Impact of quantization effects at transmitter and receiver on bit error rate for coherent optical OFDM

Michael Bernhard
Institute of Telecommunications, University of Stuttgart, Pfaffenwaldring 47, D-70569 Stuttgart, Germany
bernhard@inue.uni-stuttgart.de

Abstract: We study feasibility of coherent optical OFDM systems using hardware related simulation models considering limited word lengths in digital signal processing, digital-to-analog converter (DAC) and analog-to-digital converter (ADC).

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications

1. Introduction

An alternative to single carrier modulation in optical communications is coherent optical orthogonal frequency division multiplexing (CO-OFDM) [1]. Main advantage of CO-OFDM is the application of flexible and effective chromatic dispersion compensation techniques. Furthermore CO-OFDM reaches a high spectral efficiency because of its good bandwidth limitations compared to single carrier systems [2].

Several simulations and lab experiments in combination with offline processing have been done [1, 3–7]. A challenging task is the implementation of the inverse fast Fourier transform (IFFT) at the transmitter and fast Fourier transform (FFT) at the receiver for very high data rates of 100 Gbit/s and beyond. Usually a parallel hardware structure is employed to execute the high number of multiplications at the same time, which results in a large amount of hardware resources, even when using optimized multipliers and word lengths [8]. Often, limited codeword lengths are not considered in simulations. In this paper, we investigate the impact of limited word lengths of IFFT, FFT, DAC and ADC on the system performance. This is important for the design of a whole real-time CO-OFDM system.

2. System model

The system model shown in Fig. 1 is been used for numerical simulations. It consists of a hardware related OFDM transmitter and receiver and an optical link. We use the programming language C++. In addition the IFFT and FFT are modeled in Very High Speed Integrated Circuit Hardware Description Language (VHDL). The VHDL models are embedded in the C++-simulation system. When using VHDL the simulation can incorporate quantization effects. The VHDL model can be used for field programmable gate array (FPGA) and application-specific integrated circuit (ASIC) applications with some additional adaption.

At the transmitter, the electrical data signal from a random bit source is parallelized. The following OFDM transmitter consists of a mapper (MAP), an IFFT, a guard interval inserter (GI) and a serializer (P/S). For the IFFT, we use alternatively an ideal model implemented in C++ with double precision and a hardware model written in VHDL which takes limited word lengths into account. A requantizer unit (Requant) connects the OFDM transmitter to the two DACs. Requant is required to adapt different word lengths of OFDM transmitter output and DAC input. Two DACs are required, one for the in-phase (I) and one for the quadrature (Q) component. An external optical modulator in combination with a laser diode generates the optical transmit signal. The optical link consists of a standard single mode fiber (SSMF) with a length of 80 km. Major impairments to the optical signal are chromatic dispersion and attenuation of the fiber. At the receiver, the signal is amplified by an erbium doped fiber amplifier (EDFA) and a 90°-hybrid converts the optical signal into an analog electrical signal which is fed into two ADCs. The OFDM receiver parallelizes (S/P) the incoming data, then the guard interval is removed (GI^{-1}). The FFT converts the signal from time domain to frequency domain. Similar to the transmitter side there exists an ideal model written in C++ and a realistic model written in VHDL. The FFT is followed by an equalizer (EQ). After demapping (DEMAP) the signal is serialized and a bit error measurement can be arranged.

The mapper can be chosen to generate 4-, 16- or 64-quadrature amplitude modulation (QAM) symbols. At transmitter side the amount of zero padded subcarriers is set to one third of the total number of subcarriers. The IFFT and FFT

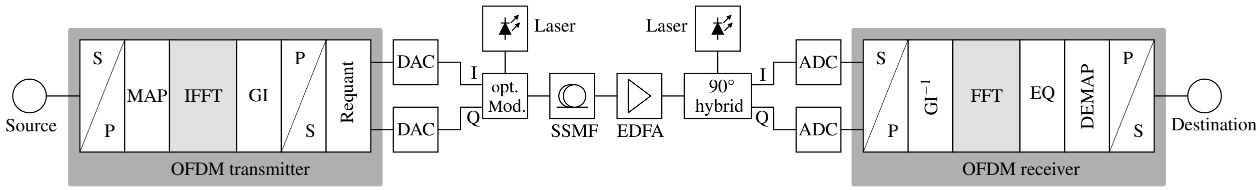

Fig. 1: System model of CO-OFDM transmission with transmitter, optical link and receiver. The model is written in the programming language C++. For the IFFT and FFT also a VHDL model is available to study the quantization effects due to limited word lengths.

