Efficient IFFT Implementation in an ACO-OFDM Transmitter

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***Abstract*—A computationally efficient IFFT implementation for asymmetrically clipped optical OFDM transmitter is proposed and implemented in a Field-Programmable Gate Array. The overall computational complexity is reduced by 68% in a real-time transmitter.**

Keywords— ACO-OFDM; intensity modulation with direct detection; IFFT implementation; FPGA; optical communication

I. INTRODUCTION

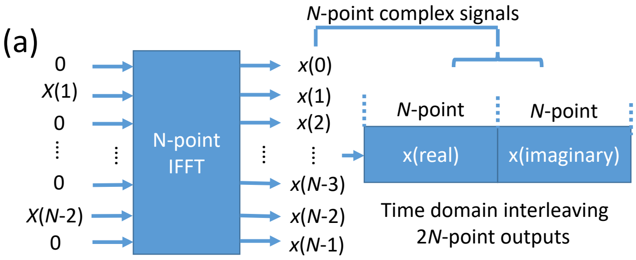
Intensity modulation with direct detection (IMDD) has emerged as a strong candidate for next-generation short-haul optic-fiber links, primarily due to the ability to fit the necessary components for transponders into small packages. Orthogonal frequency division multiplexing (OFDM) has been widely explored for IMDD-based optical communication systems, because higher-order modulation formats can be imposed on the subcarriers to achieve high spectral efficiency [1], [2]. However, OFDM signals are bipolar, so a significant DC bias needs to be added to prevent negative peaks being clipped. As a solution to the bias issue, asymmetrically clipped optical OFDM (ACO-OFDM) [3] generates unipolar OFDM signals to give a high optical power efficiency, by clipping all negative peaks at the mean level, and only loading one-half of the subcarriers. Hermitian symmetry is usually adopted in an ACO-OFDM transmitter by constraining the inputs of IFFT to achieve a real-valued output waveform. This will double the required IFFT size for a given number of subcarriers because only half of the IFFT inputs are independent. Previously, by interleaving the real and imaginary parts of the complex output signal in the time domain, size-efficient IFFT/FFTs have been simulated [4] and experimentally demonstrated [5]-[7] using off-line digital signal processing (DSP); these have the same performance as the Hermitian symmetry constrained IFFT/FFT. However, a practical implementation of an ACO-OFDM transmitter based on size-efficient IFFT has yet to be demonstrated, to identify how the logic resource requirements can be reduced.

In this paper, we implement an ACO-OFDM transmitter in a Virtex-6 FPGA chip using the existing size-efficient IFFT technique, reducing the computational resources to less than half that of a conventional IFFT. By taking advantage of the regular zero inputs of IFFT, we can gain a further one-third reduction in computation over the size-efficient IFFT, by reorganizing the IFFT implementation. Finally, the Q-factors of this ACO-OFDM transmitter for optical back-to-back and 15-km standard single-mode fiber (S-SMF) transmission are evaluated using off-line DSP in the receiver and compared with a conventional one constrained by Hermitian symmetry.

II. OPTIMIZED SIZE-EFFICIENT IFFT IMPLEMENTATION

ACO-OFDM uses only the odd-indexed subcarriers to carry information, so the IFFT generates an anti-symmetric time domain signal within each symbol. A positive-value-only signal is achieved by clipping all the negative values to zero [3]. As all of the resulting clipping distortion falls on the even subcarriers, the odd subcarriers can be decoded as a normal OFDM signal.

The proposed size-efficient technique is illustrated in Fig. 1(a). By discarding the limitation of Hermitian symmetry, N/2 IFFT inputs can be used to carry data (on the odd subcarriers), rather than N/4. The complex outputs of an N-point IFFT module, sorted into their real and imaginary parts to be interleaved in the time domain to form 2N-point signal waveform (per OFDM symbol). In the receiver, the inverse procedure can be used to decode the data [4].



(b)

ACO-OFDM Implementation Scheme	Conventional 128-point IFFT	Size-efficient 64-point IFFT	Optimized size-efficient 64-point IFFT
Number of DSP48E1s (Multipliers)	700	332	224

Fig. 1. (a) Real and imaginary parts interleaving; (b) Number of Multipliers.

Compared with conventional methods that need 2N-point IFFTs with the Hermitian symmetry input constraints, the computational complexity is reduced [8]. However, as half of the inputs of the IFFT module in an ACO-OFDM transmitter are always zero, another optimization method can be conducted to further simplify its implementation. An 8-point radix-2 decimation-in-time IFFT butterfly chart is shown in Fig. 2 to illustrate this optimization method. All of the inputs in the top-half (grayed) correspond to even-frequency subcarriers, which are always zero for ACO-OFDM. Therefore, only the numbers in the bottom-half are required to be calculated. The output signals $x(0\text{-}3)$ in the top-half can be obtained directly from $x(4\text{-}7)$ because they just differ in sign.

