# Low-complexity and Non-iterative SSBI Decomposition and Cancellation Algorithm for SSB Direct Detection System

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**Abstract:** We propose a low-complexity and non-iterative SSBI cancellation algorithm operating at the Nyquist sampling rate employing SSBI decomposition followed by sqrt operation, and experimentally validate it in a 58GBaud 16-QAM transmission system with 80km reach.

## 1. Introduction

To overcome the power fading effect [1], single-sideband (SSB) modulation with direct detection has emerged as a promising candidate since chromatic dispersion (CD) can be compensated in digital signal processing (DSP) at the receiver [2-7], but signal-to-signal beating interference (SSBI) generated by square-law detection and aggravated by accumulated dispersion severely limits the system performance. Recently, several innovative DSP methods are proposed including iterative SSBI cancellation (SSBI-C) [2], Kramers-Kronig detection (KK) [3], DC-Value iterative method [4], and their improved schemes [5-6]. However, the algorithms based on SSBI-C eliminate SSBI through iterative reconstruction, tending to present high latency and high computational complexity while the algorithms based on KK relation require 4~6 digital upsampling rate [6] since nonlinear operations including logarithm and exponential functions broaden the signal spectrum considerably. The upsampling-free KK receiver has been proposed to alleviate spectrum broadening through mathematical approximation at a sacrifice of performance [5]. In [7], sqrt operation (SQRT) is proposed to mitigate SSBI through omitting the imaginary part-induced SSBI, which exhibits minimal complexity but not significant SSBI suppression performance.

In this paper, we propose a low-complexity and iteration-free SSBI decomposition and cancellation algorithm (DCA) employing imaginary part-induced SSBI removal and square root operation. This algorithm can operate at the Nyquist sampling rate without extra digital upsampling or iteration, leading to reduced computational complexity compared with KK [3] and SSBIC [2]. The key idea is to use the received waveform as the real part of SSB signal to reconstruct the imaginary part by Hilbert transformation [8]. After removing the imaginary part-induced SSBI, the sqrt operation is used to suppress the SSBI of the real part. The nonlinear operations in our algorithm only include sqrt and square, which create nonlinear components outside of the signal bandwidth 10dB lower than that of logarithm and exponential operations [5]. We evaluate the performance of the proposed algorithm in a 58GBaud SSB 16QAM system. The BER after 80km transmission is $8.6\times10^{-3}$ below the threshold of 14% HD-FEC [9], leading to a net data rate of 203Gbit/s. In contrast to other algorithms, the performance and computational complexity of DCA are also analyzed. The proposed scheme effectively eliminates SSBI in an upsampling-free and iteration-less way, which is very practical to implement high-speed short-reach links.

## 2. Principle

The optical photocurrent detected by photodetector (PD) could be written as:

$$\begin{aligned} I(t) &= \left|C + S(t)e^{j\pi Bt}\right|^2 = CC^* + 2\mathrm{Re}\{C\cdot S(t)e^{j\pi Bt}\} + \left|S(t)e^{j\pi Bt}\right|^2 \\ &= CC^* + 2\mathrm{Re}\{C\cdot S(t)e^{j\pi Bt}\} + \mathrm{Re}\{S(t)e^{j\pi Bt}\}^2 + \mathrm{Im}\{S(t)e^{j\pi Bt}\}^2 \end{aligned} \tag{1}$$

Here $C$, $S(t)$ and $B$ are the optical carrier, optical signal and signal bandwidth, respectively. SQRT operation can be used to suppress real part-induced SSBI $\mathrm{Re}\{S(t)e^{j\pi Bt}\}^2$, assuming that $\mathrm{Im}\{S(t)e^{j\pi Bt}\}^2$ can be omitted. However, the SQRT method performs not well since the overall SSBI consists of both $\mathrm{Re}\{S(t)e^{j\pi Bt}\}^2$ and $\mathrm{Im}\{S(t)e^{j\pi Bt}\}^2$ with equal power. We propose to eliminate $\mathrm{Im}\{S(t)e^{j\pi Bt}\}^2$ before SQRT operation to suppress the total SSBI more accurately, which shows significant improvement in our experiment.

