Decision Feedback Compensation of Transmitter/Receiver Nonlinearity for DD-OFDM

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Abstract: Transmitter and receiver nonlinearity are compensated for by means of an iterative decision feedback algorithm. The sensitivity for 100 Gb/s direct detected OFDM without frequency gap is improved by approximately 6 dB.
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1. Introduction

Using direct detection, OFDM technology is implemented with minimum effort in terms of optical components [1]. Due to square-law detection, it suffers from nonlinear distortion. This is critical due to high peak-to-average power ratio of OFDM. The overall nonlinearity originates from both the characteristic of the Mach-Zehnder modulator in the transmitter and the square-law detector in the receiver, which is composed into a single $\cos^2$-shaped nonlinearity for dual-sideband back-to-back considerations [2]:

$$i_{rec}(t) \propto \cos^2\left[\frac{\pi}{2}\frac{s(t)+V_{bias}}{V_\pi}\right]. \tag{1}$$

In (1), $i_{rec}(t)$ is the detector output current, $s(t)$ is the OFDM signal, and V_{bias} and V_π represent modulator bias and switching voltage, respectively. Depending on bias voltage, specific orders of nonlinearity dominate. Biasing the modulator at quadrature point ($V_{bias}=-V_\pi/2$) suppresses all even-ordered contributions. However, this specific setting generates a strong optical carrier resulting in poor sensitivity. Decreasing the bias voltage such that $-V_\pi<V_{bias}<-V_\pi/2$ decreases carrier power but generates even-ordered nonlinearity. To eliminate the impact of quadratic nonlinearity, the lower half of the OFDM subcarriers may be set to zero [3]. This results in acceptable sensitivity but at the cost of wasting 50% of the bandwidth making it difficult to achieve 100 Gb/s data throughput. Therefore, in this paper, we propose a method to compensate for signal distortion due to the aforementioned nonlinearity by means of a decision feedback approach.

2. Method

The straightforward approach to eliminate distortion due to a nonlinear characteristic is to compute its inverse and apply it on the distorted signal. This is feasible only as long as the inverse exists. For (1) to be invertible, the argument of the cosine needs to be within the limits from $-\pi/2$ to 0. For reasonable values of effective voltage swing (quantified by its standard deviation σ_s), however, the OFDM signal does not keep these limits such that the inversion method is not applicable. Instead, our proposed method estimates the nonlinear distortion introduced on the received signal and subtracts it. The method assumes that the received signal is composed of a linear term plus a nonlinear distortion, i.e.

$$i_{rec}(t) = i_{lin}(t) + i_{nl}(t). \tag{2}$$

For a clear derivation, we now introduce a normalization that eliminates parameters like laser power, amplifier gain, modulator loss, or detector responsivity. Then, the proportionality in (1) turns into equality and the linear part in (2) is computed with the help of the gradient of the nonlinear characteristic around $s(t)=0$:

$$i_{lin}(t) = \frac{\partial}{\partial s}\left[\cos^2\left(\frac{\pi}{2}\frac{s+V_{bias}}{V_\pi}\right)\right]\Bigg|_{s=0} \cdot s(t) = -\frac{\pi}{V_\pi}\sin\left(\pi\frac{V_{bias}}{V_\pi}\right)\cdot s(t)\cdot \tag{3}$$

The nonlinear distortion is given by the difference between $i_{rec}(t)$ from (1) and $i_{lin}(t)$ from (3):

$$i_{nl}(t) = i_{rec}(t) - i_{lin}(t) = \cos^2\left[\frac{\pi}{2}\frac{s(t)+V_{bias}}{V_\pi}\right] - \left(-\frac{\pi}{V_\pi}\sin\left(\pi\frac{V_{bias}}{V_\pi}\right)\cdot s(t)\right)\cdot \tag{4}$$

The idea is now to compute the nonlinear distortion according to (4) in the receiver and to subtract it from the received signal such that the linear part remains. Obviously, this approach contains a feedback loop: The signal $s(t)$ is required to compute $i_{nl}(t)$. However, $s(t)$ contains the transmitted data that is to be detected by evaluating the received signal after compensation, i.e. after subtracting $i_{nl}(t)$. This is a situation similar to decision feedback equalization (DFE), where a detected symbol is used to compute the intersymbol interference imposed onto the next symbol(s). Still, the circumstances for our application are different than for a DFE. The nonlinearity is memoryless, such that in case the data would be encoded in time domain (e.g. TDM with QPSK modulation) detection of one symbol does not allow for computation of the distortion imposed onto neighboring symbols. Due to definition of data for OFDM in frequency domain, however, if only a few digital symbols out of all that are contained in a complete OFDM symbol are changed, the corresponding time signal is altered over the duration T_{OFDM} by low extent only. Hence, as long as the majority of the digital symbols contained in the OFDM symbol is detected correctly, the original signal $s(t)$ may be estimated with sufficient accuracy [from now on denoted as $\hat{s}(t)$] to result in fairly accurate computation of $i_{nl}(t)$ and effective compensation of nonlinearity. This strategy may be extended: Assuming that in a first step the number of incorrectly detected digital symbols within the current OFDM symbol has been reduced, in a second step a more accurate estimation $\hat{s}(t)$ of $s(t)$ enables even better compensation. Thus, with this method we suggest an iterative algorithm, which is shown in Fig. 1 assuming 16-QAM subcarrier modulation.

