Modified KK Receiver with Accurate Field Reconstruction at Low CSPR Condition

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Abstract: A modified KK receiver based on an exponential operation is proposed to accurately reconstruct the field at a low CSPR in a DD system. We experimentally demonstrate a 2-dB sensitivity improvement after 40-km SMF transmission.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation.

1. Introduction

Driven by the emerging broadband applications such as cloud computing and high definition 4K/8K video, capacity demands in data center interconnection (DCI) and fifth generation (5G) mobile fronthaul are growing rapidly [1]. To support the traffic growth in such scenarios, optical transceivers with low costs and high capacities are desired. Compared to coherent systems, direct detection (DD) systems are preferred due to their low costs and low power consumptions. Many DD systems employing various advanced modulation formats were proposed and experimentally demonstrated [2-4]. Among these systems, single-sideband (SSB) self-coherent detection (SCD) based on Kramers-Kronig (KK) field reconstruction algorithm is a promising solution [2], owing to its high spectral efficiency and good performance in signal-signal beating interference (SSBI) cancellation. In this scheme, a carrier at the edge of the signal spectrum co-propagates with the information bearing signal. The carrier should be large enough to meet the minimum phase condition (MPC), thus the phase of the SSB signal can be retrieved accurately according to the KK relation [5]. However, the relatively large carrier leads to a high carrier to signal power ratio (CSPR), thus limits the power efficiency and increases the nonlinear effects. In order to reduce the required minimum CSPR in SCD systems based on KK algorithm, an enhanced KK receiver was proposed and a 3-dB lower CSPR was achieved [6]. Comparisons between the KK algorithm and other SSBI cancellation algorithms were also investigated at low CSPRs [3,4,7].

In this paper, a novel field reconstruction scheme is proposed and experimentally demonstrated in an SSB SCD system. In a conventional KK SCD system, a direct current (DC) is simply added to the complex SSB signal to meet the MPC, leading to a relatively high required minimum CSPR [5]. In our proposed scheme, an exponential operation is applied to the complex SSB signal, thus the MPC is inherently satisfied even at a low CSPR. The accurate field reconstruction can therefore be achieved, enabling the direct detection of the complex signal. As a proof-of-concept experiment, a 30.78-Gb/s virtual carrier (VC)-assisted SSB discrete multitone (DMT) signal is successfully transmitted over a 40-km single mode fiber (SMF). A significant bit error rate (BER) reduction is observed based on the proposed scheme, under the condition that the system performance is limited by the accuracy of the field reconstruction. This shows that the proposed scheme is a promising solution for applications requiring high optical signal to noise ratios (OSNRs) to ensure high BER performances, such as in the 5G mobile fronthaul, where the transmitted signal is narrow-band but sensitive to noise and distortions [8].

2. Operation principle

The digital signal processing (DSP) block diagrams of the conventional KK scheme and the proposed modified KK scheme are shown in Fig. 1(a) and (b), respectively. In the conventional KK scheme, a large VC located at –B/2 is added to meet the MPC at the transmitter, where B denotes the valid bandwidth of a quadrature amplitude modulation (QAM) signal. The VC can be regarded as a DC item added to a complex SSB signal, which biases the SSB signal off the origin in the complex plane. The MPC is satisfied when the time trajectory of the SSB signal does not encircle the origin, thus requiring a large VC and a high CSPR. In this case, the phase of the SSB signal can be retrieved accurately according to the KK relation at the receiver [5]. However, at a low CSPR, e.g. 3 dB, the MPC is not satisfied, as shown in inset (i). The time trajectory of the reconstructed QAM signal is therefore distorted compared to that of the original QAM signal, as depicted in inset (ii). Different from the conventional scheme, an exponential operation is applied to the SSB signal in our proposed scheme, which is obtained by up-converting the baseband QAM signal. Thus, the generated signal is still an SSB signal, but it is inherently ensured that the time trajectory does not encircle the origin. The MPC is therefore satisfied even at a low 3-dB CSPR, as shown in inset (iii). After down-converted to baseband, the generated SSB signal can be sent into the channel. At the receiver, the field can be reconstructed from the detected signal intensity, after a square-root operation, a logarithm operation and an SSB filter. The accurately reconstructed QAM signal at the 3-dB CSPR is depicted in inset (iv).

