Signal-Signal Beat Noise Mitigation by Square Root Processing of the Detected Photocurrent

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Abstract: The signal-signal beat noise mitigation performances of the original received signal, the square root processed signal, and the Kramers-Kronig processed signal are experimentally compared in a 110 Gbit/s probabilistically-shaped 64 QAM direct detection system.

1. Introduction

In recent years, the cloud-based technologies have enabled collaborative data storage and processing among thousands of interconnected servers, resulting in a rapid growth of demand for data capacity in optical access and metro networks. In terms of reducing the cost and complexity of optical systems for short- and medium-reach transmissions, direct detection (DD) is preferable to coherent detection as it only requires a single-ended photodiode (PD) in the receiver side. Although DD of single sideband (SSB) signals can overcome the chromatic dispersion induced power fading effect compared to the DD of double sideband signals, the signal-signal beat noise (SSBN) that exists in the square law detection still limits the overall performance. In previous studies, many optical or digital SSBN mitigation schemes have been proposed. One can separate the signal from the carrier at the receiver side by a sharp optical filter for independent generation of the SSBN in a second PD, which can be utilized to remove SSBN in the photocurrent detected by the first PD [1]. However, the undesirable rise in system cost makes this scheme less attractive. Alternatively, by adopting a guard band as large as the signal bandwidth, the overlap between the signal and the SSBN can be avoided while the spectral efficiency is reduced by half [2]. The iterative process based SSBN pre-distortion and post-compensation schemes can be applied to reduce the required guard band at the expense of heavy computing load [3]. Recently, Kramers-Kronig (KK) detection was proposed and successfully demonstrated that the complex optical field of a SSB signal could be reconstructed by retrieving the phase information from the Hilbert transform of the logarithm of detected photocurrent once the minimum-phase condition was satisfied [4-6]. Although KK processing provides the best linearization performance among all SSBN mitigation schemes, it requires digital upsampling and Hilbert transform during the process of retrieving the phase information. By replacing the nonlinear operations, such as logarithm, with mathematical approximations, KK processing can be operated at the Nyquist sampling rate as the serious broadening of signal spectrum is avoided [7]. However, the Hilbert transform, which involves the inverse Fourier and Fourier transforms, is still inevitable in the retrieval of the phase information.

In this paper, we demonstrate that the SSBN can be mitigated by simply computing the square root (SQRT) of the detected photocurrent. The underlying principle is the SSBN resulted from the imaginary part of the shifted baseband signal is negligible when the optical carrier is strong enough. Performance comparison between the original received signal, the SQRT processed signal, and the KK processed signal is experimentally conducted in a SSB-DD system carrying 110 Gb/s probabilistically-shaped (PS) 64 QAM signal for a 100-km single mode fiber (SMF) transmission.

2. Principle

The detected photocurrent $I(t)$ for an optical SSB signal can be represented as

$$\begin{aligned} I(t) &= \left|E_0 + E_s(t)e^{j\pi Bt}\right|^2 = E_0^2 + 2E_0\Re\{E_s(t)e^{j\pi Bt}\} + |E_s(t)|^2 \\ &= E_0^2 + 2E_0\Re\{E_s(t)e^{j\pi Bt}\} + \Re\{E_s(t)e^{j\pi Bt}\}^2 + \Im\{E_s(t)e^{j\pi Bt}\}^2 \\ &= [E_0 + \Re\{E_s(t)e^{j\pi Bt}\}]^2 + \Im\{E_s(t)e^{j\pi Bt}\}^2 \qquad (1) \end{aligned}$$

where E_0, $E_s(t)$ and B represent the carrier amplitude, the complex envelope of baseband signal, and the bandwidth, respectively. The mathematical notation $\Re\{*\}$and $\Im\{*\}$ denote the real and imaginary part, respectively. By observing Eq. (1), we can find that the second term, $\Im\{E_s(t)e^{j\pi Bt}\}^2$, can be omitted if E_0 is large enough. Hence,

$$E_s(t) \approx (\sqrt{I(t)} - E_0)e^{-j\pi Bt} \qquad (2)$$

The digital upsampling is not required as the SQRT operation just broadens the signal spectrum slightly. Meanwhile, the Hilbert transform is also skipped.