Since the method for compensation is implemented as digital algorithm after the ADC, all signals are discrete. Proper normalization is assumed also. First, the time samples representing one complete OFDM symbol are converted to parallel and stored into a memory. Before the first iteration for this specific OFDM symbol, the 16-QAM symbol memory is empty such that $\hat{s}(k)$ and $i_{nl}(k)$ are equal to zero. Then, the result of the subtraction is equal to the OFDM symbol in the memory. It is demodulated and the output samples are fed into a decision device for 16-QAM symbols. These symbols are compared with those in the 16-QAM symbol memory. This is still empty, so the detected symbols are stored into this memory and used for OFDM-remodulation resulting in the estimation $\hat{s}(k)$. Using (4), the nonlinear distortion $i_{nl}(k)$ is computed and subtracted from the received OFDM symbol in memory. OFDM demodulation results in an updated set of 16-QAM symbols. In case the nonlinear distortion was low such that all symbols were detected correctly, the newly obtained symbols equal those in the memory and the algorithm is terminated. In case of a difference, the method was able to improve the signal, the newly detected symbols are stored into the symbol memory and the algorithm continues iterating until it has converged. Performance and computational effort may be balanced by defining a maximum number of iterations.

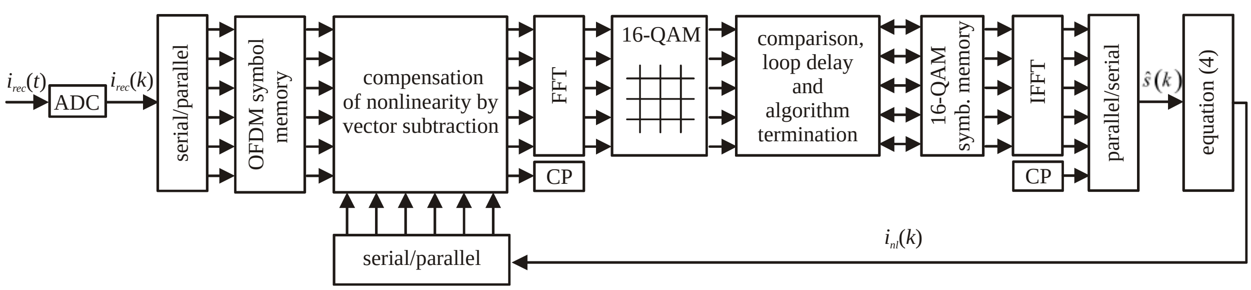

Fig. 1. Block diagram of proposed method for compensation of nonlinearity in the receiver.

3. System setup

We investigate the performance of the proposed method in a simple dual-sideband optical OFDM back-to-back transmission system using direct detection. We use 16-QAM digital modulation and IFFT length of N_{FFT} =256. Due to required symmetry to generate real IFFT output, 127 subcarriers would be available in theory (=256/2 minus the DC-subcarrier). To enable finite selectivity of DAC filter, only the lower 80 subcarriers are filled with data. A frequency gap for robustness towards quadratic nonlinearity is not used. The DAC with 100 Gsamples/s is implemented as sample-and-hold followed by a simple RLC filter with natural frequency $1/(2\pi)\cdot(LC)^{-1/2}$=30 GHz and quality factor Q equal to one [4]. The linear distortion introduced by the DAC is pre-equalized in frequency domain right in front of the IFFT. The gross bit rate is calculated as B=100 Gsamples/s·80/256·4 bit/symbol =125 Gb/s enabling 100 Gb/s data transmission leaving 25% overhead for FEC, guard interval and synchronization purposes. The DAC output signal shows a bandwidth of roughly 32 GHz and is fed to a Mach-Zehnder modulator. After an attenuator for OSNR tuning, the optical receiver consists of EDFA preamplifier, optical filter with 100 GHz

FWHM bandwidth, photo diode and electrical filter with 50 GHz bandwidth followed by an ADC with 100 Gsamples/s. The filters are broad enough such that negligible degradation of all subcarriers is observed resulting in an equalizer to be obsolete. To avoid interference between neighboring OFDM symbols due to filter impulse responses, a cyclic prefix of 3 samples is sufficient. After analog-to-digital conversion, nonlinearity is compensated for according to Fig. 1.