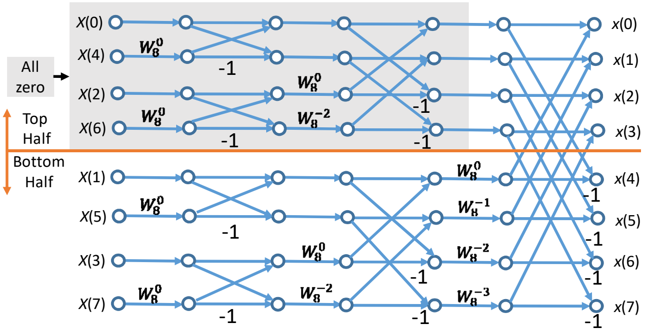


Fig. 2. An 8-point radix-2 decimation-in-time IFFT butterfly chart.

In order to see the implementation cost for different methods, we implemented one 128-point IFFT, one 64-point IFFT and one our optimized 64-point IFFT in a Virtex-6 FPGA chip separately. As multipliers dominate the hardware computational complexity, FPGA DSP48E1s resource utilization after implementation for different methods are shown in Fig. 1(b). It is clear that the size-efficient IFFT technique only needs 332 multipliers, saving approximately 52.6% of the FPGA's logic resources, compared with 700 multipliers used by the conventional IFFT implementation. Through our optimization, another 108 multipliers are not required. Therefore, overall, 68% of the logic resources can be saved by using the optimized IFFT size-efficient technique, which is a significant amount reduction of computational complexity.

III. ACO-OFDM EXPERIMENTAL SETUP

A. Transmitter Implementation

The ACO-OFDM transmitter setups based on the conventional and our optimized size-efficient IFFT implementation are shown in Fig. 3(a) and (b). QPSK modulation was imposed on OFDM subcarriers for both the implementations. After the data distribution module, the conventional ACO-OFDM transmitter used a 128-point IFFT with Hermitian symmetry constraint, so only the real parts of its output were used. The size-efficient IFFT implementation used a 64-point IFFT of which the real and imaginary parts were processed individually and then interleaved in the time domain after adding the cyclic prefix (CP). Both the IFFT modules had a resolution of 12 bits, which is a compromise between computational accuracy and hardware resource occupation [9], [10]. Both the set-range and quantization modules generated 128 5-bit words because the DAC had a resolution of 5 bits. Finally, 160 5-bit words for both techniques were parallel to serial converted through SerDes in the FPGA and sent to the DAC to generate analog OFDM output signals. As 16 subcarriers were used to carry QPSK mapped data, the overall net data rate is 5 Gb/s (2×25×16/160) for both the techniques, neglecting an overhead of two training symbols.

B. Experimental Setup

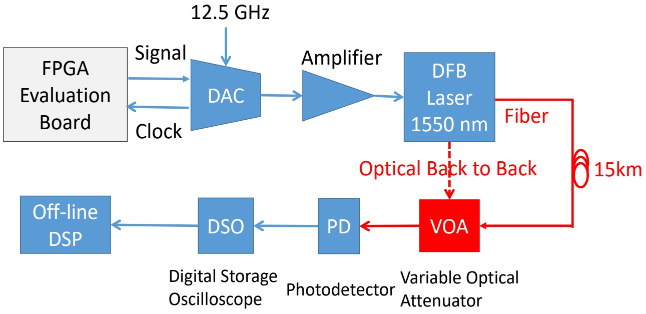


Fig. 4. Experimental setup for both ACO-OFDM transmitters.

The experiment setup of both ACO-OFDM transmitters are the same and shown in Fig. 4. A 156.25-MHz clock generated by the DAC provided a clock to the FPGA, which was not only used to control all the DSP modules in the FPGA but also synchronizes the FPGA and DAC. The synchronization method was discussed in [11] and was used in this experiment. All the twenty high-speed transmitters in the FPGA were programmed to have a data rates of 6.25 Gb/s; the four 5- bit parallel output streams from the FPGA were sampled by the 5-bit DAC at a sampling rate of 25 GS/s when clocked at 12.5 GHz.

