

Constant Envelope Optical OFDM for Improved Nonlinear and Phase Noise Tolerance

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Abstract: We introduce a new concept of OFDM transmission with constant envelope and coherent detection to reduce the sensitivity of OFDM signals to nonlinear effects and phase noise.

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1. Introduction

Orthogonal frequency division multiplexing (OFDM) in optical communications has gained a lot of interest due to its advantages of high spectral efficiency and efficient equalization of linear impairments in frequency domain. Optical OFDM is basically implemented in two techniques, namely coherent optical (CO)-OFDM [1,2] and direct detection optical (DD)-OFDM [3,4], differing in spectral efficiency and complexity of transmitter and receiver. One major problem of OFDM is the large peak-to-average power ratio (PAPR) of the transmitted signal, which has a “noise-like” character in contrast to e.g. a digital transmission in time domain. Thus occasionally an OFDM signal shows high amplitude peaks. Typically the PAPR reaches values up to 10 dB resulting in distortions in the presence of nonlinearities. Another issue of CO-OFDM systems is the compensation of phase noise of the lasers used. This requires transmission of additional information in order to estimate and compensate the effect of the phase noise resulting in an increased overhead.

In 2008 Steve Thompson et al. described a way of transmitting OFDM signals using phase modulation instead of amplitude modulation resulting in an optimal PAPR of 0 dB i.e. a constant envelope (CE-OFDM) [5]. Although this work focused on the nonlinearities in a wireless transmission system, this idea is of relevance for optical communication as well and was investigated recently, based on setups where an intermediate electrical signal was generated using phase modulation [6,7]. With this signal the optical carrier was then intensity modulated (IM) allowing direct detection at the receiver side and thus setup the PAPR could be reduced to about 3 dB. Although the optical envelope was not really constant, the nonlinear behavior was improved compared to a common OFDM signal.

In our paper we show the concept of fully CE-OFDM with phase modulation of the optical signal and with coherent detection. This modulation scheme lowers the PAPR of the optical signal to the optimal value of 0 dB which enables higher signal power on the same fiber link. In addition we can show that due to the phase modulation/demodulation of the signal the phase noise of the lasers appears as an additive and not as a multiplicative term to the received signal. This makes the phase noise estimation and compensation obsolete.

2. CE-OFDM concept

In our setup (Fig. 1) the source bits are parallelized and mapped into 87 subcarriers using QPSK modulation. A mirrored and conjugate complex set of these data subcarriers is added to obtain a real signal in time domain. 9 subcarriers around DC are left empty to avoid phase noise distortion. The whole set of subcarriers is converted to time domain via inverse fast fourier transformation (IFFT) with length 256. Cyclic prefix and postfix (CP) of 16 samples each is added to avoid ISI, resulting in total symbol duration of 14.4 ns with a sample rate of 20 GS/s. For every 128 OFDM symbols with useful data, 1 synchronization symbol and 15 symbols to train the adaptive frequency domain equalizer (FDE) are transmitted. The overall net data rate is 10.7 Gb/s. The electrical signal $x(t)$ after D/A conversion has a bandwidth of 7.18 GHz. This electrical signal $x(t)$ drives the optical phase modulator (opt. PM) and generates an optical signal with constant power and varying phase.