3. Experimental setup and results

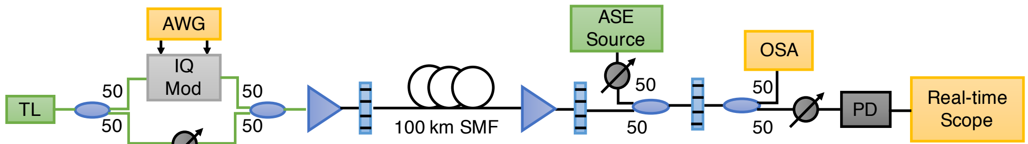

Fig. 1. Experimental setup for the SSB-DD based optical system. TL: tunable laser; AWG: arbitrary waveform generator; SMF: single mode fiber; ASE Source: amplified spontaneous emission source; OSA: optical spectrum analyzer; PD: photodiode.

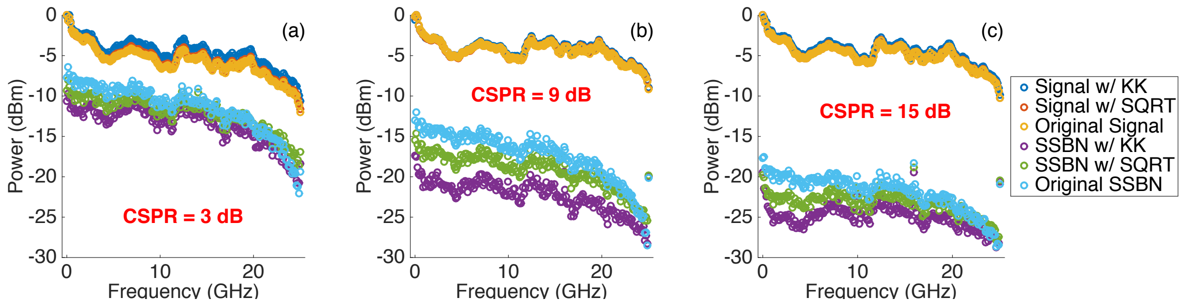

Fig. 2. Signal power and SSBN power measured from different schemes at CSPR of (a) 3 dB; (b) 9 dB and (c) 15 dB.

To evaluate the mitigation of the SSBN by SQRT processing, we build a SSB-DD optical system as shown in Fig. 1. A 1549 nm optical carrier from a tunable laser (TL) is first split into two paths. The upper path is modulated by RF signals generated from an arbitrary waveform generator (AWG) in an IQ modulator. For the lower path, the power of optical carrier is adjusted by a variable optical attenuator before it is combined with the modulated signal from the upper path. The composed SSB signal is amplified by an erbium-doped fiber amplifier (EDFA), followed by an optical filter for removing additional amplified spontaneous emission (ASE) noise before being launched into a 100-km SMF link. After transmission, an ASE source is added to vary the optical signal to noise ratio (OSNR) of the received signal, which is monitored by an optical spectrum analyzer. A single-ended PD is used to detect the incoming optical signal and the generated photocurrent is captured by a real-time oscilloscope working at 80 GSa/s.

First, we generate a specially designed OFDM signal to measure the power level of the remaining SSBN [2]. The AWG works at 64 GSa/s and the FFT size is 512. For 200 subcarriers in the upper sideband, the odd-indexed subcarriers are loaded with QPSK signals while the even-indexed subcarriers are left empty. After square law detection, the SSBN will be located at the even-indexed subcarriers. The results are shown in Fig. 2. KK processing reduces a larger amount of SSBN compared to the SQRT scheme at different carrier to signal power ratios (CSPR) as the latter scheme ignores the SSBN resulted from the imaginary part of the signals. In the low CSPR region, such as CSPR equals to 3 dB shown in Fig. 2 (a), the reduction of SSBN is not obvious since the minimum-phase condition is not satisfied for KK processing and the second term in Eq. (1) still plays a role for SQRT scheme. When the CSPR increases to 9 dB, KK processing reduces the SSBN greatly while the SQRT scheme also provides acceptable performance as shown in Fig. 2 (b). Further rise of CSPR to 15 dB makes the original SSBN closer to the noise floor, leading to a weaker degree of SSBN mitigation as shown in Fig. 2 (c), .

