30 Gbaud 128 QAM SSB Direct Detection Transmission over 80 km with Clipped Iterative SSBI Cancellation

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Abstract: We demonstrate a novel SSBI cancellation technique operable without digital upsampling for a 30 Gbaud 128 QAM SSB transmission with a record low CSPR of 5 dB, showing 4.6 dB performance improvement compared to the Kramers-Kronig scheme.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications.

1. Introduction

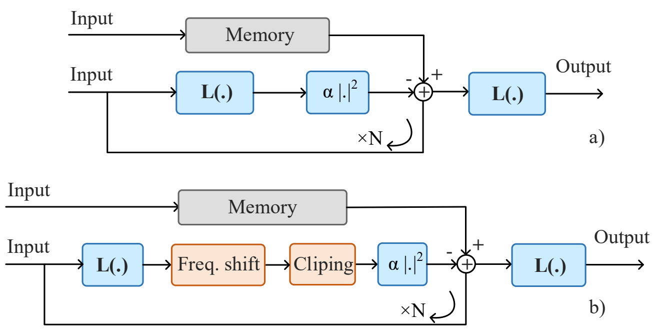

Fig. 1. Block diagrams of the iterative SSBI cancellation scheme without a) and

Over the last few years, single-side-band (SSB) direct-detection (DD) has been investigated intensively as a potential transmission technique for high-speed data center interconnect (DCI) applications [1-7]. The main advantages of SSB transmission scheme are the simple transceiver's architecture and the possibility of electrical dispersion compensation (EDC). In addition, many effective signal processing techniques, such as Kramers-Kronig (KK) [1] and iterative signal-signal beat interference cancellation (SSBIC) [3-4] have been proposed to combat the SSBI resulted from the direct detection (DD) process using single-ended photodetector (PD). These techniques have enabled high performance SSB transmissions with net data rate beyond 400 Gb/s over 80 km [5].

Unfortunately, SSB transmission scheme suffers from several challenges, which prevent its practical implementation. These include: *i*) – the high bandwidth requirement of the receiver digitizer; *ii*) – the high carrier to signal power ratio (CSPR) requirement (usually around 10 dB), which limits the number of SSB channels in WDM transmission due to the limited power of the EDFA; *iii*) – The KK scheme requires an oversampling factor of around 6, which is unacceptable for practical ASIC implementation.

It was shown in [4], that the high bandwidth requirement of the receiver's digitizer in SSB transmissions can be overcome by employing high-speed ADC frontend and parallel digitization at lower speed. A clever KK scheme operable without digital upsampling has been proposed in [6], but its core approximation does not hold well for low CSPR values (< 6 dB). Similarly, iterative SSBI cancellation can also be applied without upsampling but its performance becomes unstable and very poor if the CSPR is small (below 6 dB). To conclude, none of the existing SSBI cancellation techniques can be operated effectively with a low CSPR value and without digital upsampling, which are two important requirements for practical DSP implementation in ASIC.

In this work, we solve this crucial problem by proposing a novel iterative SSBI cancellation technique with clipping, showing stable performance without digital upsampling at low CSPR values. Using this technique, we have experimentally demonstrated a 30 Gbaud 128 QAM SSB transmission over 80 km with a record low CSPR of 5 dB, showing a significant improvement of ~ 4.6 dB compared to the KK scheme [6].

2. Iterative SSBI cancellation with clipping

The block diagram of the conventional iterative SSBIC scheme is shown in Fig. 1(a). The detected signal after PD can be written as:

$$I(t) = |A|^2 + A^* \cdot S(t) + A \cdot S^*(t) + |S(t)|^2, \quad (1)$$

where A is the optical carrier amplitude (assumed to be a real value for simplicity), $S(t) = U(t)e^{2j\pi Bt}$ is the SSB signal and B is the frequency spacing between the optical carrier and the baseband signal $U(t)$. The algorithm in Fig. 1(a) can be applied without digital upsampling, as along as the sampling frequency is high enough to accurately digitize $I(t)$. However, when the CSPR is 3 dB lower than the peak to average power ratio (PAPR), it is shown below that this algorithm is unstable.

