

# Reach Enhancement for WDM Direct-Detection Subcarrier Modulation using Low-Complexity Two-Stage Signal-Signal Beat Interference Cancellation

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**Abstract** We describe a novel low-complexity SSBI cancellation scheme, and experimentally investigate its performance in a 7×25 Gb/s WDM direct-detection single-sideband 16QAM Nyquist-subcarrier modulation system. The scheme achieves a doubling of the transmission reach.

## Introduction

Due to their use of a low-cost, simple transceiver structure, single-polarization direct-detection (DD) wavelength division multiplexing (WDM) systems may be favourable for metro, access and inter-data centre links. Moreover, high spectral efficiency (SE) can be achieved through the use of DD Nyquist-pulse shaped subcarrier modulation (Nyquist-SCM) with high-order QAM<sup>1-3</sup>. However, a nonlinear effect, termed signal-signal beat interference (SSBI), arises during the square-law detection and significantly degrades the receiver sensitivity.

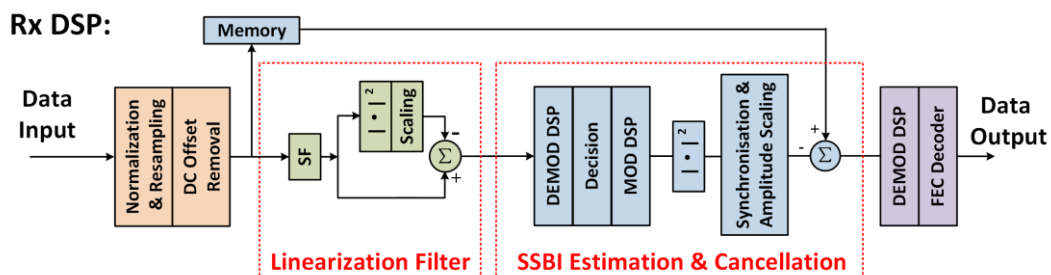
A receiver-based digital iterative SSBI mitigation scheme has been proposed<sup>4</sup> to effectively mitigate the SSBI but it requires multiple iterations of signal modulation and demodulation at the receiver, thus leading to significantly increased DSP complexity. We have shown that the need for multiple iterations can be avoided by implementing transmitter-based digital pre-distortion combined with receiver-based non-iterative SSBI cancellation<sup>5</sup>. However, this approach has the drawback of generating unwanted extra beating interference introduced by SSBI pre-distortion and does not offer compensation gains as high as the digital iterative SSBI post-compensation. In this paper, we present a novel receiver-based two-stage digital SSBI compensation technique which combines linearization filtering<sup>6,7</sup> and non-iterative SSBI estimation and cancellation. This

technique provides the best reported performance to date while, at the same time, significantly reducing the DSP complexity. An experimental assessment of the performance using this technique is presented in a spectrally-efficient (2.4 b/s/Hz) 7×25 Gb/s WDM DD SSB 16-QAM Nyquist-SCM system. This technique is shown to reduce the required OSNR by 6.3 dB at the HD-FEC limit, and enhances the achievable transmission distance by 100%.

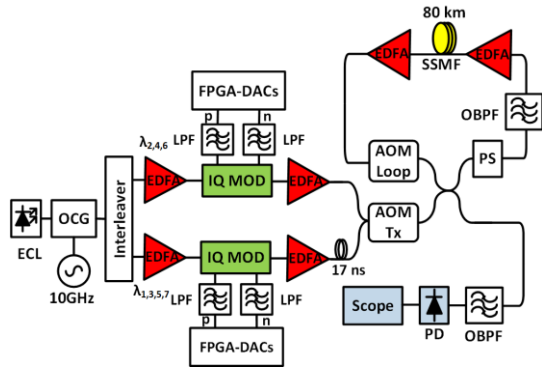
## Low-complexity Two-Stage SSBI Cancellation

As shown in Fig. 1, the proposed technique has two stages: a simple linearization filter<sup>6</sup> followed by a non-iterative SSBI estimation and cancellation. The linearization filter stage partially compensates the SSBI, leading to an improved estimation of the signal-signal beating terms in the estimation and cancellation stage. Hence, the DSP complexity can be significantly reduced without carrying out multiple iterations as used in Ref. 4.

