Realisation of a real-time 12.1 Gb/s optical OFDM transmitter and its application in a 109 Gb/s transmission system with coherent reception

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Abstract *For the first time a realisation of a real-time 12.1 Gb/s FPGA-based O-OFDM transmitter is demonstrated (Q=19.1 dB) and successfully applied in a 9x12.1 Gb/s transmission over 400 km SMF.*

Introduction

Recently optical OFDM systems have been extensively studied [1,2] and especially coherent optical OFDM was found to deliver high sensitivity and high CD/PMD tolerance. Due to unavailability of real-time OFDM transmitters in many experimental investigations pre-calculated OFDM signals using floating point arithmetic signal processing are stored in the memory of an arbitrary waveform generator (AWG) and sent sequentially. Hence a limitation in the number of different OFDM symbols is mandatory. First online FPGA-based OFDM transmitters and receivers have been reported strongly limited in data-rate at 2 to 3.1 Gb/s [3-5]. A direct increase in data-rates suffers from available FPGA resources.

In this paper we report for the first time a high data rate real-time FPGA based OFDM transmitter integrated with two 10 GSa/s digital to analog converters (DACs). PRBS sequences of 2^{31}-1 length are applied to a 256 point IFFT using reduced complexity full integer arithmetic with 10-bit resolution maximum. Pilot symbols for frequency offset correction, symbol synchronization and channel estimation are calculated and added to payload exhibiting a net data-rate of 12.1 Gb/s. Finally, 400 km transmission experiments at 109 Gb/s with coherent reception are performed using an online transmitter and an offline receiver. Hence for the first time random pattern can be applied in OFDM transmission experiments at data rates beyond 10 Gb/s.

FPGA-based transmitter

The real-time transmitter is based on a Xilinx Virtex 5 FX 200T FPGA. A 2^{31}-1 length PRBS generator is realized driving the QPSK mapper. All 256 IFFT inputs are realized with 5 input levels [-1-j, -1+j, +1-j, +1+j, 0] for QPSK subcarrier modulation and for optionally zero padding each subcarrier. The IFFT function is a 3 to 10 bit resolution integer arithmetic realization for real and imaginary part, respectively.

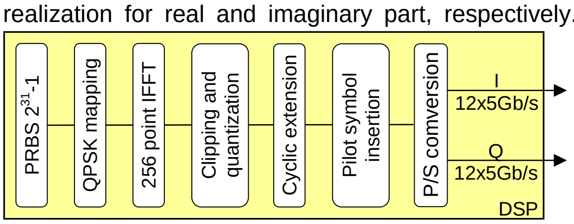

Fig. 1. Real time O-OFDM transmitter: DSP architecture.

The IFFTs twiddle factors are 2x5 bit in resolution. After IFFT a combined 1 bit clipping and 3 to 1 bit re-quantization is applied to limit the data resolution to 6 bit. 8 samples are applied for cyclic pre- and postfix, each. Every 126 payload symbols two synchronization symbols are applied. A first pilot symbol is generated for symbol synchronization and local oscillators frequency offset correction applying 4 positive and 4 negative subcarriers (every 16th is applied) generating a periodic symbol with 16 periods [6]. Due to low number of applied subcarriers the time domain samples are amplified by a factor of 8 to equalize the symbol power. A second pilot symbol containing a regular data pattern mapped to 168 subcarriers is applied for channel estimation.

The time domain samples for real and imaginary signal components are reorganized, parallel to serial converted and output via 2x12 Rocket I/Os operated at 5 Gb/s. A further 1:16 DEMUX was required to interconnect the FPGA with the commercial 10-GSa/s DACs. The resolution of DAC was limited to 6 bit.

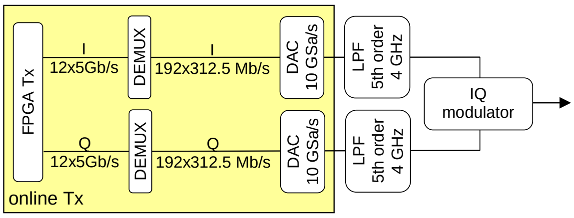

Fig. 2. Real time OFDM transmitter: FPGA-DAC integration.

Q-factor measurements have been performed in an electrical back-to-back configuration using a real-time scope. A mean Q-factor of 19.1 dB and a minimum Q of 18.97 dB has been measured.

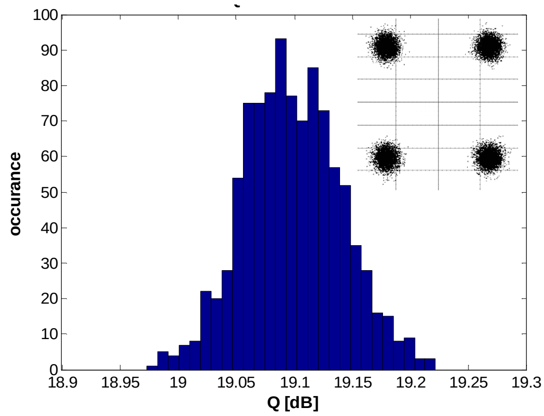

Fig. 3. Distribution of electrical Q-factor for PRBS 2^{31}-1.

