Single-IFFT Real-Time Layered/Enhanced ACO-OFDM Transmitter

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Abstract: Using only a single middle-out Fourier transform, we are able to generate all layers of a 16-QAM-encoded layered/enhanced ACO-OFDM transmitter. We transmit over 10-km of standard single-mode fiber without error propagation in the receiver.
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1. Introduction

Optical orthogonal frequency division multiplexing (O-OFDM), also known as discrete multi-tone (DMT), encoded with high-spectral-efficiency modulation formats such as 16-QAM, is a promising candidate to further increase the data rate in short-haul optical communication systems [1,2]. As the OFDM signal is bipolar, a large DC bias is usually added to achieve a non-negative signal output. This scheme is usually called DC-biased OFDM (DCO-OFDM). Several short-haul real-time intensity modulated direct-detection (IMDD) DCO-OFDM transmission experiments using field-programmable gate arrays (FPGA) have been demonstrated [3,4]. However, DCO-OFDM is not power efficient, due to the dominant unmodulated optical carrier. Asymmetrically clipped optical OFDM (ACO-OFDM) [5] and pulse-amplitude-modulated optical DMT (PAM-DMT) [6] can improve the energy efficiency of optical OFDM but sacrifice half of its spectral efficiency. Layered/enhanced asymmetrically clipped OFDM (L/E-ACO-OFDM) [7-11] and augmented spectral efficiency DMT (ASE-DMT) [12] have been developed to improve the spectral efficiencies of ACO-OFDM and PAM-DMT towards that of DCO-OFDM, while still maintaining a power advantage. As all these demonstrations used off-line digital signal processing (DSP), the increasing computational complexity brought by multiple IFFTs in the transmitter was not considered. We have recently demonstrated a hardware-efficient QPSK-encoded L/EACO-OFDM transmitter, showing that it is possible for L/E-ACO-OFDM transmitter to use almost the same logic resources as the DCO-OFDM transmitter [13]. However, the requirement of optimizing each IFFT's implementation still remains complicated. At ECOC'17 we demonstrated a simple real-time ASE-DMT transmitter using only one IFFT [14,15].

In this paper, we present a single-FFT transmitter for L/E-ACO-OFDM in a similar vein to our ASE-DMT single-FFT transmitter. We show how a standard FFT can be modified to extract the waveforms for each layer from within the core of the FFT, so that they can be individually clipped before summation, which is critical to the operation of L/E-ACO-OFDM. We experimentally demonstrate this transmitter using 16-QAM, giving a net data rate up to 18.75 Gb/s. The measured Q-factor is 19.08 dB after 10-km standard single-mode fiber (SSMF) transmission, using offline signal processing in the receiver.

2. DSP implementation in the transmitter

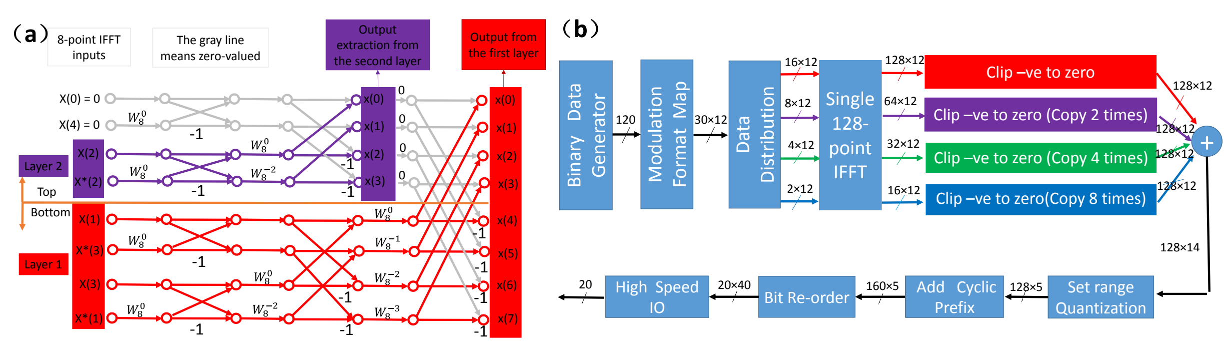

Fig. 1: (a) Middle-out IFFT implementation illustrated by an 8-point 2-radix decimation-in-time IFFT butterfly. Four layers requires a 32-input IFFT, with Layer 1 at the bottom/right of the diagram, and the higher layers nested within it. (b) Data flow in the FPGA using only one IFFT.