In the transmitter, the SSB SCM signal is first generated by the modulation DSP (MOD DSP)<sup>3</sup>. Digital chromatic dispersion pre-compensation (CDP) is used to compensate for fibre dispersion. Following optical modulation, fibre transmission, direct detection and A/D conversion, two copies of the detected signal waveform are made with one being stored in memory and the other being passed through a linearization filter, in which, the detected signal passes through a sideband filter,

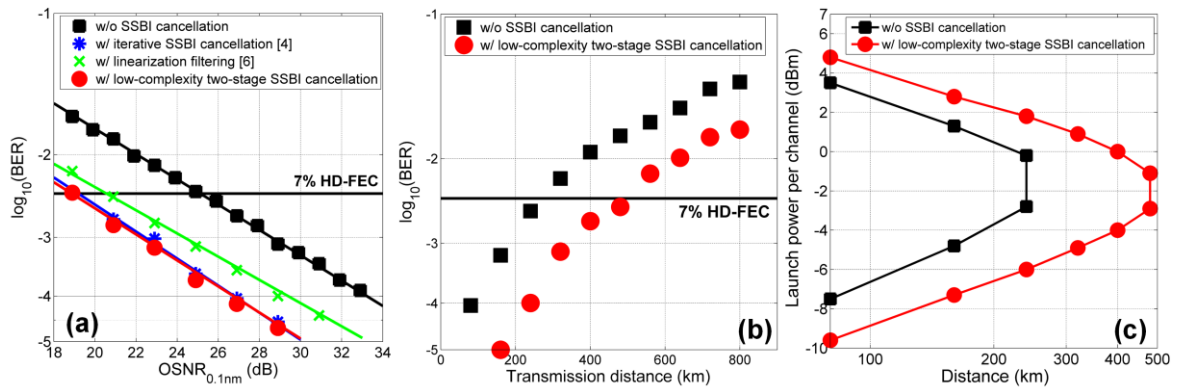


**Fig. 1:** Receiver DSP with low-complexity two-stage SSBI post-compensation. MOD&DEMOD DSP: single-sideband subcarrier modulation signal generation and demodulation, SF: sideband filter.



**Fig. 2:** Optical transmission experimental testbed. ECL: External cavity laser, OCG: Optical comb generator, DAC: Digital-to-analog converter, LPF: Low-pass filter, EDFA: Erbium-doped fiber amplifier, AOM: Acousto-optic modulator, PS: Polarization scrambler, OBPF: Optical band-pass filter, PD: Photodiode.

and a digital approximation of the signal-signal beating products is calculated, which are then subtracted from the original signal, partially eliminating the SSBI terms. This technique is described in detail in Ref. 6. Following this, SSBI estimation and cancellation is carried out; a digital representation of the SSB SCM signal is generated and an approximation of the signal-signal beating products is re-constructed and then subtracted from the stored waveform. Since the symbol decisions are significantly more accurate due to the preceding linearization filtering stage, multiple iterations of the SSBI estimation and cancellation are not required, which significantly reduces the digital hardware complexity. Furthermore, compared with the proposed technique in Ref. 5, this approach avoids the unwanted extra beating interference introduced by SSBI pre-distortion leading to an improved performance. At the same time, since there is no need to perform the SSBI pre-distortion on the reconstructed SSB SCM signal in the receiver DSP, the total computational complexity of the proposed SSBI cancellation technique can be further reduced.



**Fig. 3:** (a) BER versus OSNR. (b) BER versus transmission reach (c) Optical launch power per channel versus maximum transmission reach to achieve  $\text{BER} \leq 3.8 \times 10^{-3}$ .

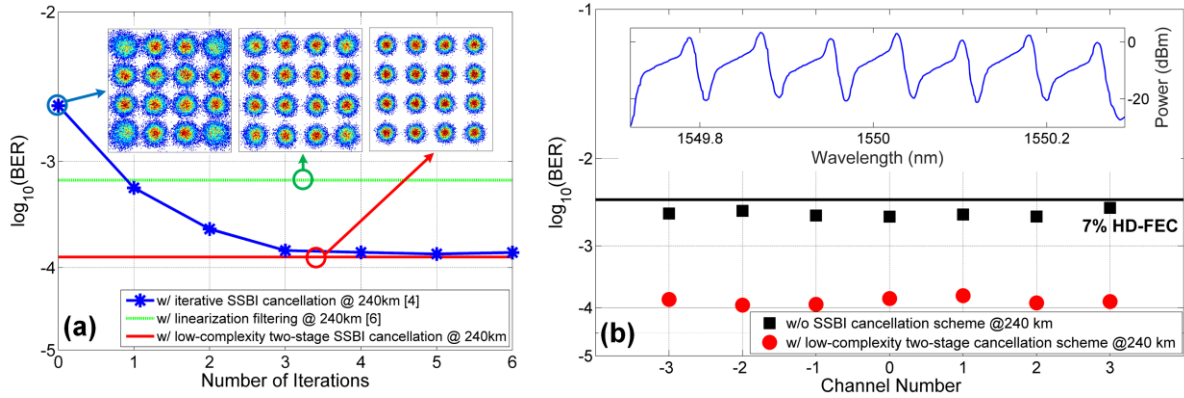
## Experimental Setup

The experimental setup is shown in Fig. 2. The odd and even channels were generated using two IQ-modulators, which were driven by two DACs with a sampling rate of 25 GSa/s. In the transmitter DSP, a 25 Gb/s SSB Nyquist-SCM signal was generated with a subcarrier frequency of 3.4375 GHz (subcarrier frequency equal to  $0.55 \times$  symbol rate). CDP was performed and the WDM channel spacing was set to 10 GHz.

