Spectral Efficiency Improvement with Beating Interference Reduction by Iterative DSP in a Multiband DDO-OFDM Receiving System

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***Abstract* —For an efficient enhancement of the data capacity, multiband configuration has been widely applied in direct-detection optical orthogonal frequency division multiplexing (DDO-OFDM) system recently. To improve the spectral efficiency, we propose a signal-signal beating interference (SSBI) noise reduction mechanism achieved by an iterative digital signal processing (DSP). Through removing the SSBI noise in the receiver DSP, such mechanism keeps all retrieved signals immune from the SSBI contamination. With 4-QAM and 16-QAM formats, we design a 3-band DDO-OFDM signal both in simulation and experimental demonstrations, of which total data rates achieve 34 Gb/s and 68 Gb/s, respectively. Within 2 iterations, the SSBI noises are greatly mitigated with ignorable performance penalty. The spectral efficiency is therefore improved from 2 b/s/Hz to 3.26 b/s/Hz with 16-QAM format.[1]**

I. INTRODUCTION

In the progress of developing signal transmission efficiency, orthogonal frequency division multiplexing (OFDM) technique has been employed in optical communication for years. [1] With the inherent orthogonal configuration of data sub-carriers and the employment of high-bit-rate vector signals, OFDM signal promises a spectral efficiency approach. The generating of OFDM signals heavily relies on digital signal processing (DSP) techniques and the speed of digital-to-analog (D/A) converter. Therefore, it's not an efficient manner to adopt large bandwidth OFDM signals for higher transmission capacity. [2] Multiband configuration has then become a promising solution recently.

To date, based on the receiving mechanism, optical OFDM systems can be mainly classified as coherent optical OFDM (CO-OFDM) [3], [4] and direct-detection optical OFDM (DDO-OFDM). [5], [6] CO-OFDM not only requires less communication bandwidth, but also possesses better receiving sensitivity. However, these fascinating features are only available with relatively costly and complicated receiver implementation, conventionally including a local oscillating laser, an optical/electrical phase-locked loop and a set of balanced photo-detection devices. In contrast, DDO-OFDM, with an embedded optical carrier which experiences the same channel effects, can be demodulated easily by applying only one single-end photo-detector (PD) at the receiver side. Therefore, it exhibits a relatively low complexity and effectively relieves the implementation demand in the receiver end. Unfortunately, signal-signal beating interference (SSBI) noise, one of the deleterious noises introduced by the square-law detection in O/E conversion, is a dominate factor to the received OFDM signal performance. [7] Conventionally, a blank guard band between the optical carrier and OFDM signal band is usually assigned to keep the receiving signals immune from SSBI noise contamination. But SSBI noise will become more complicated in multiband configuration. The related guard band is forced to be extended, and therefore more bandwidth resources are wasted. Some approaches have been proposed to solve this problem, such as special filtering technique [5] and self-coherence receiving technique [8]. But the demand of expensive optical components, such as narrow bandwidth optical filter and balance receiver, make those solutions complicated and inefficient.

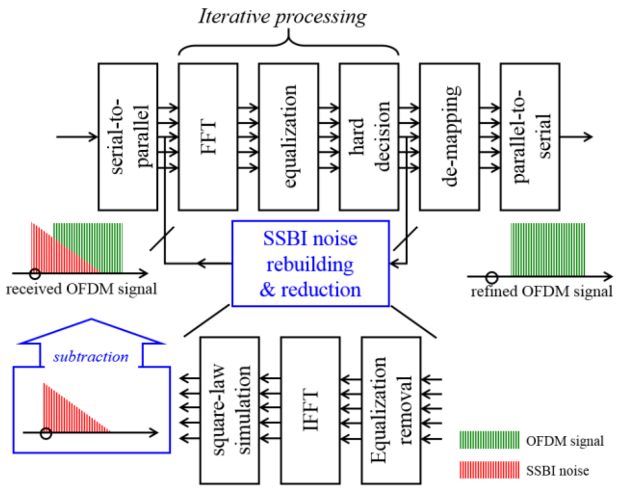

Fig. 1 The conceptual diagram of the iterative DSP

In this proposed paper, we introduce an effective solution with iterative DSP to eliminate the SSBI noise without any other physical component. With the inherent square-law detection, the SSBI noise is generated through the beating among data sub-carriers. Based on the noise analysis in [7], the proposed iterative DSP mainly consists of two procedures, rebuilding the SSBI noise and then removing it from the