The output of the algorithm at the n^{th} iteration is $S_n(t) = S(t) + e_n(t)$, where $e_n(t)$ is the algorithm error from the n^{th} iteration, which can be calculated in an iterative manner as follow:

$$e_0(t) = \boldsymbol{L}(|S(t)|^2)/A \text{ and } e_{n+1}(t) = -\boldsymbol{L}(|e_n(t)|^2 + 2\text{Real}(e_n(t) \cdot S^*(t)))/A, \quad (2)$$

where $\boldsymbol{L}(.)$ is the single-side band filter. For the real part, we have: $\text{Real}(e_0(t)) = |S(t)|^2/(2A)$ (3)

If $\max\{|S(t)|^2\} = \max\{|U(t)|^2\} > 2\,A^2$ (PAPR > 3 dB + CSPR), and considering the random nature of the modulated signal $S(t)$ we can find a time instant t_0 satisfying these following conditions:

$$|S(t_0)|^2 > 2A^2, \mathrm{Real}(S(t_0)) > \mathrm{Imag}(S(t_0)) > 0 \text{ and } \mathbf{H}(|S(t_0)|^2) > 0,$$

where $\mathbf{H}(.)$ is the Hilbert transformation. Thus, $\mathrm{Real}(S(t_0)) > A$ we have:

$$\mathrm{Real}(e_0(t_0)) > A, \mathrm{Imag}(e_0(t_0)) > 0 \quad (4)$$

Using these inequalities, we have:

$$|\mathrm{Real}(e_1(t_0))| = \frac{|e_0(t_0)|^2}{2A} + \frac{2\mathrm{Real}(e_0(t_0)\cdot S^*(t_0))}{2A} > \frac{|e_0(t_0)|^2}{2A} + \frac{\mathrm{Real}(e_0(t_0))\,\mathrm{Real}(S(t_0))}{A}$$
$$> \frac{|\mathrm{Real}(e_0(t_0))|^2}{2A} + |\mathrm{Real}(e_0(t_0))| > \frac{A}{2} + |\mathrm{Real}(e_0(t_0))|$$

This analysis shows that: instead of being reduced, the processing error at high-peak samples can grow superlinearly fast after each iteration. This leads to an unstable overall performance of the conventional SSBIC algorithm when the CSPR value is 3 dB lower than the PAPR. Given the fact that high order modulation formats, such as 128 QAM, with pulse shaping can have an PAPR above 10 dB, conventional SSBIC technique becomes unreliable if the CSPR < 7 dB.

To solve this problem and take the advantage of the low sampling rate requirement of iterative SSBIC scheme, we propose here a novel iterative SSBI cancellation scheme with clipping as shown in Fig. 1(b) (clipped SSBIC). We use clipping to remove high peaks which might appear in the reconstructed signal after each iteration due to processing error. In this case, the clipper acts as an error controller in the iterative processing loop. It effectively trades a small clipping noise to a possibly much bigger SSBI estimation error, which grows after each iteration. In this case, with a proper choice of the clipping level, the overall SSBI estimation error can be reduced continuously when the number of iterations is increased. In this case, we can achieve a stable and much better performance in comparison with the conventional approach without clipping. Using simulation in the noiseless case, we compare the performance of SSBI cancellation techniques, with and without clipping for 30 Gbaud 128 QAM SSB signal with a CSPR of 5 dB in Fig. 2. Without clipping, the performance of the conventional SSBIC technique become unstable after 5 iterations, with a lowest noise to signal ratio (NSR) of ~ -16.5 dB. When the clipping technique is applied with an optimized clipping level of 8 dB (compared to the mean signal power), the NSR keeps decreasing with the number of iteration and reaches an NSR of -21 dB. This shows a significant performance improvement of ~ 4.5 dB, which is extremely valuable for systems with high order modulation formats, such as 128 QAM.