The transmission experiment was performed using a recirculating fibre loop, with a single span of 80 km standard single-mode fibre (SSMF). Two erbium-doped fiber amplifiers (EDFAs) with 5 dB noise figure were used to compensate the loop loss (31 dB per span, including the loss of the fibre and other components). At the receiver, the channel of interest was demultiplexed using a 10 GHz bandwidth optical band-pass filter and then detected by a single-ended PIN photodiode and digitized with a single ADC at 50 GSa/s. In the receiver DSP (Rx DSP), the proposed low-complexity two-stage digital SSBI compensation process was employed as shown in Fig. 1. The performance of the proposed SSBI mitigation scheme was compared with both the linearization filtering<sup>6</sup> and iterative SSBI post-compensation<sup>4</sup> schemes. In the latter case, we used four iterations for optimum cancellation performance.

## Experimental Results

First, the optical back-to-back performance was evaluated (Fig. 3(a)). The optimum performance was achieved by sweeping the carrier-to-signal power ratio (CSPR) from 7.5 dB to 13.5 dB and setting it at the optimum value for each OSNR value. By utilizing the proposed two-stage SSBI compensation approach, the required OSNR (at the HD-FEC limit, taken to be at  $\text{BER} = 3.8 \times 10^{-3}$ ) was reduced from 25.3 dB to 19.0 dB (a 6.3 dB reduction), which is similar to the improvement using the more complex iterative SSBI post-



**Fig. 4:** (a) BER versus number of iteration. Inset: Received constellations without (EVM = 17.9%) and with linearization filter (EVM = 15.7%) / two-stage (EVM = 12.8%) post-compensation (b) BERs for each channel after transmission. Inset: WDM spectrum.

compensation (Fig. 3(a)). The two-stage compensation technique offers 1.7 dB better performance than the nonlinear filtering approach alone, though at the expense of additional complexity. The system was further assessed through WDM transmission experiments over distances from 80 km to 800 km without and with the proposed compensation scheme. The BER (at the optimum optical launch power and CSPR) versus transmission distance is plotted in Fig. 3(b). It can be seen that the WDM transmission performance is significantly improved at all distances. The reduction in gain at the longer distances is due to fibre nonlinearity dominating the performance. Fig. 3(c) shows the reach curves indicating the range of launch powers at which the pre-FEC BER  $\leq 3.8 \times 10^{-3}$ . Reach enhancement from 240 km to 480 km was achieved through the use of the proposed scheme.

Furthermore, the transmission performance of these three SSBI cancellation techniques was compared by measuring the BER at a transmission distance of 240 km (Fig. 4(a)). In the case of the iterative approach<sup>4</sup>, BER is plotted versus the number of iterations employed in the SSBI compensation DSP. It can be observed that the proposed scheme offers better performance than the linearization filtering approach and similar performance to that of the iterative compensation scheme while avoiding the need to perform multiple iterations. Fig. 4(b) shows all 7 WDM channels' performance at the optimum optical launch power at a distance of 240 km. The average BER for all the channels was reduced from  $2.6 \times 10^{-3}$  to  $1.3 \times 10^{-4}$ . Based on the theoretical hard-decision decoding bound for the binary symmetric channel at the  $3.8 \times 10^{-3}$  BER, the achieved net optical SE was 2.4 (b/s)/Hz.

## Conclusions

We proposed a novel low-complexity receiver-based two-stage digital SSBI cancellation

technique, which combines simple linearization filtering and non-iterative SSBI estimation and cancellation at the receiver for direct detection SSB subcarrier modulation systems. The system performance was experimentally assessed on a  $7 \times 25$  Gb/s WDM SSB 16-QAM Nyquist-SCM system and compared with previously proposed compensation schemes. To the best of our knowledge, this is the first experimental assessment of this digital SSBI cancellation technique, which combines the best reported performance to date with significantly reduced DSP complexity

## Acknowledgements

This work was supported by the UK EPSRC UNLOC project, EU FP7 ASTRON project and Semtech Corp.

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