Realization of a Real-Time 93.8-Gb/s Polarization-Multiplexed OFDM Transmitter with 1024-Point IFFT

Beril Inan [1], Susmita Adhikari [2], Ozgur Karakaya [1], Peter Kainzmaier [3], Micheal Mocker [3], Heinrich von Kirchbauer [3], Norbert Hanik [1], Sander L. Jansen [3]

1. Institute of Communications Engineering, Technische Universität München, Arcisstrasse 21 D-80333, Munich, Germany, beril.inan@tum.de

2. Chair for Communications, Christian-Albrechts-Universität, Kiel, Germany

3. Nokia Siemens Networks GmbH & Co. KG, Munich, Germany

Abstract: We demonstrate a 93.8-Gb/s real-time optical OFDM transmitter with 1024-point IFFT using polarization-multiplexing and 4-QAM modulation. A required OSNR of 26.5 dB is measured for a BER of 10^{-3}.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

Coherent orthogonal frequency division multiplexing (CO-OFDM) offers all advantages of coherent detected modulation formats, such as dispersion un-managed transmission and electronic compensation of polarization-mode dispersion [1, 2, 3]. In addition, CO-OFDM is highly suitable for the implementation of flexi-rate transponder technology, i.e. the ability to switch between modulation format depending on the physical infrastructure. In next-generation transmission systems this is particularly important to find the optimum balance between maximum transmission reach and maximum feasible spectral efficiency. The negligible out-of-band signal power [3] of CO-OFDM makes it possible to multiplex multiple channels or sub bands with only small frequency spacing. Several experiments have been reported showing the generation of multi-band channels using CO-OFDM, realizing up to 1 Tb/s super-WDM channels for long-haul transmission systems [1, 2]. This indicates that CO-OFDM is an ideal candidate for next-generation 400G/1T transmission

Real-time OFDM implementations have attracted significant attention since it is essential to understand the limits of realistic digital signal processing (DSP) algorithms. In particular, a high IFFT size is required in order to keep the overhead for cyclic prefix at a minimum. In addition, a high FFT size provides a clear separation of OFDM symbol and RF pilot used for laser phase noise compensation [4]. Table 1 summarizes recent real time OFDM transmitter achievements.

Ref	Bandwidth (GHz)	Data Rate (Gb/s)	IFFT size	Cyclic Prefix
[5]	4.2	8.4	128	0
[6]	6.3	12.1	256	8
[7]	1.9	11.3	32	8
[8]	25.4	101.5	64	0
[9]	11.9	23.9	1024	64
This Work	**23.4**	**93.8**	**1024**	**64**

Table 1: Some recent real time transmitter work.

In this paper we demonstrate a real-time CO-OFDM transmitter that utilizes 1024 point IFFT and polarization multiplexing. Two FPGA boards with Xilinx Virtex 5 chips are used in synchronization for the implementation. 4 QAM is used as a modulation format resulting in a nominal data rate of 93.8-Gb/s. For a BER of 10^{-3} a required OSNR is measured of 26.5 dB.

2. Experimental Setup

Fig. 1 illustrates the electrical and optical blocks of the real-time transmitter. The processing of the 1024-point FFT is realized with two synchronized Xilinx ML525 boards. Each ML525 board is connected to a high speed DAC using 24 differential connections at 6.25 Gb/s each. On the DAC board four groups of 6 bit each are built from the 24 inputs and then 4:1 multiplexed in order to form a stream of 25 GS/s at 6-bit vertical resolution. The DAC boards are fed with a 12.5 GHz clock. One of the DACs provides a reference clock at 195.3 MHz to the two FPGA boards. The data is QAM mapped and a gap of 20 subcarriers is inserted in the middle of spectrum for the RF-pilot laser phase noise compensation technique [4]. The payload is concatenated with the training symbols whose peak-toaverage power ratios (PAPR) is minimized so that nonlinearities do not degrade the performance of channel equalization at the receiver. The digital signal processing in the real time transmitter is depicted in Fig. 1. Initially the QAM mapped bits are prepared for the complex IFFT. This preprocessing allows using one complex IFFT as two real valued IFFTs. Consequently the processing speed of the FPGA can be reduced to half [9]. After the IFFT, data stream is clipped, the cyclic prefix is added. The real and imaginary parts are reorganized in deinterleaving block so that they are one after another in order to get a real output stream for DACs. Finally, the parallel data streams are multiplexed together into 24 channels that are sent to the Rocket I/Os.