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desired signal. A conceptual diagram is depicted in Fig. 1. Through the proposed SSBI re-building algorithm, even the desired OFDM signals are totally overlapped with SSBI noise, the proposed iterative processing can fully restore the signals with negligible performance penalty. As a result, we can greatly reduce the blank guard band and enhance the spectral efficiency of multiband DDO-OFDM system. An experimental demonstration of a 3-band multiband DDO-OFDM signal with 16-QAM format is conducted, and the result reveals that the received signals will be completely retrieved within 2 DSP iterations. The resultant spectral efficiency is enhanced from 2 b/s/Hz to 3.26 b/s/Hz in single polarization DDO-OFDM system.

II. THE OPERATION PRINCIPLE

After the analog-to- digital (A/D) conversion, the received OFDM signal is fed into the decoding DSP. In the forward procedure, after de-serializing the received OFDM signal, there are three major steps before de-mapping the OFDM signal, which are fast-Fourier transform (FFT), equalization, and hard decision.

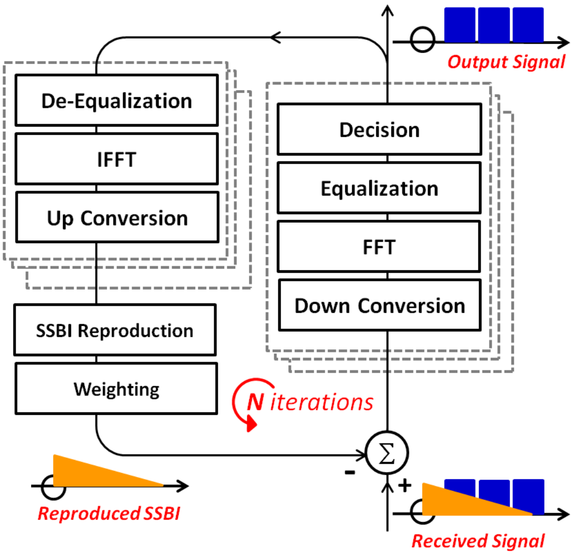

Fig. 2 The proposed iterative DSP in 3-band DDO-OFDM system

In the iterative processing, the received time domain signal is first transformed to frequency domain by FFT. After that we apply a simple one-tap equalizer to remove the channel response. A successive hard decision will re-generate the OFDM signal, which acts as the output of this iterative DSP loop. To eliminate the deleterious SSBI from the contaminated OFDM signal. We then apply such retrieved OFDM signal to the backward procedure for rebuilding the SSBI noise, as shown in Fig. 2. First, since the SSBI noise generated in the photo-detection comes from the transmitted OFDM signal, to rebuild it more precisely, the channel response should be applied back to the OFDM signal in the step of equalization removal. Second, because of a time-domain execution of the square-law detection in physical layer, before simulating this function, an inverse FFT (IFFT) is necessary for converting the OFDM signal back to time domain. At the end of backward procedure, we have to up-convert each OFDM signal band to their corresponding bands and sum all of them, thus the original received electrical multiband OFDM signal before O/E conversion is regenerated. To simulate a PD with DSP approach, we embed a square-law operator to retrieve the SSBI noise. Since the DC term is always removed for better vertical resolution in quantization, a weighting function is employed to compensate for the signal power mismatch for a more accurate SSBI reproduction. Since the received electrical signal is the signal-carrier beating term introduce by PD, the power of carrier is needed for reconstructing origin signal. The weighting parameter W is then estimated by (1),