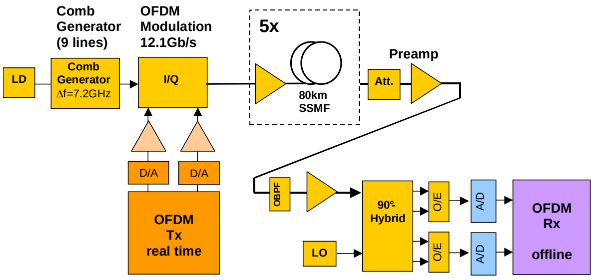

Fig. 4. Setup for transmission experiments.

109 Gb/s transmission experiments

For evaluation of the BER performance of the real-time FPGA transmitter, an optical transmission setup similar to [7] was used (cf. Fig. 4.). For reception a coherent receiver with subsequent offline processing, including synchronization, frequency offset compensation and channel estimation by a reference symbol was used.

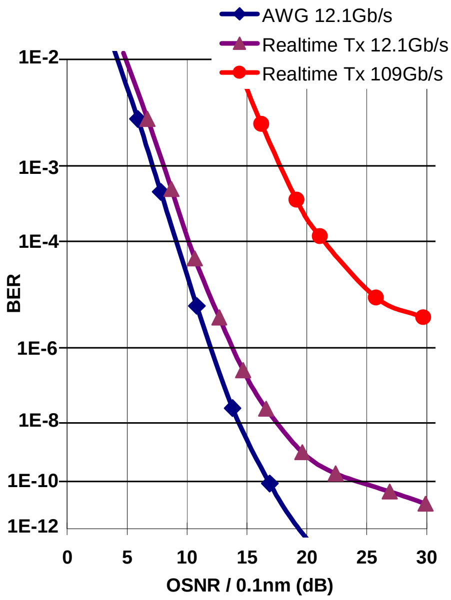

Fig. 5. Estimation of BER in back-to-back configuration of offline Tx with AWG (diamonds), FPGA based real-time Tx (triangles) and 109Gb/s transmission (bullets)

Back-to-back measurements have been performed using the real-time transmitter and for comparison a setup using an arbitrary waveform generator (AWG) with a D/A-resolution of 8 bit and a full floating point accuracy during signal calculation. As shows in fig. 5 an OSNR-penalty of 1 dB at BER 1E-3 for the real-time transmitter was found. Also a penalty in the low noise regime (BER<1E-8) was observed. This is attributed to the limited numerical accuracy of the signal generation in the FPGA and a higher I/Q-imbalance when driving the optical I/Q-modulator due to experimental constraints.

To generate a 109 Gb/s O-OFDM signal a comb generator consisting of two cascaded Mach-Zehnder modulators was used [7]. The MZ-modulators were driven with a sinusoidal signal of 21.6 GHz and 7.2 GHz, respectively, thus generating 9 lines with a spacing of 7.2 GHz out of a single optical cw-source. All 9 lines were simultaneously modulated with the OFDM signal. Since no polarisation multiplexing was introduced in this setup, we achieve a spectral efficiency of 1.6 bit/s/Hz for single polarization transmission considering 7% FEC-overhead. The excess penalty due to narrow multiplexing of the OFDM spectra is about 0.3 dB, however some penalty in the low noise regime due to spectral overlap of out of band noise was observed (Fig.5)

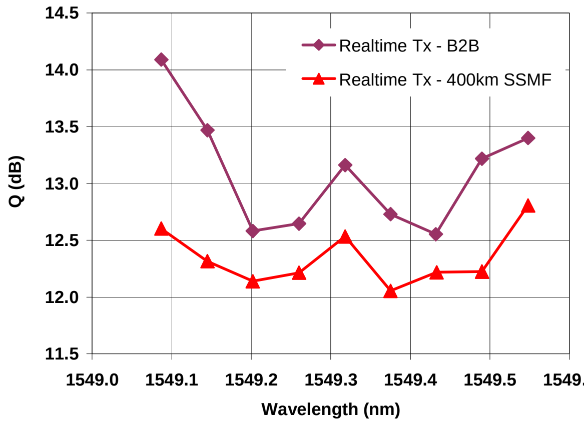

Fig. 6. Q-factor measurement in back-to-back configuration(diamonds) and after transmission over 400km SSMF(triangles)

Fig. 6 shows the Q-factor measurement for all 9 OFDM-subbands in back-to-back configuration and after transmission over 5x80 km SSMF. The variation of the Q-factor over wavelength is determined by the position of the respective subband within the spectrum. The average Q-factor for 109-Gb/s transmission was 13.1 dB (back-to-back) and 12.35 dB (400km SSMF) respectively, showing a mean penalty for transmission over 400 km SSMF of about 0.75 dB. The worst estimated BER after transmission was 3.24E-5.

Conclusion

We have demonstrated for the first time a real-time FPGA based OFDM transmitter at high speed data-rate of 12.1 Gb/s. A high speed IFFT implementation was realized requiring full integer arithmetic leading to a competitive Q-factor of 19.1 dB for electrical back-to-back performance and the minimum Q was 0.13 dB below mean value even for long PRBS with 2^{31}-1 length. 109 Gb/s 400 km transmission experiments have been successfully performed using the real-time transmitter in combination with a 9 line comb generator and a coherent OFDM receiver with offline processing.

References

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