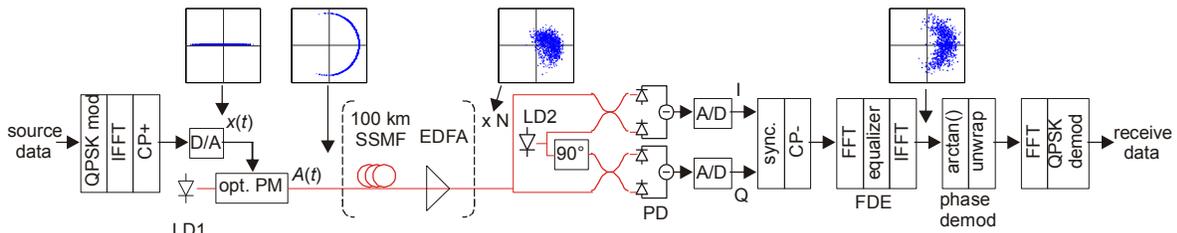


Fig.1: Block diagram of CE-OFDM along with complex envelope

The complex envelope of the optical signal after phase modulation is

$$A(t) = A_{\text{Laser}} \cdot \exp(j2\pi h x(t)), \quad (1)$$

where h is the modulation index which defines the variance $\sigma_\phi^2 = (2\pi h)^2$ of the optical phase and we normalized the electrical signal $\sigma_x^2 = 1$. The optical transmit spectrum in Fig. 2b shows a strong carrier peak and out-of-band emission due to the nonlinear character of phase modulation. The carrier-to-sideband ratio and the amount of out-of-band power can be adjusted with the modulation index. The value of $2\pi h$ has to be optimized. Up to a certain limit, an increase of $2\pi h$ leads to an increase of the sideband power and reduces the required OSNR. Further increase of $2\pi h$ however increases the probabilities of errors due to 2π -phase jumps. In our setup the lowest OSNR required for $\text{BER}=10^{-3}$ was achieved for $2\pi h=0.7$. In order to maintain the constant envelope character of the optical signal, both sidebands have to be transmitted.

At the receiver the optical signal is demodulated coherently, thus the in-phase and quadrature part of the signal are detected. After A/D conversion, the signal is synchronized in order to separate training and data symbols and to adjust the start of the fast fourier transform (FFT) window. Cyclic prefix and postfix are removed and the linear distortions are equalized. Due to its nonlinear character this step has to be done before phase demodulation. Like in common OFDM systems the FDE is implemented by using FFT and multiplication of each subcarrier with a complex value $C[k]$. Another IFFT is required because the phase demodulation has to be achieved in time domain using arctangent function and phase unwrapping. The resulting real signal can be handled like a usual OFDM time signal including FFT and subcarrier demapping.

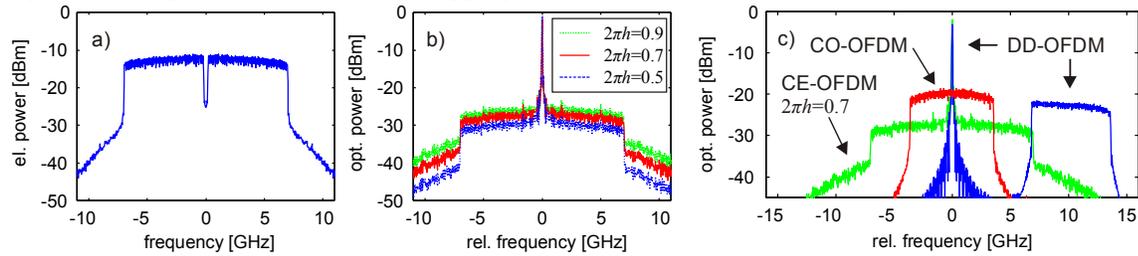


Fig. 2: Spectrum before (a) and after (b) optical phase modulation with various mod.-indices. (c) comparison of OFDM spectra with 0dBm each

3. Performance on nonlinear fiber link

The performance of CE-OFDM was compared to CO- and DD-OFDM in the presence of nonlinearity. In all OFDM systems, the number of subcarriers used for data transmission, the duration of an OFDM-symbol including CP, the overhead and the net data rate (10.7 Gb/s) are kept equal. Due to different degrees of freedom and the required bandwidth for DD-OFDM the FFT length and the sampling rate are chosen differently:

- CO-OFDM: $N_{FFT} = 128$; 10 GS/s
- CE-OFDM: $N_{FFT} = 256$; 20 GS/s
- DD-OFDM: $N_{FFT} = 512$; 40 GS/s

Fig. 2c shows that CE-OFDM requires approximately the same bandwidth as DD-OFDM (gap and single sideband) and twice the bandwidth of CO-OFDM. The transmission over nonlinear fiber was simulated for each OFDM format by varying the optical launch power. Each fiber span consisted of 100 km SSMF ($A_{eff}=8 \cdot 10^{-11} \text{ m}^2$ and $n_2=3.2 \cdot 10^{-20} \text{ m}^2/\text{W}$) and an EDFA to compensate for the loss. In order to focus on the nonlinear effects, the transmission was simulated without phase noise. Fig. 3 shows the required OSNR for $\text{BER}=10^{-3}$ after the transmission over 1 and 10 spans respectively. With low signal power (e.g. -15 dBm) the fiber behaves linearly and CE-OFDM requires an OSNR of about 9.7 dB, which is a penalty of 5 dB against CO-OFDM and is similar for DD-