$$W = \frac{1}{P_{\mathrm{RX,carrier}}} = \frac{1}{P_{RX}\cdot\left(\frac{CSPR}{CSPR+1}\right)\cdot G} \qquad (1)$$

where $P_{RX,\ carrier}$ is the power of received carrier, P_{RX} is the total power received at the PD, $CSPR$ is carrier to signal power ratio, and G is the total power gain produced by the PD and electrical amplifier. At the final step of this DSP loop, the reproduced SSBI is deducted from the original received OFDM signal by a subtractor to clear out the undesired SSBI noise. A square-law simulating function is active now to rebuild SSBI noise in a DSP manner, and the rebuilt SSBI noise is then available. This rebuilt noise term is supposed to be identical to real SSBI generated in photo-detection. Therefore, at the end of backward procedure, the algorithm will subtract this rebuilt SSBI noise from the received OFDM signal, and feed the resultant signal again into the forward procedure.

At the decision output, an error vector magnitude (EVM) operator is used to determine either the signal need to send to backward procedure or not. Where EVM defined as the root mean square of the percentage that the error vectors magnitude occupied in the ideal signal constellation, as shown in (2),

$$EVM_{RMS} = \sqrt{\frac{\sum_{i=1}^{N}\left|s_i - r_i\right|^2}{\sum_{i=1}^{N}\left|s_i\right|^2}} \times 100\% \qquad (1)$$

where N is the number of symbols, as well as s_i and r_i represent the original signal and the received signal, respectively. Theoretically, with the reverse and subtraction functions, the SSBI noise will be eliminated from this OFDM signal.

III. SIMULATION AND EXPERIMENTAL DEMONSTRATIONS

A. System Setups

The experimental setup is shown in Fig. 3. We apply a field modulation scheme with optical carrier insertion to generate the desired multiband DDO-OFDM signal. [9] The baseband OFDM signal is generated offline with Matlab$^{\mathrm{TM}}$ coding. It's worth noting that to correctly estimate the channel response in the fiber link, a specific design of the training signals is employed via spectrally interleaving with zero data sub-carriers, thus, by proper interpolation, the training signals can provide accurate channel response without the influence of SSBI noise. Such special designed OFDM signal then digital-to-analog converts by an arbitrary waveform generator (AWG) at a sampling rate of 12 GSa/s. Each signal band occupies 5.67-GHz bandwidth with 120 sub-carriers modulated by 16-QAM format out of 256 FFT sizes. The tunable laser is set at 1552.52 nm with 100-kHz linewidth. An optical frequency comb generator (FCG) and an in-phase/quadrature-phase modulator (IQM) are cascaded to establish a 3-band DDO-OFDM signal with total rough data rates of 34.02 Gb/s and 68.04-Gb/s for 4-QAM and 16-QAM formats, respectively. After the carrier insertion, the desired OFDM signal is generated with the carrier-to-signal power ratio (CSPR) of 12 dB.