L/EACO-OFDM uses multiple layers to increase its spectral efficiency by individually clipping the negative waveforms of different layers before adding them together in the transmitter. Layer L (L = 1, 2, 3, …) must use the subcarriers that have frequency indices $2^{(L-1)}(2n+1)$, where n = {0, 1, 2, 3, …}, to allow the unused even-frequency subcarriers of ACO-OFDM to carry data. In the receiver, the demodulation of each layer requires an iterative algorithm to remove the clipping distortion generated by the lower layers. Each layer requires one IFFT, making its implementation more complicated compared with DCO-OFDM. By extracting signals from within IFFT, which we call a *middle-out* IFFT, we show that only one IFFT is required in the L/EACO-OFDM transmitter.

In Fig. 1(a), an 8-point 2-radix decimation-in-time IFFT butterfly is used to illustrate the middle-out IFFT implementation method. Layer 2 uses a 4-point IFFT in the top half of the butterfly because smaller IFFT size can be used in the higher layers [8]. As the data in the first layer flows only in the bottom-half butterfly except in the final butterfly, we can extract the IFFT's outputs from Layer 2 before they pollute the IFFT's output from Layer 1. The same extraction method also applies to all the higher layers. Therefore, only one IFFT is required in the implementation of L/EACO-OFDM transmitter, by slightly modifying the standard IFFT butterfly.

In the experimental demonstration, all the DSP functions were implemented in a Virtex-6 FPGA as shown in Fig. 1(b). Test data and training symbols were stored in the FPGA. During each clock cycle, 120 data bits were mapped to 30 16-QAM symbols. Afterwards, these 30 complex numbers, combined with their Hermitian counterparts, were distributed to four layers through a data distribution module. The subcarriers in the four layers were 16, 8, 4, 2, giving 93.75% (30/32) of the spectral efficiency of DCO-OFDM. Each layer generated its own outputs within a middle-out fully-streaming 128-point IFFT with 12-bit resolution. As the waveforms in the high layers are periodic, the outputs in all layers were clipped to remove all negative values before they were duplicated to generate 128 12-bit real outputs separately. Then 128 14-bit words were generated by adding waveforms from all the layers, before they were transformed into 128 5-bit words by the set-range and quantization module. Finally, a 32-sample cyclic prefix was appended to the front of every OFDM symbol, producing 160 positive 12-bit words, which were rearranged in the 20 high-speed transmitters of the FPGA. Of the available resources on the Vertix-6 FPGA (XC6VLX240T), the design used 13% of the slice registers (41830), 25% of the slice LUTs (38035) and 82% of the DSP48E1s (630). Compared with our hardware-efficient demonstrations of L/EACO-OFDM transmitter modulated with QPSK [13], the slight increase of logic resource utilization comes from the 16-QAM modulation format encoded on the OFDM subcarriers.

3. Experimental setup

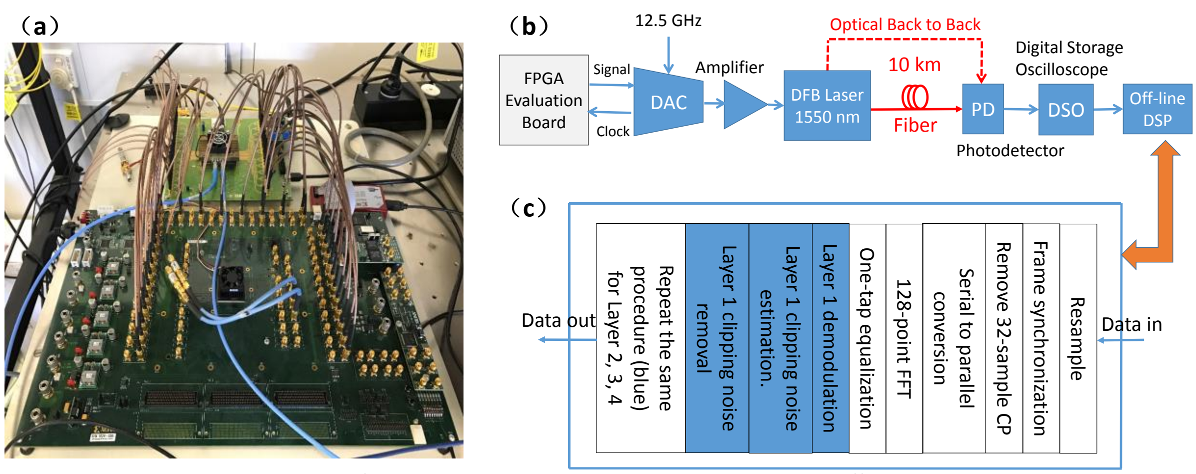

Fig. 2: (a) Connection of FPGA and DAC. (b) Experimental setup diagram. (c) Off-line DSP algorithm.

