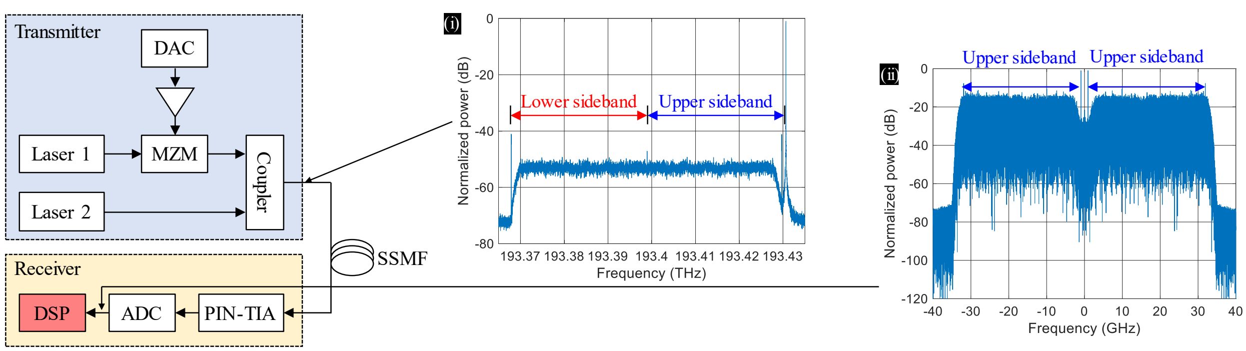

Fig. 2. Experimental setup used to evaluate the proposed scheme. (i) Optical spectrum measured at the output of the transmitter. (ii) Photocurrent spectrum at the receiver.

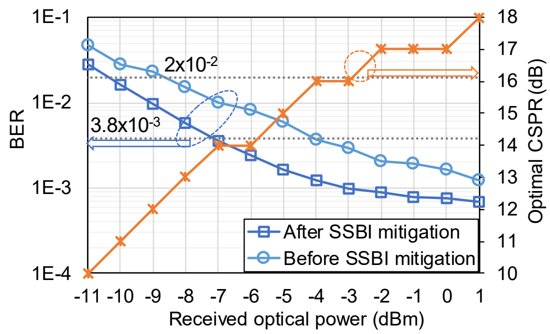

Fig. 3. Optimal CSPR and corresponding performance measured at various received powers in back-to-back configuration.

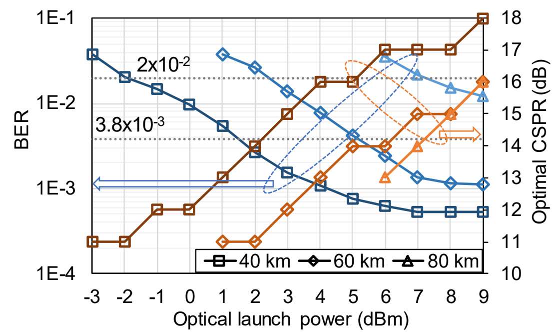

Fig. 4. Optimal CSPR and corresponding performance after SSBI mitigation measured at various optical launch powers for 40 km, 60 km and 80 km transmission.

4. Results

The performance is first measured in back-to-back (BtB) configuration at various received optical powers (including both signal and carrier power). Various carrier-to-signal power ratios (CSPRs) are achieved by adjusting the output power of two laser sources. The CSPR that provides the best performance after one iteration of SSBI mitigation is recorded as the optimal CSPR. Fig. 3 shows the optimal CSPR at different received optical power and the corresponding BER measured before and after SSBI mitigation. The optimal CSPR increases and the performance improves when increasing the received optical power. The best performance is obtained at the received optical power of 1 dBm, achieving a BER of 6.9×10^{-4}. Performance at higher received optical power is not measured, constrained by the maximum input power of the PIN-TIA. To achieve a BER below 3.8×10^{-3} and 2×10^{-2}, received optical power higher than −7 dBm and −10 dBm is required respectively.

Measurements are then conducted for transmissions over 40 km, 60 km and 80 km SSMF. For different transmission distances, the optimal CSPR and the corresponding BER after the SSBI mitigation are shown in Fig. 4, as a function of the optical launch power. The stimulated Brillouin backscattering occurs when the optical launch power exceeds 9 dBm, which places a constraint on the maximum optical launch power. For a given transmission distance, higher optical launch power results in higher received optical power, which leads to a decrease of the BER accompanied by an increase of the optimal CSPR. After 40 km transmission, the best performance is obtained at the optical launch power of 7 dBm, achieving a BER of 5.3×10^{-4}, which is slightly lower than the lowest BER achieved in BtB configuration. Such improvement comes from the SSBI mitigation, where the CD of 40 km fiber is added to the estimation of the transmitted signal. The CD-induced signal-pulse broadening helps to reduce the impact of errors in the estimation. For 80 km transmission, better performance is expected if the CSPR can be further decreased for given optical launch power, which is prevented by the limited signal power in this experiment. As shown in Fig. 4, a BER below 3.8×10^{-3} is achieved for 40 km and 60 km transmissions with optical launch power of 2 dBm and 6 dBm respectively. A BER below 2×10^{-2} can be achieved for all distances, requiring optical launch power of −1 dBm, 3 dBm and 8 dBm for 40 km, 60 km and 80 km transmissions respectively.

5. Conclusion

We proposed a new receiver DSP scheme for IM/DD systems, which enables optical field reconstruction with a receiver bandwidth only slightly larger than half of the full optical spectral width. With 33 GHz receiver bandwidth, we reconstruct the optical field of 60 GBd PAM-4 signal. The signal is successfully transmitted over 80 km SSMF, achieving a BER below 2×10^{-2}. No active or passive optical management has been applied in the system.

6. References

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