After verifying the effectiveness of SSBN mitigation by the SQRT processing scheme, the modulation format is changed to 20 Gbaud PS-64 QAM with 5.5 bit/symbol entropy. A line rate of 110 Gbit/s and a net rate of 90.8 Gbit/s are obtained considering a forward error correction (FEC) code rate of 0.8402 (19.02% overhead) where spatially-coupled low-density parity-check (SC-LDPC) code of code rate 0.8469 together with an outer hard-decision BCH (8191, 8126, 5) code are applied [8]. As for the digital signal processing at the receiver side, decision directed least mean square (DD-LMS) equalization is utilized to recover the constellation diagram and normalized generalized mutual information (NGMI) is selected as the evaluation metric with a threshold at 0.8798 [9]. In optical back to back scenario, we measure the performance of the received signal under three different processing schemes for CSPR ranging from 3 dB to 15 dB. The results are shown in Fig. 3 (a). As expected, the NGMI of the SQRT scheme assisted signal is slightly worse than the case of KK processed signal while significantly outperforms that of the original received signal. Compared to the performance of the original received signal, KK processing and SQRT scheme can reduce the required CSPR at NGMI threshold by 3.9 dB and 2.7 dB, respectively. Next, we fix the CSPR at 15 dB and launch the optical SSB signal into a

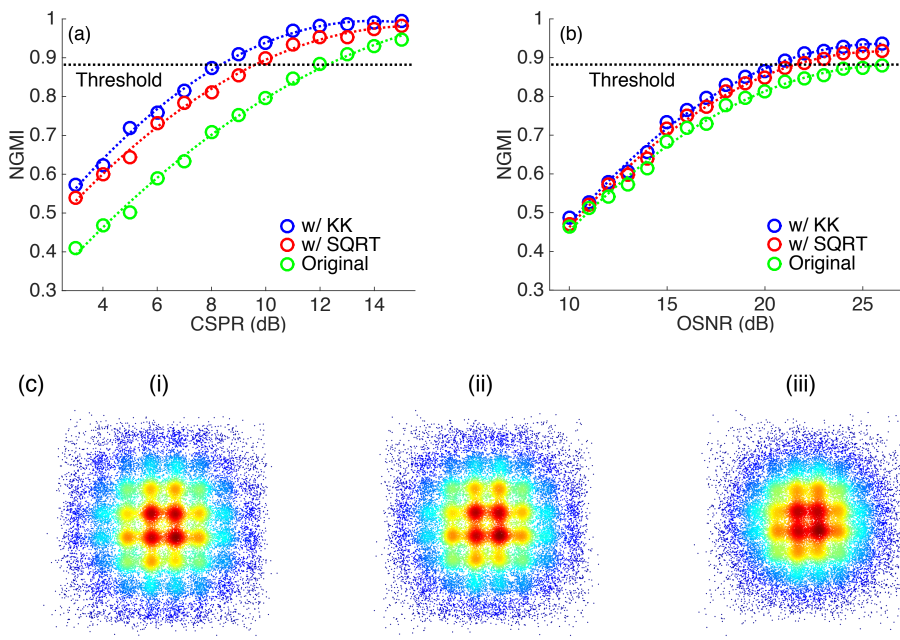

Fig. 3. (a) NGMI against CSPR in optical back to back scenario; (b) NGMI against OSNR after 100-km transmission; (c) constellation diagram (i) with KK processing (ii) with SQRT scheme (iii) with original received signal at an OSNR of 26 dB after 100-km transmission .

100-km SMF link with 9-dBm total optical power. At the receiver side, ASE noise is added to vary the OSNR from 10 dB to 26 dB. As shown in Fig. 3 (b), the NGMI improvements provided by KK processing and SQRT scheme are not obvious in low OSNR region as the ASE noise dominates over the SSBN. Further increase of OSNR leads to a more distinctive performance difference between the three signals as the SSBN mitigation begins to take effect. By setting the performance of the original received signal as the benchmark, KK processing and SQRT scheme can improve the OSNR sensitivity by 5.7 dB and 4.6 dB, respectively. Fig. 3 (c) shows the recovered constellation diagrams from different schemes at a 26-dB OSNR after 100-km transmission, which exhibits the SSBN mitigation in a more intuitive way.

4. Conclusion

In this work, we realize the mitigation of SSBN by processing the received signal with simple SQRT operation. The SQRT scheme reduces the required CSPR and OSNR by 2.7 dB and 4.6 dB respectively with reference to the performance of the original signal, while induces additional penalty compared to the KK scheme that relies on the Hilbert transform. The performance comparison is conducted in a 110 Gbit/s PS-64 QAM SSB-DD system with 100-km transmission.

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