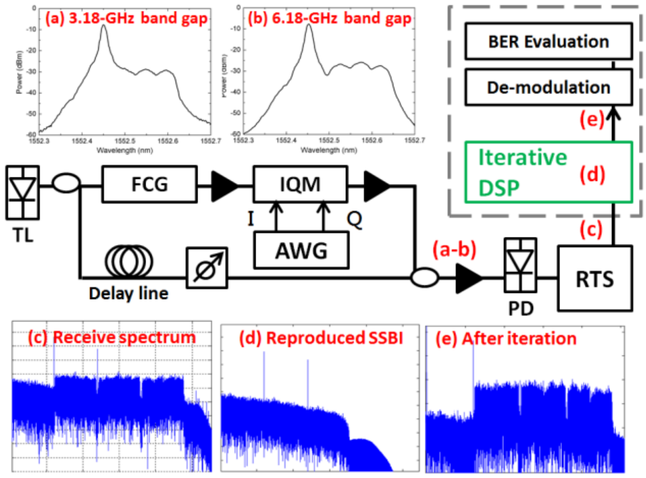

Fig. 3 Experimental setup of a multiband DDO-OFDM system

Two spectral layouts of the multiband DDO-OFDM signals are employed: one with 6.18-GHz band gap, which is slightly larger than the bandwidth of one OFDM band, thus the outmost signal band immune from SSBI, while the other is with almost half bandwidth of one OFDM bandwidth, 3.18 GHz, and makes all the signal bands polluted. The corresponding optical spectra are displayed in insets (a) and (b) of Fig. 3. The O/E down-conversion is achieved by only a single-end PD as the specified direct-detection scheme, and the received OFDM signal is then A/D converted by a real-time oscilloscope (RTS) at a sampling rate of 80 GSa/s. A parallel scenario is adapted to de-multiplex each OFDM signal band by down-converting it from each RF band to baseband. After that we apply a low pass filter to sift out each band, and then feed into the main part of iterative DSP, as mentioned in the last section. The corresponding spectra for the reproduced SSBI noise, and the signal after iterative DSP are provided in inset (d) to (e) of Fig. 3.

B. Demonstration Results

As expected, the EVM performances of outer band are the same after several iterations in DSP since it has no interference of SSBI in band gap 6.18-GHz scenario. For 4-QAM signal, corresponding to the left column of Fig. 4(a), the middle band and inner band can achieve SSBI-free with doing 1 time of iteration, while 2 iterations are needed for 16-QAM signal, as shown in the right column of Fig. 4(a). This is because the distance between the points in the constellation of 16-QAM is smaller than one of 4-QAM. It makes 16-QAM signal pay a penalty for error tolerance. For the case with a band gap of almost half bandwidth of one OFDM bandwidth, 3.18 GHz, all the signal bands are polluted. Compared with previous case, the outer band now needs iterative DSP to reconstruct the desired signal, too. Figure 5 (b) gives the experiment results of 4-QAM and 16-QAM in left and right column respectively, which satisfy simulation results, which is shown in figure 5 (a).

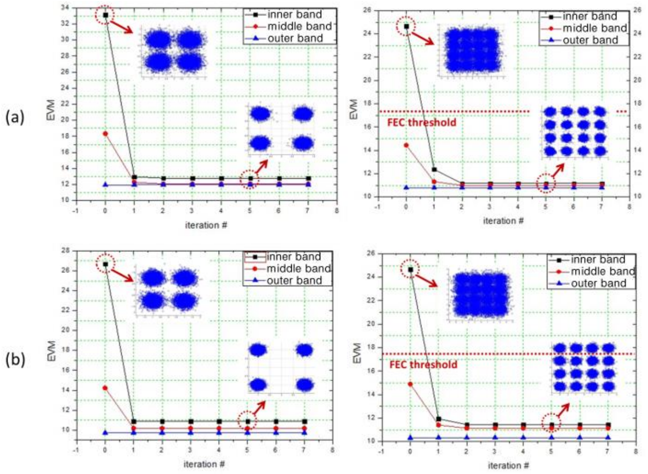

Fig. 4 The EVM performance for multiband DDO-OFDM with band gap of 6.18-GHz: (a) simulation results; (b) experimental results. Left column is the results of 4-QAM. Right column is the results of 16-QAM