size is 256. In the VHDL model, the basic structure is the butterfly diagram of the radix-2 FFT algorithm. At the two outputs of each butterfly unit we inserted a *saturation/truncation* block to limit the word length to a maximum fixed amount, either by saturation of data to a maximum value or by truncation. For the multiplication with the twiddle factor in the butterfly unit, dedicated multipliers are used. The principle behind the multiplier are shift and add operations. Complete structure of the IFFT including the dedicated multipliers is described in more detail in [8].

The input word length of the IFFT in the VHDL model is 7 bit and its output word length is 14 bit which is also the maximal internal word length. For the internal twiddle factors the word length is 7 bit for real and imaginary part each. The guard interval consists of 8 samples and is implemented as cyclic pre- and postfix. The DAC operates with 32 GSa/s and its input word length L_{DAC} was adjusted in the range from 5 bit up to 7 bit. Similarly, the ADC operates with a sampling frequency of 32 GSa/s and output word length L_{ADC} in the range from 5 bit up to 7 bit. Furthermore, it is possible to use DAC and ADC without additional quantization. The input word length $L_{\mathrm{rx,in}}$ of the VHDL model of the FFT at receiver was chosen in the range from 6 bit up to 8 bit. Its internal twiddle factor word length is 7 bit and the internal maximal word length is 14 bit which is also the output word length of the FFT.

3. Simulation Results

The different simulation models are labeled with *ideal* for the model without word length limitation, label *vhdl-tx*$_5$ for the simulation model with VHDL implementation of the IFFT at transmitter side. And the model with VHDL implementation of the IFFT at transmitter and also the FFT at receiver side is labeled as *vhdl-tx-rx*$_a$. Parameter a indicates the word length of the DAC and ADC. A summary is given in Table 1.

Table 1: Word lengths of different simulation models. Bit resolution of DAC and ADC is L_{DAC} and L_{ADC} respectively. Input word length of FFT at receiver is $L_{\mathrm{rx,in}}$.

model	L_{DAC}	L_{ADC}	$L_{\mathrm{rx,in}}$
vhdl-tx-rx$_5$	5 bit	5 bit	6 bit
vhdl-tx-rx$_6$	6 bit	6 bit	7 bit
vhdl-tx-rx$_7$	7 bit	7 bit	8 bit
vhdl-tx$_5$	5 bit	64 bit	64 bit
ideal	64 bit	64 bit	64 bit

The bit error rates (BERs) as a function of optical signal-to-noise ratio (OSNR) for all simulation models listed in Table 1 are shown in Fig. 2 for 4-, 16- and 64-QAM. In Fig. 3 the required OSNR to achieve a BER of 10^{-3} for the different simulation models and QAM orders is given. The 4-QAM is robust and there is only a small penalty between the different simulation models (0.3 dB in the worst case). For 16-QAM the penalty between the model *ideal* and *vhdl-tx-rx*$_6$ is still small (1.4 dB) but it also shows, that if the available OSNR is 27.2 dB a BER of 10^{-3} is achievable with model *vhdl-tx-rx*$_5$. With model *vhdl-tx-rx*$_5$ the effective number of bits (ENOB) of DAC and ADC is 5 bit which is a realistic value. 64-QAM is more susceptible to the ENOB of DAC and ADC and word lengths of the number representation of digital signal processing than the other modulation formats. A data rate of 41.4 Gbit/s can be achieved with 4-QAM. With 16-QAM the data rate can increase to 82.8 Gbit/s. The maximal bit rate which could be achieved is 124.1 Gbit/s with 64-QAM and if the ENOB of DAC and ADC reaches 7 bit.