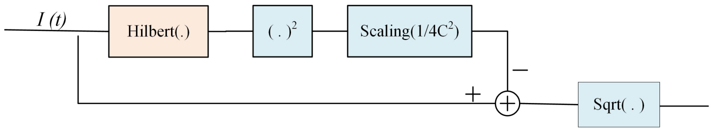


Fig. 1. The block diagram of proposed DCA.

The block diagram of the proposed DCA is shown in Fig.1. First, we reconstruct approximately $\mathrm{Im}\{S(t)e^{j\pi Bt}\}$ using original SSBI-contained $\mathrm{Re}\{S(t)e^{j\pi Bt}\}$ and Hilbert transformation as $\mathrm{Im}\{\hat{S}(t)e^{j\pi Bt}\} \approx \mathrm{Hilbert}\{I(t) - \langle I(t)\rangle\}$.

After square and scaling operation, the $\mathrm{Im}\{\hat{S}(t)e^{j\pi Bt}\}^2$ is reconstructed approximately and then we subtract the reconstructed $\mathrm{Im}\{\hat{S}(t)e^{j\pi Bt}\}^2$ from photocurrent, given as:

$$I(t) - \mathrm{Im}\{\hat{S}(t)e^{j\pi Bt}\}^2 \approx \left(C + \mathrm{Re}\left\{S(t)e^{j\pi Bt}\right\}\right)^2 \tag{2}$$

After $\mathrm{Im}\{\hat{S}(t)e^{j\pi Bt}\}^2$ is removed from $I(t)$, sqrt operation is used to obtain the linear term $C + \mathrm{Re}\left\{S(t)e^{j\pi Bt}\right\}$. All operations are performed in the real number domain.

## 3. Experimental setup and results

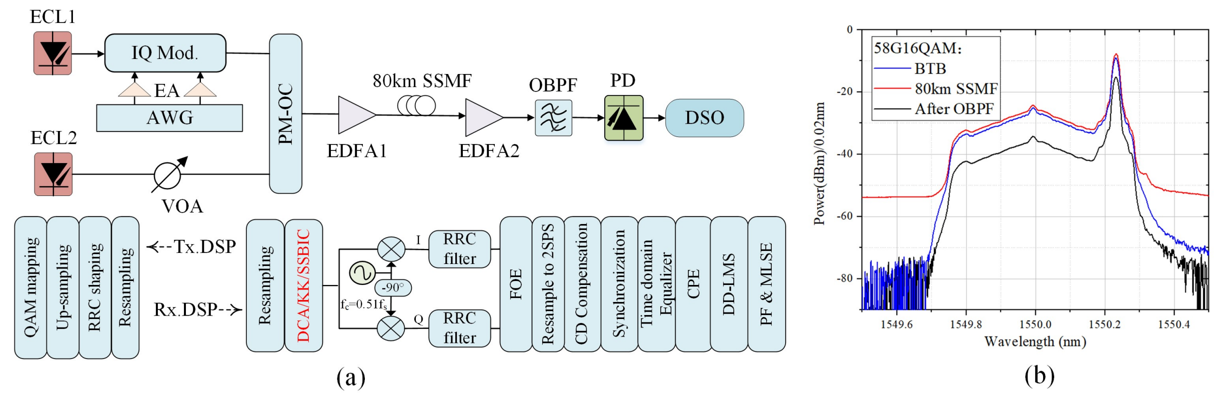


Fig. 2. (a) Experimental setup and DSP; (b) Optical spectra at BTB, after 80km SSMF and after OBPF, respectively.