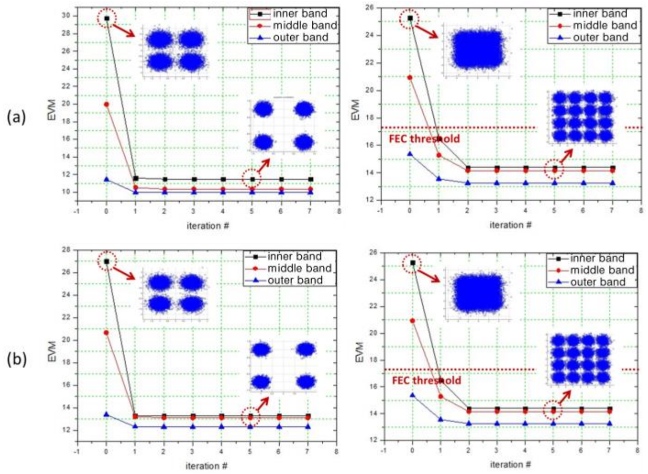

Fig. 5 The EVM performance for multiband DDO-OFDM with band gap of 3.18-GHz: (a) simulation results; (b) experimental results. Left column is the results of 4-QAM. Right column is the results of 16-QAM

The iterative results of all the 3 bands exhibit an identical result as the signal performance converges. Without iteration, the EVM performance among the 3 bands is not uniform for the both cases in two different QAM size due to different degree of SSBI contamination accumulated at their spectral bands. With a proper guard band the outmost band exhibits the best performance for its least SSBI influence. However, due to heavy contamination by SSBI, before iterative DSP, the inner band in both cases cannot reach the threshold of forward error correction (FEC) limit, which is bit error rate (BER) = $3.8\text{x}10^{-3}$. [10] Since BER can be expressed in terms of EVM, as shown in (3), [11]

$$BER = \frac{2\left(1-{}^{1}\!/\!{}_{L}\right)}{\log_2 L} \times Q\left[\sqrt{\frac{3\log_2 L}{L^2-1}\cdot\frac{2}{\left(EVM_{RMS}\cdot\log_2 M\right)^2}}\right] \qquad (2)$$

where L is the level of the applied M-ary QAM format, and EVM_{RMS} is the value without percentage weighting. From (3), we have the FEC limit of EVM 37.46% for 4-QAM and 17.39% for 16-QAM is needed to achieve FEC limit.

By introducing the iterative DSP, the performances among the 3 bands are improved and converge quickly, and all achieve the FEC limit for both cases, which exhibits the effectiveness of this iterative algorithm. We also observe that while it achieves obtaining a satisfactory EVM, more iteration doesn’t further improve the EVM values. Such results imply the latency caused by the proposed iteration DSP may be kept at a low scale. In addition, the performance deviation among the 3 bands becomes uniform. The inner band is observed to have a slightly higher EVM which is due to larger ASE-ASE beating noise accumulated in lower frequency band.

IV. DISCUSSIONS AND CONCLUSIONS

In DDO-OFDM, a guard band is typically introduced to accommodate the SSBI, but seriously degrades the precious spectral efficiency. In our proposed iterative scheme, with the iterative DSP algorithm designed for SSBI rebuilding and reduction, the demand of such guard band can be greatly relieved. In the signal band arrangement with a blank guard gap of 6.17G-Hz, the spectral efficiencies are 1.43 b/s/Hz (4-QAM) and 2.86 b/s/Hz (16-QAM). While in the case of only 3.17-GHz blank guard gap, the spectral efficiencies are further improved to 1.63 b/s/Hz (4-QAM) and 3.26 b/s/Hz (16-QAM). Compared with previous work, which has spectral efficiencies of 0.93 b/s/Hz (4-QAM) and 1.87 b/s/Hz (16-QAM), [12] iterative DSP gives remarkable improvement. In Fig. 5(b), even though the guard band is only half of one OFDM band, the BER still can be below FEC limit after 2 iterations. However, the corresponding performance is worse than the case with an one OFDM bandwidth guard band in Fig. 4(b). Such degradation can be attributed to that it’s more difficult to make a proper decision to discern the SSBI from real OFDM signals in our simple hard decision circuit. Applying nonlinear equalization and soft decision can alleviate this problem. However, this issue is beyond the scope of this paper. In conclusion, the spectral efficiency can be improved by 64.50% in comparison with the broadband OFDM system which preserves a full band gap for SSBI noise.

APPENDIX

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