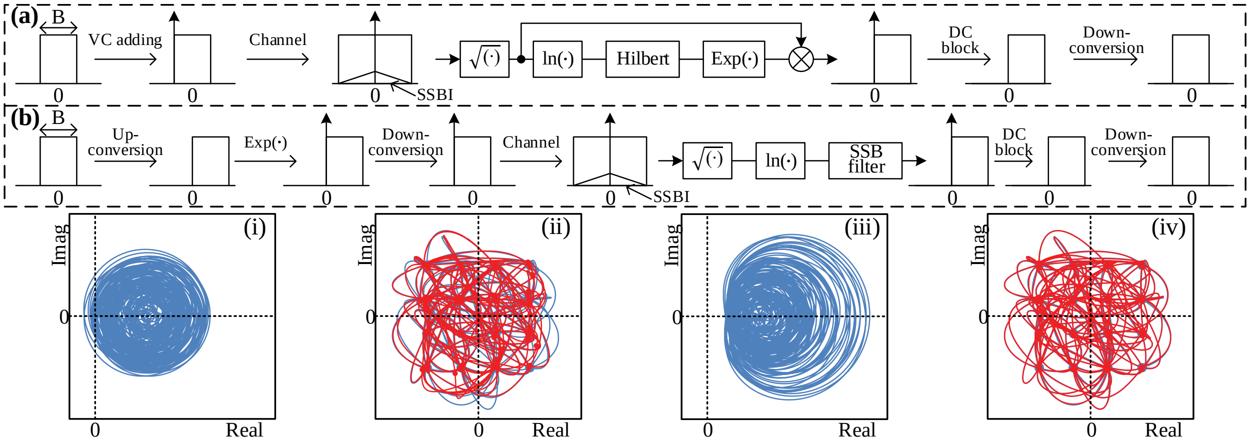

Fig. 1. DSP block diagrams of the conventional KK scheme (a) and the proposed modified KK scheme (b), respectively. (i) Time trajectory of the conventional SSB signal at a 3-dB CSPR. (ii) Time trajectory of the original QAM signal (blue line) and that of the reconstructed QAM signal (red line) with the conventional scheme at a 3-dB CSPR. (iii) Same as (i), but with the proposed scheme. (iv) Same as (ii), but with the proposed scheme. The blue and red dots are the original and reconstructed symbols, respectively.

3. Experimental setup and results

Fig. 2 shows the experimental setup, with DSP flow charts depicted in insets (i-iv). The in-phase and quadrature (IQ) parts of a DMT signal are output by two channels of a 56-GSa/s arbitrary waveform generator (AWG) (Keysight M8195A). After amplified by two electrical amplifiers (EAs), the two signals are used to drive a 22-GHz IQ modulator (IQM). A continuous wave light from a 1550-nm distributed feedback (DFB) laser is fed into the IQM biased at the null point. After electrical-to-optical (E/O) conversion, the optical signal is boosted by an erbium-doped fiber amplifier (EDFA) before launched into a 40-km SMF. At the receiver, the received optical signal is firstly amplified by an EDFA and then filtered by a 1-nm optical bandpass filter (OBPF). Followed by a 40-GHz alternating current (AC)-coupled PD, an 80-GSa/s digital storage oscilloscope (DSO) (LeCroy 36Zi-A) is utilized to capture the signal. In the experiment, 160 subcarriers of the DMT signal in the center frequency are loaded with 16QAM symbols among the total 1024 subcarriers, while the DC is set to be null. A VC located at the left side of the valid subcarriers is generated for the two schemes, with a 2-subcarrier guard band. The guard band is used to mitigate the superposition between the valid subcarriers and the sidelobe after DD [2]. A relatively low ~8.76-GHz bandwidth is employed to avoid distortions, enabling us to precisely investigate the influence of the reconstruction accuracy on the BER performance. A zeros-padding scheme is also proposed to avoid the use of a DC-coupled PD, with only 0.07% overhead. By padding zeros before the payload signal samples, the desired DC item is estimated at the receiver. Thus a DC signal is obtained after adding the estimated DC item to the detected AC signal, following the field reconstruction algorithm.