The picture and block diagram of the transmitter setup are shown in Fig. 2(a) and (b). The DAC clocked at 12.5 GHz provided a 156.25-MHz clock to the FPGA, which was not only used to control all the DSP modules in the FPGA but also to synchronize the FPGA and DAC. Each FPGA's high speed transmitter was programmed to have a data rate of 6.25 Gb/s. Therefore, each four parallel output streams from the FPGA were multiplexed to form 25-GSa/s digital input in the DAC. Since 16QAM modulation was used for all of the 30 subcarriers, the overall net data rate was up to 18.75 Gb/s (4×25×30/160).

The peak-to-peak (p-p) voltage of the DAC analog output signal was 500 mV. The signal was fed through 18-dB attenuators and a DC block, and then were amplified by 24 dB via a 40-GHz linear electrical amplifier (SHF-807). The resulting 1-volt (p-p) output was connected to a distributed feedback (DFB) laser, which was biased at 36 mA. After transmission over a 10-km span of SSMF, a 16-GHz photodetector (DSC-40S) was used to convert optical signals to electrical signals, which were then sampled by a real-time Digital Storage Oscilloscope (DSO-X92804A) at 80-GS/s. Finally, off-line DSP was performed in the MATLAB and is illustrated in Fig. 2(c). Basically, it is the same as used in typical OFDM receivers; however, for L/EACO-OFDM, an iterative demodulation algorithm is required to decode the data layer by layer [7-11].

4. Experimental results

Firstly, the Q-factor performance for a back-to-back optical link was measured by directly connecting the laser output to a photodetector. As shown in Fig. 3(a), the average Q-factor of optical back-to-back is 19.58 dB. As the Q-factors of adjacent-index subcarriers in different layers are very similar, we conclude that the iterative algorithm in the receiver substantially cancels the clipping distortion. There is a 3-dB penalty for the highest-frequency subcarriers due to the bandwidth limitation of the laser [13]. Finally, the Q-factor was evaluated after transmission over a 10-km SSMF. Without using optical amplifiers, the Q-factor is still above 19 dB (Q = 16.54 corresponding to a BER of 3.8×10^{-3} for 16QAM) and there is no error propagation to higher layers, as shown in Fig. 3(b). However, the higher-index subcarriers suffer a penalty ~3 dB, compared with the low-frequency subcarriers, most probably because of the interaction of laser chirp and fiber dispersion [13].

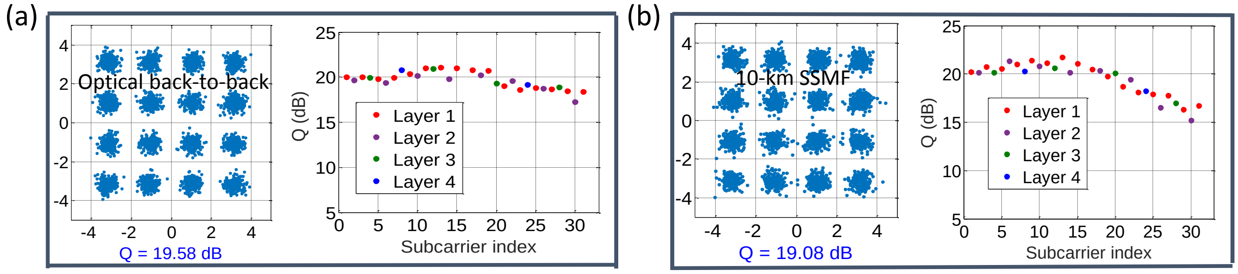

Fig. 3: Q-factors for: (a) Optical back-to-back. (b) 10-km SSMF transmission.

5. Conclusions

In this paper, a middle-out IFFT has been developed and then implemented in an FPGA to generate the L/EACO-OFDM signal. By using a DML and off-line signal processing in the receiver, this 16-QAM-encoded L/EACO-OFDM transmitter has been successfully transmitted over 10-km SSMF with a Q-factor of 19.08 dB. In the future, single sideband modulation, bit- and power-loading could be used to further improve the transmission distance.

Acknowledgements
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