The experimental setup together with the Tx and Rx DSP are shown in Fig. 2(a). At the transmitter, the 58GBaud 16QAM sequences are shaped by a root raised cosine (RRC) filter with the roll-off factor of 0.01, leading to 58.58GHz bandwidth. The I/Q components of the signal are generated by an arbitrary waveform generator (AWG, Keysight M8194A) of 45 GHz 3-dB bandwidth, operating at 120GSa/s, and then loaded into an IQ modulator of 25GHz 3dB bandwidth to modulate the light from ECL1 (1549.98 nm) after amplified by a dual-channel electrical amplifier (OA4SMM4). ECL2 (1550.23 nm) is used as the optical carrier and the variable optical attenuator (VOA) is set to adjust the carrier-to-signal power ratio (CSPR). Before being launched into an 80 km SSMF link, the combined SSB signal is amplified by an erbium-doped fiber amplifier (EDFA) to adjust the launch power. At the receiver, the signal is amplified, filtered using an optical bandpass filter (OBPF), detected by a 70GHz bandwidth PD (XPD3120R), and then captured by a real-time digital storage oscilloscope (DSO) with a 59GHz brick-wall electrical bandwidth (Tektronix DPO75902SX) operating at 200GSa/s for offline DSP. The optical spectra of 58GBaud 16QAM SSB signal at BTB, after 80km transmission and after OBPF are depicted in Fig. 2(b), respectively. The DSP stack is shown in Fig.2(a). At the receiver DSP, the detected waveform is firstly resampled, and then SSBI cancellation is conducted using proposed DCA, and compared with KK/SSBI-C schemes. After down-conversion and matched filter, the residual frequency offset is estimated by the $4^{th}$ power method. After re-sampled to 2 samples-per-symbol (SPS), CD compensation, synchronization, and equalization are applied to the sequences. The equalizer taps are updated by the recursive least square (RLS) algorithm. After equalization, the carrier phase recovery based on blind phase search is conducted to eliminate phase noise. Then a decision-directed least minimum square (DD-LMS) is applied to correct residual ISI. Finally, post filter and maximum likelihood sequence estimation (MLSE) are used to whiten colored noise enhanced by equalizers.

The measured BERs versus CSPR at the BTB scenario with a fixed received optical power (ROP) of 0dBm are displayed in Fig.3(a). To illustrate the performance of the proposed DCA, we compare it with the standard KK receiver [3] operating at 240GSa/s (slightly larger than 4SPS) and SSBI-C iterative compensation [2] in our experiment. Both SSBI-C and the proposed DCA operate at 120Gsa/s (slightly larger than 2SPS) to avoid spectral overlap. It can be observed that DCA significantly improves the performance of the original SQRT algorithm at CSPR ranging from 8 dB to 18dB. The performance of the DCA and KK receiver is almost the same while they both outperform SSBI-C with one iteration (SSBI-C w 1 iter) at CSPR lower than 18dB. Fig.3(b) shows the BERs as a function of ROP with different SSBI cancellation algorithms at 14dB CSPR. It shows only the KK receiver and our proposed algorithm can reach the 7% HD-FEC threshold of $3.8\times10^{-3}$ at the ROP of 2 dBm.