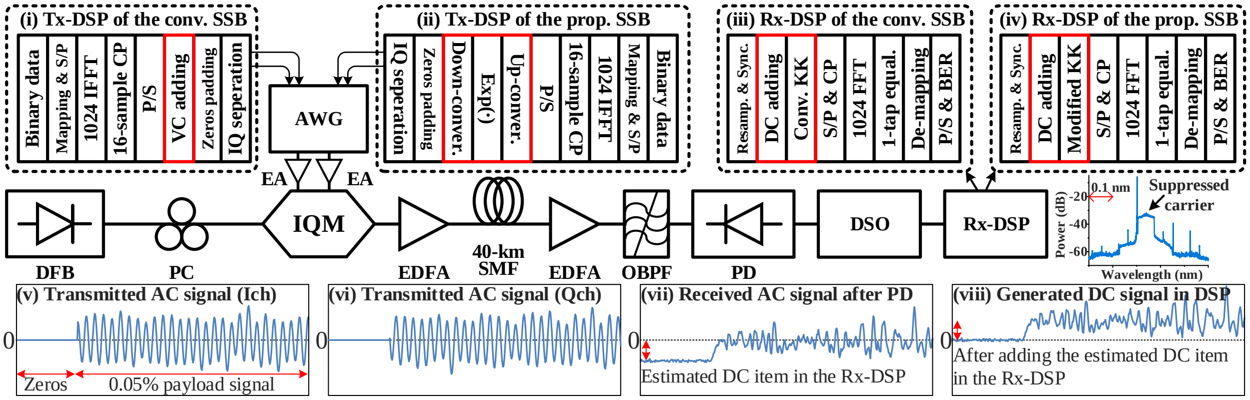

Fig. 2 Experimental setup with the proposed SSB spectrum after IQM at a 10-dB CSPR. (i-iv) DSP flow charts at the transmitter and receiver for the investigated two schemes, respectively. (v-viii) Signal waveforms at different stages respectively. S/P: serial-to-parallel; CP: cyclic prefix.

The experimental results in the optical back-to-back (OBTB) case and after 40-km SMF transmission are provided in Fig. 3 and Fig. 4, respectively. In the back-to-back case, we firstly optimize the CSPR at a constant –8-dBm optical received power. In Fig. 3(a), an optimum 12-dB CSPR is observed for the conventional SSB scheme, while the optimum CSPR for the proposed SSB scheme is 10 dB, leading to a 2-dB reduction. The reduction of the optimum CSPR is attributed to the better field reconstruction accuracy of the proposed SSB scheme, owing to the satisfied MPC at the transmitter. When the CSPR is higher than the optimum value, BER degrades with the increase of the CSPR. This is mainly due to the increased quantization noise with the limited effective number of bits (ENOB) of the DACs. Moreover, in the case of low CSPRs, decreasing the CSPR also degrades the BER performance, due to the violation of the MPC. After the optimization of the CSPR, BER curves are measured at 6-dB, 8-dB and 10-dB CSPRs respectively, as shown in Fig. 3(b-d). For the conventional SSB scheme, BERs converge to relatively higher error floors at both the three CSPRs, compared to the cases of the proposed SSB scheme. At the 6-dB CSPR, the 7% forward error correction (FEC) threshold cannot be reached due to the violation of the MPC. However, a BER lower than 3.8×10^{-3} is achieved with the proposed SSB scheme. We further note that the BER reduction brought by the proposed scheme is more effective with the decrease of the CSPR in the back-to-back case. This fact is consistent with the principle that the proposed SSB scheme enables higher field reconstruction accuracy compared to the conventional SSB scheme, while the field reconstruction accuracy is a main limitation at low CSPRs. In Fig. 4(a), the CSPR optimization is also performed after 40-km fiber transmission at a constant –4-dBm optical received power, with a same 12-dB optimum CSPR for both the conventional scheme and the proposed scheme. We attribute this to the violation of the MPC for the proposed SSB signal, due to the increased PAPR during the transmission in the chromatic dispersion (CD) channel [3]. Although the MPC is satisfied at the transmitter, the generated high peaks induced by CD have a detrimental influence on the MPC, leading to a degraded BER performance at the receiver. BER curves at different CSPRs are also plotted in Fig. 4(b-d). At the optimum 12-dB CSPR, a 2-dB sensitivity improvement is achieved, with a BER reduction from 1.6×10^{-3} to 7.7×10^{-4} at the –4-dBm optical received power.

