21.4 GS/s Real-Time DSP-Based Optical OFDM Signal Generation and Transmission Over 1600 km of Uncompensated Fibre

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Abstract *We report a real-time optical OFDM transmitter with the highest sampling rate to date. Generation and transmission of an 8.36Gb/s digitally up-converted single sideband OFDM signal over 1600km of uncompensated fiber with a BER<10^{-3} was achieved.*

Introduction

Major advances in extending the range, tolerance and data throughput of optical orthogonal frequency division multiplexing (OFDM) have been achieved both for coherent and direct detection[1, 2]. However these were achieved using arbitrary waveform generators at the transmitter and fast sampling oscilloscopes at the receiver coupled with offline processing at both the transmitter and the receiver. In order to go one step further towards deploying optical OFDM in real systems and confirming its viability, it is necessary to investigate the OFDM techniques and algorithms in real-time transceivers. Recently, a 2.5 GS/s real-time coherent optical OFDM receiver and a 2GS/s transceiver system have been reported[3, 4]. In this paper we present the design and experimental results of a 21.4GS/s real-time, FPGA-based optical OFDM transmitter. Using a 10-bit 128-point IFFT core, we carried out a recirculating loop experiment with an 8.36 Gb/s single sideband QPSK direct-detection OFDM over 1600 km of uncompensated standard SMF with a BER < 10^{-3} and an OSNR penalty of 0.6 dB, a major improvement on our previous results[5].

Transmitter Design

Figure 1a shows the FPGA-based optical OFDM transmitter top level design. The DSP was performed on a Xilinx Virtex-4 (4VFX100) FPGA which was interfaced to a 21.4 GS/s, 4-bit resolution DAC constructed from discrete components[6]. The FPGA functions are shown in Fig. 1b. A bit sequence comprising a 2^{15} DeBruijn pattern and synchronization overhead were stored in a read only memory (ROM) on the FPGA and a block of N=50 bits was read out each clock cycle. The choice of N is related to the oversampling rate, modulation format and the IFFT size deployed. In this work, we used 128-point IFFT, 1.28 oversampling and QPSK format resulting in an effective bandwidth of 4.18GHz and a bitrate of 8.36 Gb/s. The 50-bits were modulated to form 25 complex 10-bit values representing the QPSK constellation and fed to the 26:50 IFFT ports. This maps the OFDM data onto 25 sub-channels over the 4.18 – 8.36 GHz band selected so that no second order intermodulation products fall on the used subcarrier frequencies. During each clock cycle, the IFFT core generated 128 10-bit complex outputs, only the real parts of which were sent to the clipping module and converted into 4-bit words compatible with the 4-bit DAC deployed. We utilised the automated tool Spiral[7] to generate the 128-point IFFT hardware core utilising a mix of radix 8 and radix 16 algorithms. This processed all 128 words (two's complement fixed point format) in parallel to support a throughput of one transform per cycle at a frequency of 167.2 MHz.

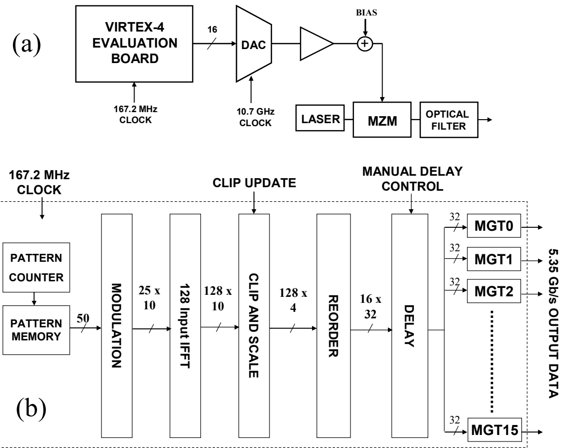

Fig. 1: Transmitter design a) top level hardware b) FPGA functions.

The clipping and scaling could be updated during operation and the resulting 128 4-bit words were rearranged to 16 32-bit words for outputs by the multi-gigabit transceivers (MGT's) on the FPGA. The amount of clipping is mainly dependent on the resolution of the DAC utilised and we found the optimum clipping ratio in this case to be 4.5 dB.

Transmitter Performance & Optical Transmission

First, the output of the DSP/DAC was measured using a 50 GS/s real-time sampling scope and demodulated by offline processing using an ideal receiver model (electrical back-to-back). Synchronization was carried out by sending two consecutive OFDM symbols carrying identical known data. The quality of the signals was assessed from the resulting constellations through the use of the error vector magnitude (EVM). Fig. 2a shows the OFDM spectrum obtained by FFT of the time domain waveform. The EVM and the equivalent BER (assuming Gaussian statistics) for each channel is shown in Fig. 3a (hollow circles) where channels 1 and 25 represent the lowest and the highest frequencies respectively (4.18 and 8.36 GHz). Due to the frequency roll-off of the DAC, the quality of the channels decreases with increasing subcarrier frequency which could be mitigated by employing a pre-equalisation function in the DSP (this was not implemented in this work). Next, the DAC was connected to the optical modulator and the back-to-back optical performance was assessed using direct-detection and the same receiver model. The output QPSK constellation is shown in Fig. 2b. The EVM for each sub-channel is shown in Fig. 3a (triangles) where a 1 dB penalty compared to the electrical back-to-back can be observed.