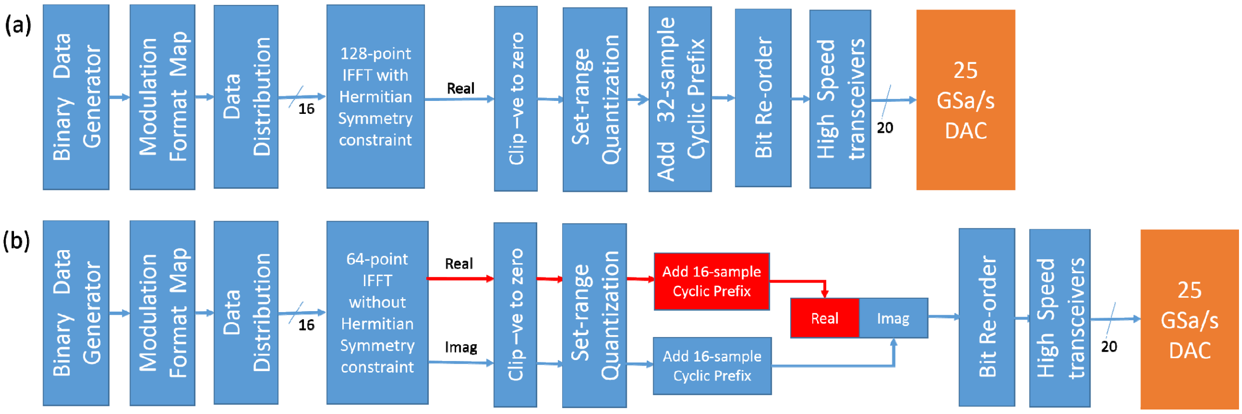


Fig. 3. ACO-OFDM transmitter using: (a) A conventional IFFT; (b) The proposed optimized & size-efficient IFFT.

The peak-to-peak voltage of DAC analog output signal was around 500 mV. The signal was fed through 18-dB attenuators and a DC block, followed by a 24-dB gain 40-GHz linear electrical amplifier (SHF-807). The resulting 1-volt (p-p) output signal was connected to a distributed feedback laser, which was biased at 33 mA. After transmission over a 15-km S-SMF, a variable optical attenuator (VOA) was used to adjust the output optical power, followed by a 16-GHz photodetector (DSC-40S) to convert optical signals to electrical signals, which were then sampled by a real-time Digital Storage Oscilloscope (DSO-X92804A) with an 80-GS/s sampling rate. Finally, the captured samples were analyzed by off-line DSP in MATLAB. All the parameters in the transmission link were the same for both ACO-OFDM transmitters.

IV. EXPERIMENTAL RESULTS

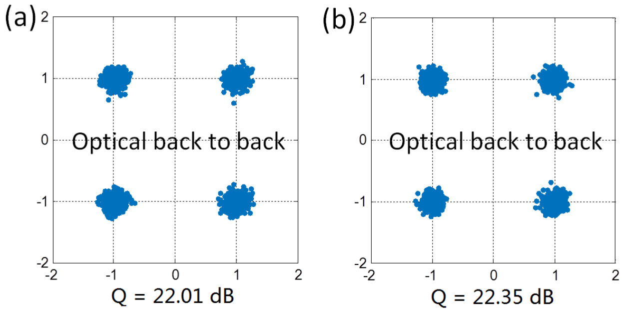


Fig. 5. Q-factors for optical back-to-back using: (a) A conventional IFFT; (b) The proposed optimized & size-efficient IFFT.

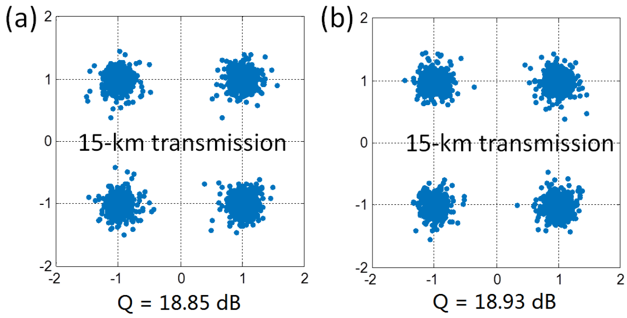


Fig. 6. Q-factors for 15-km S-SMF transmission using: (a) A conventional IFFT; (b) The proposed optimized & size-efficient IFFT.

The results for both implementations of ACO-OFDM transmitter are shown in Fig. 5. The Q-factors for a back-to-back optical link were measured by directly connecting the laser output to the VOA. No optical attenuation was added by the VOA in this experiment. For Fig. 6, 15-km S-SMF was used for the optical transmission link. It can be clearly seen both in Fig. 5 and Fig. 6, that the Q-factors are not affected by the IFFT implementation, which means that our optimized size-efficient IFFT implementation can be used to replace the conventional Hermitian symmetry constrained IFFT implementation in real-time ACO-OFDM transmission links, significantly saving logic resource occupation and power.

ACKNOWLEDGMENT

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