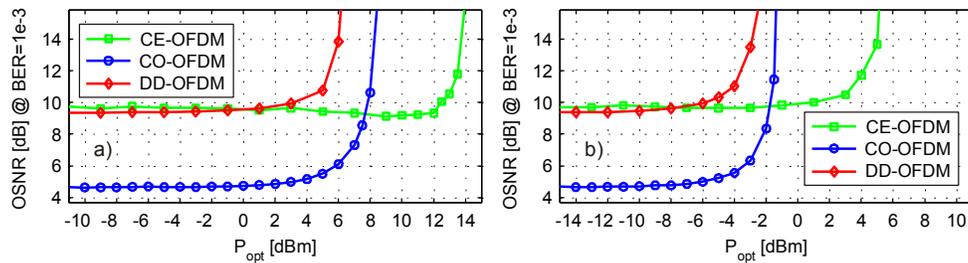


Fig. 3: Nonlinear performance after (a) 1x100km and (b) 10x100km SSMF

OFDM. With increasing power, the nonlinear effect becomes dominant resulting in increased OSNR required for CO- and DD-OFDM. Due to its low PAPR, CE-OFDM is less sensitive to the nonlinear Kerr effect tolerating higher optical powers. The simulation showed that with CE-OFDM the launch power can be increased by 6 dB compared to CO-OFDM such that the OSNR penalty of 5 dB is overcompensated.

If the CE-OFDM signal would keep its constant envelope character along the whole transmission length, it would show maximum robustness against nonlinearities. However, due to chromatic dispersion the spectral components suffer from different phase shifts and sum up in a different way thus the optical complex envelope shows a time varying amplitude (see inset Fig.1). This linear distortion effect itself is not so critical because it can be equalized at the receiver to restore the transmitted signal. But with varying amplitude, the CE-OFDM suffers from nonlinear distortions, too. This is the reason for the power limit for CE-OFDM.

4. Performance with phase noise

The effect of phase noise (PN) can be regarded as a random rotation of the optical signal in the complex plane with the factor $e^{j\varphi_{pn}(t)}$. The bandwidth of $\varphi_{pn}(t)$ is defined by the linewidth of the laser. In OFDM systems with linear amplitude modulation, this rotation in time domain results in a rotation of all subcarriers in frequency domain, too. For correct decision, the PN has to be estimated and all subcarriers need to be derotated. In CE-OFDM the received complex time signal is rotated as well, but after phase demodulation the PN is transformed from a multiplicative into an additive noise term:

$$\arg\{Ae^{j2\pi h x(t)} \cdot e^{j\varphi_{pn}(t)}\} = 2\pi h x(t) + \varphi_{pn}(t). \quad (2)$$

As the bandwidth of $\varphi_{pn}(t)$ is much smaller than signal $x(t)$ bandwidth, only a small number of low frequency subcarriers are affected by phase noise. Leaving these frequencies empty by inserting a small band gap allows successful communication without active PN compensation, thus the transmission of additional information for phase estimation and compensation at the receiver side is not necessary. The required bandgap depends on the linewidth of the laser. In Fig. 4, the OSNR-penalty of CE-OFDM is compared to CO-OFDM. With CO-OFDM a PN compensation scheme is required. We use estimation of the common phase error (CPE) with 5 pilot subcarriers [1]. With CE-OFDM phase noise is simply removed by leaving a small number of N_{gap} OFDM subcarriers around zero frequency empty. $N_{gap}=9$ results in improved OSNR penalty.

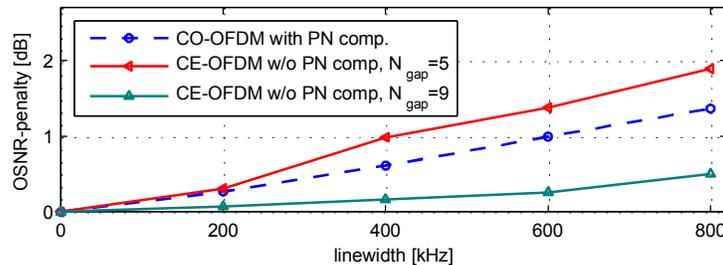


Fig. 4: OSNR-penalty due to PN. For CO-OFDM with PN compensation. For CE-OFDM without PN compensation

5. Conclusion

We introduce the concept of CE-OFDM with optical phase modulation and show that due to low PAPR of the signal the sensitivity towards nonlinearities is reduced significantly. The nonlinear OSNR penalty can be overcompensated with a higher acceptable signal power. In addition, with CE-OFDM the impact of PN can be easily mitigated by simply leaving a small number of OFDM subcarriers unused thus PN compensation becomes obsolete.

4. References

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