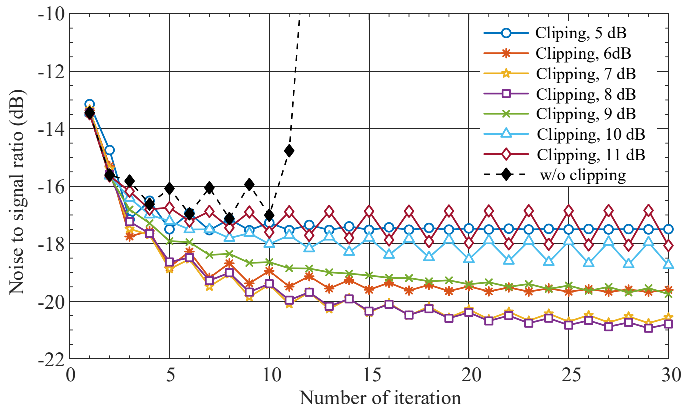

Fig. 2. Performance comparison of the SSBI cancellation schemes with and without clipping for 128 QAM SSB signal with a CSPR of 5 dB (simulation)

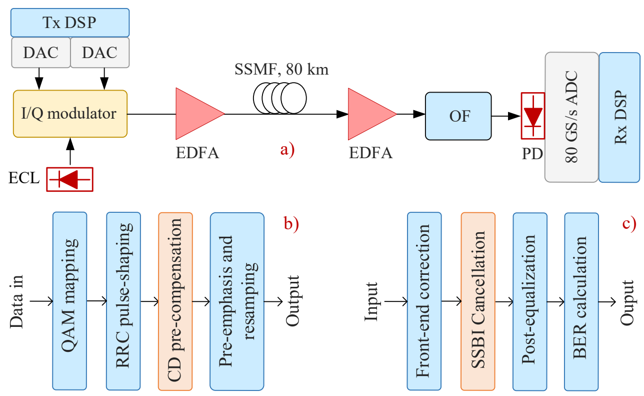

Fig. 3 a) – Experimental transmission setup and b) – c) Basic block diagrams of the Tx and Rx DSP; OF – Optical filter, ECL – External cavity laser

3. Experimental setup and results

The block diagram of the experimental setup together with the Tx and Rx DSP are shown in Fig. 3. First, at the Tx side, 30 Gbaud 128 QAM modulated signal with RRC pulse shape with a roll-off factor of 0.05 was generated offline at baseband. After that, the signal was upconverted to an intermediate carrier frequency of 16 GHz to generate a complex SSB signal. To minimize the PAPR at the receiver, we applied CD pre-compensation at the Tx side. Next, digital pre-emphasis was performed to compensate for the linear response of the DACs, RF drivers and IQ modulator. Then, the I and Q signal components were loaded into the memories of 2 DACs running at 88 GS/s. The outputs of the 2 DACs were then fed into a single polarization IQ modulator, which was off-biased to generate an optical SSB signal with a CSPR of 5 dB. At the Rx side, the signal was filtered using an optical filter with a bandwidth of ~ 35 GHz and then detected using a wideband PD (~ 70 GHz of bandwidth). After detection, the signal was digitized using an ADC at 80 GS/s and stored for offline processing. For SSBI cancellation we consider 4 techniques, namely: SSBI schemes with and without clipping,