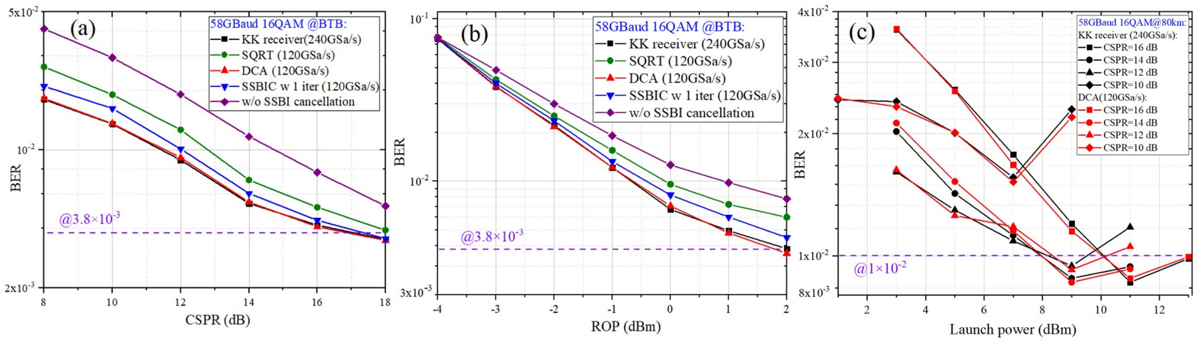

Fig. 3. BERs versus CSPR with different SSBI cancellation at BTB. (b) BERs versus ROP with different SSBI cancellation at BTB. (c) BERs versus optical launch power with different SSBI cancellation after 80km SSMF.

CSPR is a critical parameter in SSB systems. As shown in Fig.3(c), we evaluate the performance as a function of launch power with different CSPRs after 80km SSMF transmission. For the CSPRs of 10, 12, 14, 16 dB, the optimal launch powers are 7dBm, 9dBm, 9dBm and 11dBm, respectively. A larger CSPR requires higher launch power since the signal occupies a smaller ratio in the total optical power. Among all these CSPRs, the CSPR of 14 dB shows the best performance at 9dBm optimal launch power with a BER below 14% HD-FEC threshold of $1\times10^{-2}$.

## 4. Computational complexity analysis

Table 1. Computational complexity comparison

| | **Standard KK [3]** | **Upsampling-free KK [5]** | **Iterative SSBI-C [2]** | **Proposed DCA** |
|---|---|---|---|---|
| **Number of multiplier** | $(3Ns+2+4\log_2 RN)RN$ | $(4N\log_2 N+3N)+4N\log_2 N$ (optional) | $(4N\log_2 N+3N)\ k$ | $4N\log_2 N+2N$ |
| **Number of adder** | $(3Ns+6\log_2 RN)RN$ | $(6N\log_2 N+2N)+6N\log_2 N$ (optional) | $(6N\log_2 N+2N)\ k$ | $6N\log_2 N+N$ |
| **Memory** | $16RN^{\dagger}$ | $4N^{\dagger}$ | $8N^{*}$ | $4N^{\dagger}$ |
| **1-bit shift** | 0 | 3 | 0 | 0 |

Ns: Length of up/down-sampling filter. R: Oversampling rate. N: Block length; k: Number of iterations; †: kbits; *: bits

According to the computational complexity analysis in [5], similarly, we estimate the complexity for the DCA method shown in Table 1. For fair comparison, the Hilbert transformation is realized through FFT/IFFT pairs implemented in the frequency domain. The estimated computational complexity comparison of standard/upsampling-free Kramers-Kronig [3,5], the iterative SSBI-C [2], and proposed DCA is presented in Table I. Note that the output of standard/upsampling-free KK is complex-valued SSB signal, while SSBI-C and DCA generate real-valued signal. The optional part accounts for the sideband filter included in upsampling-free KK. The required multiplier and adder of the DCA are less than half of other algorithms, since that:1) it is upsampling-free and iteration-less; 2) sqrt operation can be implemented by look-up-table [5]. We believe that these reductions of computational complexity would make the DCA practical for the implementation of compact and power-efficient SSB direct-detection optical transceivers.

## 5. Conclusion

We have proposed a low-complexity and non-iterative decomposition and cancellation algorithm to eliminate SSBI at the Nyquist sampling rate without requiring digital upsampling and validated it in 58GBaud 16QAM 80km transmission system with a BER of $8.6\times10^{-3}$ below the threshold of 14% HD-FEC. The experimental results show that DCA at Nyquist sampling rate exhibits similar performance with the KK receiver operating at 4SPS. Therefore, we believe the DCA enables low-latency and low-complexity short-reach optical communication links.

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