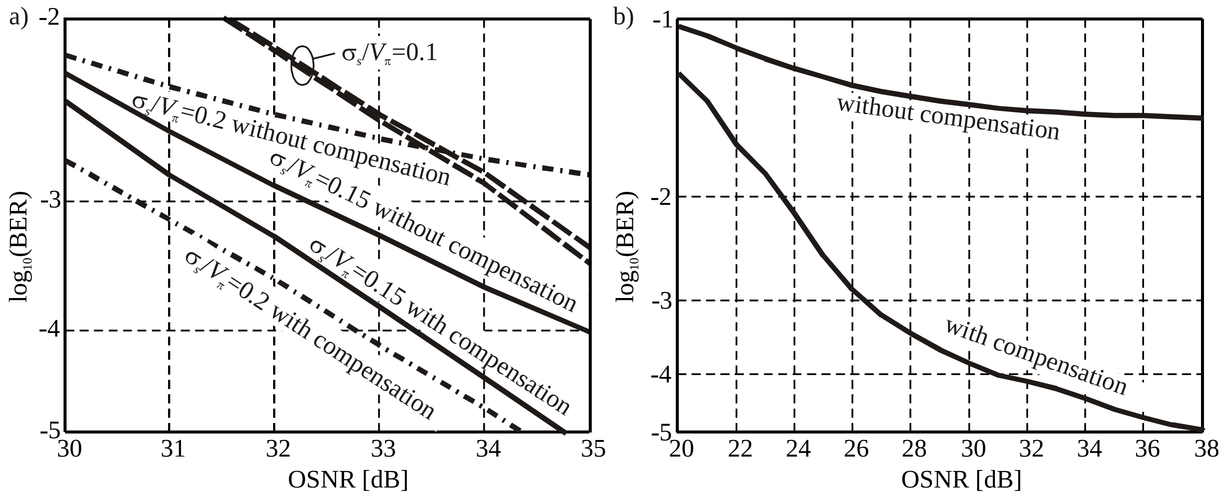

Fig. 2 a) BER vs. OSNR (measured within 0.1 nm bandwidth) for quadrature bias; b) BER vs. OSNR for V_{bias}=-0.8V_π and σ_s=0.1V_π.

4. Simulation results

Sensitivity and nonlinear distortion heavily depend on bias setting and driving voltage swing. Values considered in this paper are $-V_\pi<V_{bias}<-V_\pi/2$ with a granularity of 0.1 V_π and 0.1 $V_\pi<\sigma_s<$ 0.2 V_π with a granularity of 0.05 V_π. Fig. 2a compares the BER in case of quadrature bias ($V_{bias}=-V_\pi/2$) for three different values of driving voltage swing with and without application of the proposed method. For $\sigma_s=0.1V_\pi$, the system can be considered nearly linear with poor sensitivity beyond 34 dB@BER=10^{-3} due to low voltage swing. Clearly, in case of linear transmission for the proposed method there is nothing to compensate resulting in negligible improvement. Increasing the voltage swing to $\sigma_s=0.15V_\pi$, without compensation a sensitivity of 32.3 dB@BER=10^{-3} is achieved. Here, the system already shows nonlinear behavior since the proposed method is able to improve sensitivity by approximately 1 dB. Finally, for $\sigma_s=0.2V_\pi$ the system is highly nonlinear such that an error floor is obtained preventing the BER to fall below 10^{-3} for reasonable values for the OSNR without compensation. However, using the proposed method sensitivity of 30.7 dB@BER=10^{-3} is achieved.

Decreasing bias voltage to decrease carrier power gives rise to quadratic nonlinearity. For the system without compensation, distortion due to quadratic nonlinearity is strong such that no combination of bias voltage and driving voltage swing has been found that results in better sensitivity than 32.3 dB achieved for quadrature bias and $\sigma_s=0.15V_\pi$. On the other hand, applying the proposed method the quadratic nonlinearity can be successfully compensated. The best sensitivity of 26.4 dB@BER=10^{-3} is obtained for $V_{bias}=-0.8V_\pi$ and $\sigma_s=0.1V_\pi$ which is shown in Fig. 2b). For this parameter setting, the system without compensation is severely limited by nonlinearity such that the BER does not fall below 10^{-2}. However, drastic improvement is observed in case of nonlinearity compensation.

5. Conclusion

Applying a method of decision feedback compensation of transmitter and receiver nonlinearity, it has been shown that OFDM transmission based on direct detection is possible with acceptable sensitivity without having to use a frequency gap. Omitting the frequency gap doubles spectral efficiency. In a single-sideband scenario, 100 Gb/s could be transmitted in a 50 GHz grid resulting in 2 bit/s/Hz spectral efficiency.

6. References

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