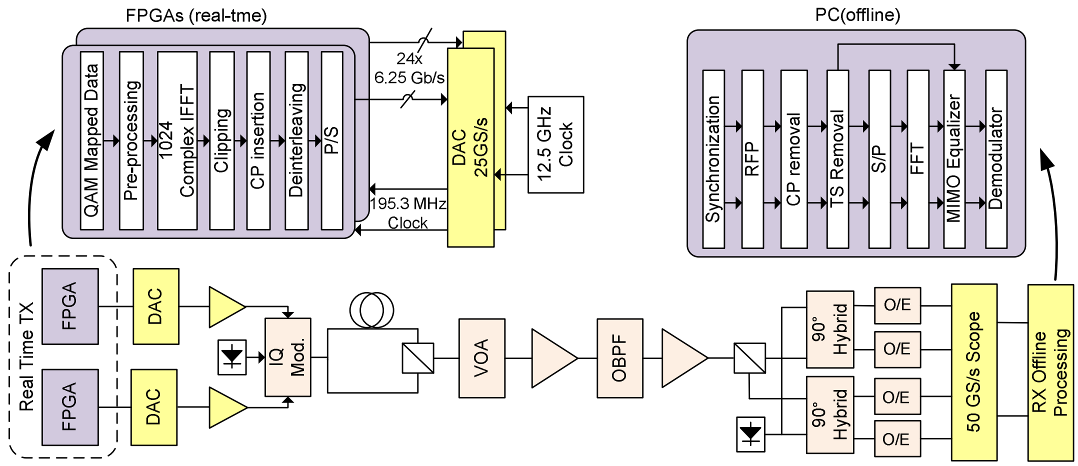

Fig. 1: Experimental setup including real time transmitter with FPGA and DAC boards, optical setup and offline processing blocks.

The optical setup is demonstrated in Fig. 1. DAC outputs are amplified and fed to an IQ modulator. The laser used at the transmitter and receiver are ECL lasers with a linewidth of ~100 kHz. The polarization multiplexing is emulated by the use of one symbol delay and polarization beam splitter. At the receiver, coherent detection is realized with a polarization diverse 90 degrees hybrid and single ended photodiodes. After coherent detection offline processing is used including laser phase noise equalization, synchronization, and channel equalization with training symbols [3].

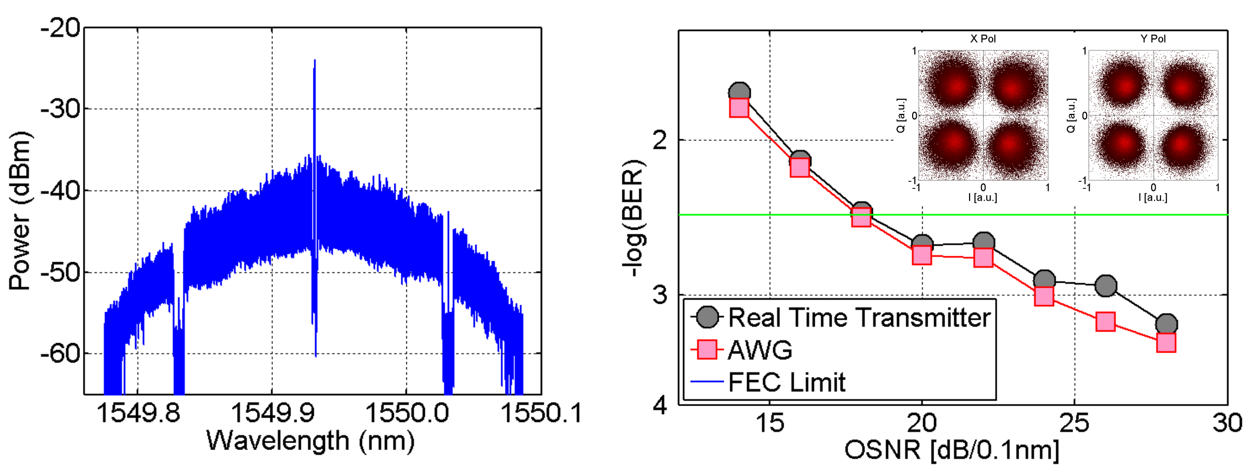

Fig. 2a: Optical spectrum of the 93.8-Gb/s OFDM signal, Fig. 2b: BER performance as a function of the OSNR (inset: constellation diagram of both polarizations at high OSNR).

3. Results

A back-to-back performance evaluation was carried out in order to evaluate the performance of the real-time CO-OFDM transmitter. The following parameters were used; 960 subcarriers out of 1024 are 4 QAM modulated and 64 samples of cyclic prefix are added to each OFDM symbol in this experiment. 20 subcarriers in the middle of the spectrum are unmodulated in order to spare a gap for RF-pilot compensation. The rest of the subcarriers are used for oversampling. Two training symbols are sent every 40 payload symbols. Fig. 2a shows the optical spectrum at the output of the PDM-OFDM signal. Aliasing products of the DAC are visible at both sides of spectrum. Optionally LPFs can be used to eliminate these spectral components. Moreover, a pre-equalization function can improve the frequency roll-off of higher frequencies. The constellation diagram of the real time transmitter at high OSNR is depicted in the inset of Fig 2b. In this constellation diagram the effects of residual laser phase noise and quantization noise are clearly visible. Fig. 2b, in which for all measured points a minimum of 2 million bits are evaluated, shows the required OSNR for a BER of 10^{-3}. In this figure a comparison between the real time transmitter and the performance when the FPGAs are utilized as arbitrary waveform generator (AWG). For high BER values up to $5x10^{-3}$ a relatively small penalty of ~0.2 dB is observed between the real-time transmitter and the AWG. For lower BER values the penalty of the real-time transmitter gradually increases up to approximately a 2dB difference for $7x10^{-4}$.