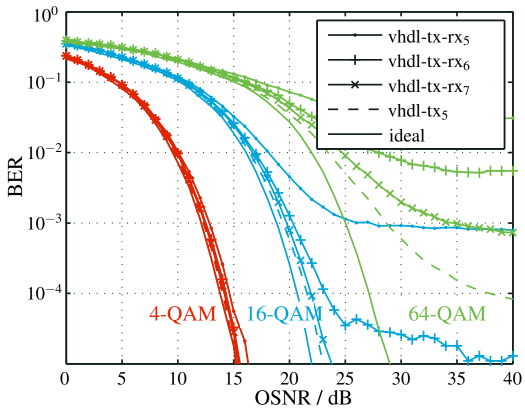

Fig. 2: BER as a function of OSNR for different modulation orders and simulation models. Corresponding word lengths of the different simulation models are given in Table 1.

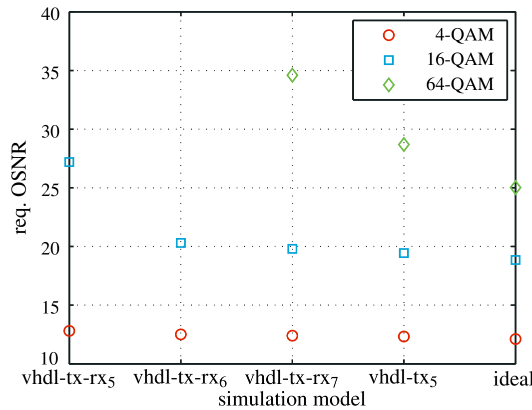

Fig. 3: Required OSNR to achieve a BER of 10^{-3} for different modulation orders and the simulation models listed in Table 1.

4. Conclusion

We have investigated the impact of limited word lengths of transmitter and receiver processor, DAC and ADC on the BER. Output word length of IFFT and FFT are 14 bit and for the twiddle factors 7 bit. Input word length of IFFT is 7 bit. FFT input word length requires 6 bit and DAC and ADC require word lengths of 5 bit for 4- and 16-QAM to achieve a BER of 10^{-3}. For higher order QAM, such as 64-QAM, the FFT input word length have to be increased to 8 bit and the word length of DAC and ADC to 7 bit.

5. Acknowledgment

This work was carried out in the framework of DFG project “Elektronische Schlüsselbausteine für optische OFDM-Systeme hoher Bitrate”. The support of the DFG is gratefully acknowledged.

6. References

1. W. Shieh and C. Athaudage, “Coherent optical orthogonal frequency division multiplexing,” Electronics Letters **42**, 587 – 589 (2006).
2. W. Shieh, H. Bao, and Y. Tang, “Coherent optical OFDM: theory and design,” Opt. Express **16**, 841–859 (2008).
3. W. Shieh, “OFDM for adaptive ultra high-speed optical networks,” in “IEEE Optical Fiber Communication Conference and Exposition (OFC/NFOEC),” (2010), pp. 1 –51.
4. W. Shieh and I. Djordjevic, *OFDM for optical communications* (Elsevier Academic Press, Amsterdam, 2010).
5. F. Buchali, R. Dischler, A. Klekamp, M. Bernhard, and D. 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 “European Conference and Exhibition on Optical Communication (ECOC),” (Vienna, Austria, 2009).
6. B. Inan, O. Karakaya, P. Kainzmaier, S. Adhikari, S. Calabro, V. Sleiffer, N. Hanik, and S. Jansen, “Realization of a 23.9 Gb/s real time optical-OFDM transmitter with a 1024 point IFFT,” in “IEEE Optical Fiber Communication Conference and Exposition (OFC/NFOEC),” (2011), pp. 1 –3.
7. R. Bouziane, R. Schmogrow, D. Hillerkuss, P. A. Milder, C. Koos, W. Freude, J. Leuthold, P. Bayvel, and R. I. Killey, “Generation and transmission of 85.4 Gb/s real-time 16QAM coherent optical OFDM signals over 400 km SSMF with preamble-less reception,” Opt. Express **20**, 21,612–21,617 (2012).
8. M. Bernhard and J. Speidel, “Implementation of an IFFT for an Optical OFDM Transmitter with 12.1 Gbit/s,” in “ITG-Fachtagung Photonische Netze,” (Leipzig, 2010), pp. 41–46.