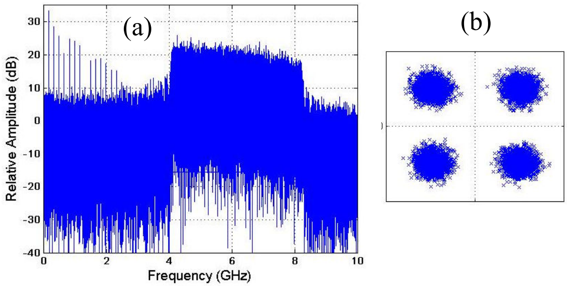

Fig. 2: a) Electrical back-to-back spectrum b) Optical back-to-back constellation

The EVM against OSNR (0.1nm RBW) of the transmitter was measured in the optical back-to-back configuration using noise loading and is shown in Fig. 3b. The circle markers show the average EVM across all 25 sub-channels where it can be observed that an EVM of -9.8 dB (BER = 10^{-3}) was measured for an OSNR of 17 dB. The dashed and the solid lines represent the theoretical curves for a 3 and 4-bit DAC respectively. These curves were generated by modelling a 10-bit IFFT core and a DAC with no frequency roll-off. Electrical noise of the DAC was not included in the simulation. The average EVM of the system is higher than the theoretical one because of the difference in the quality between the higher and lower frequency sub-channels due to the DAC response. We expect the average EVM of the system to be in the same range as the first 5 sub-channels should pre-equalisation be deployed and this is in good agreement with the theoretical curves of Fig. 3b where the effective number of bits of our DAC is between 3 and 4 (triangles). Finally, we used the transmitter in a recirculating loop that consisted of an 80 km span of standard SMF and no optical dispersion compensation[8]. The signal was circulated 20 times for a total distance of 1600 km with -3 dBm launch power and the received OSNR was 20dB. No cyclic prefix was implemented in this experiment and dispersion equalization was performed off-line at the receiver. The EVM per sub-channel is shown in Fig. 3a (squares) where the average EVM of the system after 1600 km was -11.1dB, equivalent to a BER of 2 $\times 10^{-4}$. From Fig. 3b, the back-to-back EVM at 20 dB OSNR was -11.7dB and therefore the back-to-back penalty after transmission was 0.6 dB.

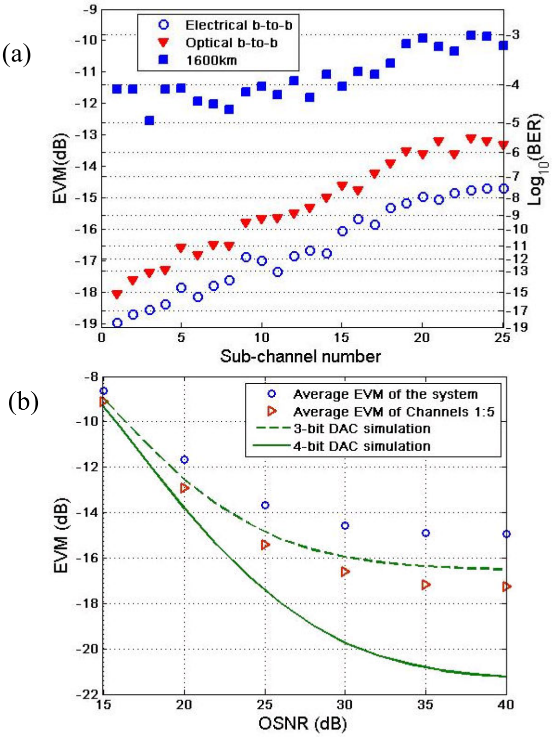

Fig. 3: a) EVM per sub-channel for electrical & optical back-to-back and 1600 km b) b-to-b EVM vs. OSNR

Conclusions

We presented a 21.4 GS/s real-time FPGA-based optical OFDM transmitter that was used to generate and transmit 8.36 Gb/s single sideband OFDM signals over 1600 km of standard fibre. The back-to-back OSNR penalty was 0.6 dB and an EVM of -11.1dB corresponding to a BER < 10^{-3} was achieved. The performance of the transmitter could be further improved by using a higher resolution DAC and deploying a DAC pre-equalisation function.

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