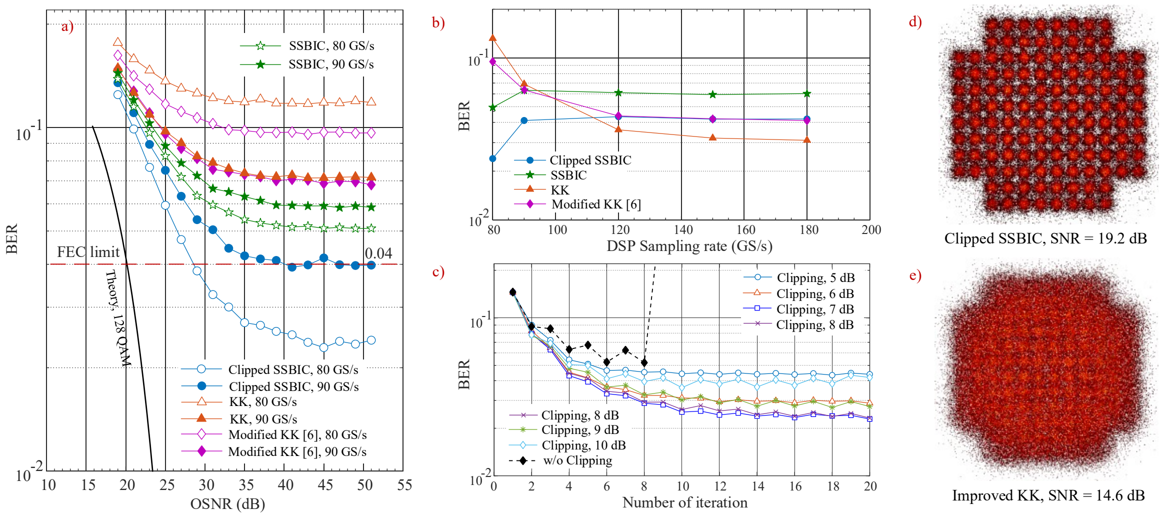

Fig. 4 a) – B2B performance of 30 Gbaud 128 QAM SSB transmission system with various SSBI cancellation techniques; b) – BER versus DSP sampling rate for clipped SSBIC with a clipping level of 7 dB, SSBIC, KK and improved KK at OSNR ~ 50 dB; c) – BER versus number of iteration for SSBIC with different clipping levels; d) – e): Constellations for clipped SSBIC and improved KK

the conventional KK scheme and a modified KK scheme operable without digital upsampling as proposed in [6]. Without digital upsampling, these SSBI schemes were operated at the ADC sampling rate of 80 GS/s. For performance comparison, we also performed digital upsampling up to 180 GS/s (an oversampling factor of 6). The B2B performances of the systems under test are summarized in Fig. 4, showing an outstanding performance of the proposed SSBIC scheme (with 10 iterations) compared to other considered schemes. For achieving a stable performance with the conventional SSBIC scheme, only up to 6 iterations were used. At a processing sampling rate up to 90 GS/s, an BER < 0.04 (25% FEC limit) was only achieved with the clipped SSBIC scheme operated without digital upsampling (at 80 GS/s). It also shows a performance improvement of ~ 4.6 dB compared to the improved KK scheme (~ 19.2 dB compared to ~ 14.6 dB). Unlike the KK schemes, where oversampling increases the system performance (Fig. 4(b)), the optimum performances of SSBIC schemes were achieved at the ADC sampling rate (80 GS/s). In addition, the proposed scheme operated at 80 GS/s also outperforms KK schemes with a high processing sampling rate of 180 GS/s (Fig. 4(b)). The optimum clipping level was found to be 7 dB and the optimum performance could be reached after 10 iterations (Fig. 4(c)). The transmission performance of systems under test without digital upsampling over 80 km of SSMF is depicted in Fig. 5, showing that a BER below the 25% FEC limit could be achieved with a low launched power below 0 dBm. The optimum launched power was ~ 1 dBm, which is ~ 6 dBm lower than those value of previously reported 30 Gbaud SSB systems using a CSPR > 10 dB [7]. In a WDM transmission, this improvement translates into ~ 4 times increase in the total number of WDM channels, which can be supported by a single EDFA.

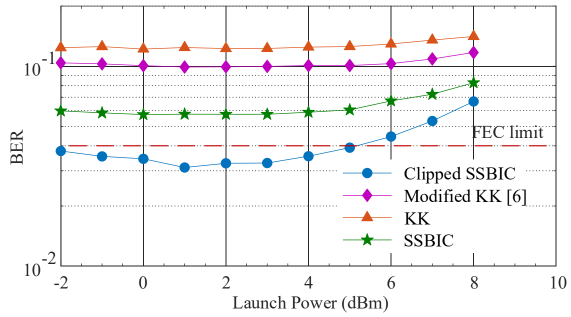

Fig. 5 – Transmission performance over 80 km. SSBIC techniques were operated at 80 GS/s (no digital upsampling)

4. Conclusion

We have proposed a novel iterative SSBIC scheme which can be applied effectively without digital upsampling for power-efficient SSB transmission with a low CSPR. This technique provides ~ 4.6 dB gain compared to existing KK schemes for a 30 Gbaud 128 QAM transmission with a record low CSPR of 5 dB over 80 km.

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5. References

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