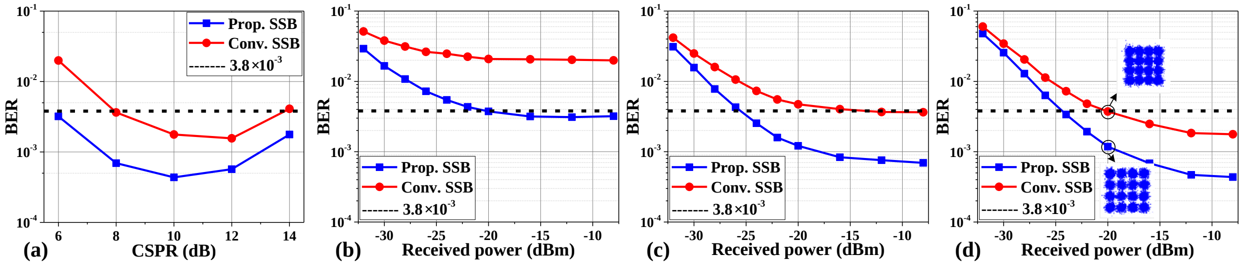

Fig. 3. (a) CSPR optimization in the OBTB case. (b-d) BER curves at the 6-dB, 8-dB and 10-dB CSPRs, respectively.

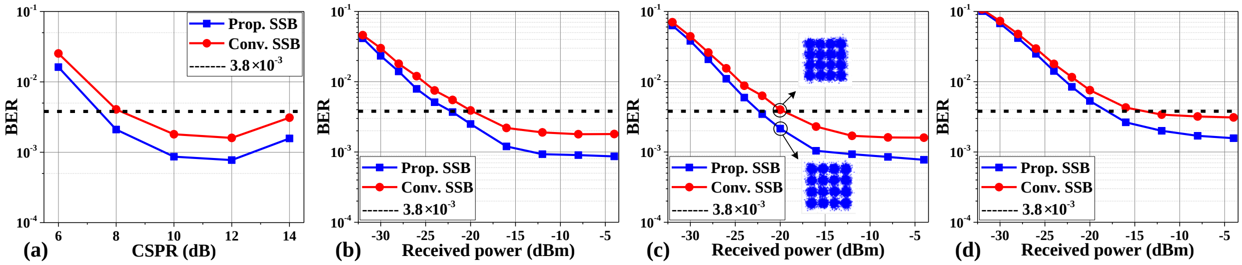

Fig. 4. (a) CSPR optimization after 40-km SMF transmission. (b-d) BER curves at the 10-dB, 12-dB and 14-dB CSPRs, respectively.

4. Conclusion

We proposed and experimentally demonstrated a novel modified KK receiver to accurately reconstruct the field at the low CSPR condition. By applying an exponential operation to an SSB signal, the MPC is inherently satisfied. The experimental results show a 2-dB sensitivity improvement after 40-km SMF transmission in a DD system.

5. Reference

[1] Cisco Global Cloud Index: Forecast and Methodology, 2016–2021.

[2] X. Chen, C. Antonelli, S. Chandrasekhar, G. Raybon, A. Mecozzi, M. Shtaif, and P. Winzer, "Kramers–Kronig Receivers for 100-km Datacenter Interconnects," J. Lightwave Technol. **36**, 79-89 (2018).

[3] S. Le, K. Schuh, M. Chagnon, F. Buchali, R. Dischler, V. Aref, H. Buelow, and K. Engenhardt, "1.72-Tb/s Virtual-Carrier-Assisted Direct-Detection Transmission Over 200 km," J. Lightwave Technol. **36**, 1347-1353 (2018).

[4] Z. Li, M. Sezer Erkılınç, K. Shi, E. Sillekens, L. Galdino, T. Xu, B. Thomsen, P. Bayvel, and R. Killey, "Digital Linearization of Direct-Detection Transceivers for Spectrally Efficient 100 Gb/s/λ WDM Metro Networking," J. Lightwave Technol. **36**, 27-36 (2018).

[5] A. Mecozzi, C. Antonelli, and M. Shtaif, "Kramers–Kronig coherent receiver," Optica **3**, 1220-1227 (2016).

[6] L. Blech, Y. Eldar, C. Antonelli, A. Mecozzi, and M. Shtaif, "The Enhanced Kramers Kronig Receiver," in Proc. OFC, Tu2D.7, (2018).

[7] C. Sun, D. Che, and W. Shieh, "Comparison of Chromatic Dispersion Sensitivity between Kramers-Kronig and SSBI Iterative Cancellation Receiver," in Proc. OFC, W4E.4, (2018).

[8] B. Kim, S. Bae, H. Kim, and Y. Chung, "Blind Compensation of Nonlinear Waveform Distortions in Radio-over-Fiber System," in Proc. OFC, Tu3J.6, (2018).