4. Challenges of the 1024 Point IFFT realization

The IFFT uses the decimation in time radix 2 algorithm and for the 1024-point implementation almost all resources of the FPGA are used. The DSP uses 82% of DSP48E, 28% of block RAMs, 85% slice registers and %72 slice look up tables, one phase locked loop and one digital clock manager. The excessive usage of FPGA makes it challenging to place and route the code in the FPGA without any timing violations. [9] shows the single polarization performance of previous generation of DACs at 25 GS/s. The new generation of DACs used for this paper work in principle sampling rates up to 30 GS/s. However, in this experiment the sampling rate was limited to 25 GS/s because of the limitations of the FPGAs. In comparison to the previous generation of DACs a synchronization code with the FPGAs was required which involved shifting a PRBS sequence that required extra FPGA resources. As a result, the complete FPGA code drew 16 A of current at 25 GS/s. At such high current it is challenging to keep the internal voltage of FPGAs within the operating range ($0.9V < V_{int} < 1.1V$). At higher sampling rates a higher current would have been required which would lead to a too large voltage drop to the FPGA core in addition to a performance degradation caused by the fact that the FPGA boards heat up. In [9], where the data rate is less than 25 Gb/s, the penalty between the AWG and real time transmitter was negligible. On the other hand, in this paper, more subcarriers are modulated to achieve a higher data rate and some new functionalities are added such as the PRBS scrambling, PRBS shifter and pre-processing function. Consequently, the resource limitations of the FPGA are pushed even further resulting in an increase of the real-time implementation penalty.

5. Conclusions

We successfully demonstrate a real time optical OFDM transmitter at 93.8 Gb/s with a 1024 point IFFT size and polarization multiplexing. Compared to arbitrary waveform generator a significantly power increase observed in FPGA resulting in an OSNR penalty of up to 2 dB at a BER of 10^{-3}. This clearly shows the challenges involved for the implementation of a real time 1024 point IFFT.

6. Acknowledgement

The authors would like to thank Hans-Peter Rosinger, Paolo Novellini from Xilinx; Dirk Van den Borne, Erik De Man, Eugen Widmann from Nokia Siemens Networks, Vincent A.M.J. Sleiffer, Mohammed S. Alfiad from Technische Universitaet Eindhoven, Paolo Leoni and Adriana Lobato from der Bundeswehr Universitaet Muenchen for their support in this work.

6. References

[1] W. Shieh, "OFDM for Adaptive Ultra High-Speed Optical Networks", in Proc. OFC, (2010)
[2] S. Chandrasekhar and Xiang Liu, "Terabit Superchannels for High Spectral Efficiency Transmission", in Proc. ECOC, (2010)
[3] S. L. Jansen, Itsuro Morita, T. C.W. Schenk, and Hideaki Tanaka, "121.9-Gb/s PDM-OFDM TransmissionWith 2-b/s/Hz Spectral Efficiency Over 1000 km of SSMF", JLT, vol. 3, no 3, pp 177-188 (2009)
[4] S. Randel, S. Adhikari, S.L. Jansen, "Analysis of RF-Pilot-based Phase Noise Compensation for Coherent Optical OFDM Systems ", PTL vol. 22, no. 17, 1288-1290, (2010).
[5] Y. Benlachtar, P. M. Watts , R. Bouziane , P.Milder, R. Koutsoyannis, J. C. Hoe, M. Püschel, M. Glick and R. I. Killey, "21.4 GS/s Real-Time DSP-Based Optical OFDM Signal Generation and Transmission Over 1600 km of Uncompensated Fibre", in Proc. ECOC (2009).
[6] F. Buchali, R. Dischler, A. Klekamp, M. Bernhard, Daniel Efinger, "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", in Proc. ECOC, (2009).
[7] R. P. Giddings, E. Hugues-Salas, B. Charbonnier, and J. M. Tang, " Experimental Demonstration of Real-Time Optical OFDM Transmission at 11.25 Gb/s Over 500-m MMFs Employing Directly Modulated DFB Lasers", IEEE Photonics technology Letters, Vol. 23, no. 1, (2011).
[8] R. Schmogrow, M. Winter, B. Nebendahl, D. Hillerkuss, J. Meyer, M. Dreschmann, M. Huebner, J. Becker, C. Koos, W. Freude, and J. Leuthold, "101.5 Gbit/s Real-Time OFDM Transmitter with 16QAM Modulated Subcarriers", in Proc. OFC (2011).
[9] B. Inan, O. Karakaya, P. Kainzmaier , S. Adhikari, S. Calabro, V.A.J.M. Sleiffer, N. Hanik , S. L. Jansen, "Realization of a 23.9 Gb/s Real Time Optical-OFDM Transmitter with a 1024 Point IFFT", in Proc. OFC (2011).