Pilot-Tone-based Nonlinearity Compensation for Optical OFDM Systems

B. Inan[(1)], S. Randel[(2)], S. L. Jansen[(3)], A. Lobato[(4)],S. Adhikari[(5)], N. Hanik[(1)]

[(1)] Institute of Communications Engineering, Technische Universität München, Munich, Germany, beril.inan@tum.de
[(2)] Siemens AG, Corporate Technology, Communication Technologies, Munich, Germany
[(3)] Nokia Siemens Networks GmbH & Co. KG, Munich, Germany
[(4)] Fakultät für Informationstechnik, Hochschule Mannheim, Mannheim, Germany
[(5)] Chair for Communications, Christian-Albrechts-Universität, Kiel, Germany

Abstract *We propose a pilot-tone based phase noise compensation method for the mitigation of nonlinearities in OFDM transmission. This scheme allows for the compensation of XPM-induced transmission impairments without direct knowledge of the optical field of the co-propagating channels.*

Introduction

Orthogonal frequency division multiplexing (OFDM) has emerged as a promising modulation technique in optical communication area. Coherent optical OFDM (CO-OFDM) is one of the modulation formats that have been proposed to overcome limitation due to linear transmission impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD) [1]. In addition CO-OFDM offers a well-defined spectrum that limits the linear crosstalk [2, 3].

The main limitation of transmission systems in which practically all linear impairments can be compensated are nonlinear transmission impairments caused by the Kerr effect. Many methods have been proposed to mitigate nonlinear transmission impairments for OFDM transmission. Most predominantly, peak-to-average power ratio (PAPR) reduction has been investigated. Since OFDM has a significantly higher PAPR compared to single carrier this is potentially a promising technique. However, in an uncompensated dispersion map the PAPR changes quickly depending on the accumulated CD [4] and as a result the feasible nonlinear tolerance improvement is limited. In [5] pre- and post-compensation is proposed where a phase shift is applied at both transmitter and receiver that is proportional to signal instantaneous power. This technique is effective for the compensation of SPM only and shows limited benefits for an uncompensated dispersion map. Ip et al. [6] therefore investigated backpropagation, which allow for a more significant improvement of the SPM tolerance but is as well very complex to implement.

None of the so far proposed techniques is very effective for the compensation of XPM. In this paper, we investigate the use of RF-pilot-tone based phase noise compensation (RFP), which allows for the compensation of both SPM and XPM. Although RFP has originally been proposed for the compensation of laser phase noise [7, 8], we show here with numerical simulations that the RFP scheme can be used as well to increase the nonlinear tolerance. We show the nonlinear tolerance improvement for a 7 x 62.2 Gb/s CO-OFDM modulated signal at 50 GHz channel spacing and over 2000 km of un-compensated transmission. An improvement in nonlinear tolerance of up to 0.5 dB is observed for high launch powers without direct knowledge of the optical field of the co-propagating channels.

RF-Pilot–tone based compensation concept

The concept of RF-pilot nonlinearity compensation is in essence the same as that of RF-pilot based phase noise compensation. An RF-pilot or optical carrier is inserted in the middle of the OFDM spectrum and at the receiver the phase noise information is recovered from this pilot tone. Around the pilot tone several subcarriers are left unmodulated so that the RF-pilot and OFDM subcarriers do not spectrally overlap. At the receiver, a digital filter is applied around the pilot which is now broadened due to laser phase noise and nonlinear effects. This filter will be referred as RFP filter from this point on. The pilot is affected by the neighboring subcarriers (SPM) and by WDM channels (XPM) in a similar fashion as the modulated subcarrier. Consequently, the nonlinear distortions can be mitigated by inverting the pilot phase and by multiplying the OFDM symbol with it, analogue to phase noise compensation. The pilot-to-signal ratio (PSR) is an important parameter for the RFP method. It is defined as

$PSR\ (dB) = 10 \log_{10}(P_{pilot}/P_{OFDM})$,

where P_{pilot} and P_{OFDM} are the electrical powers of pilot and OFDM symbol respectively. If the PSR is too high, the relative signal power is too low and if the PSR is too low, then the ASE noise in the pilot reduces the efficiency of the phase noise compensation.

Fig. 1 shows the optical spectrum of a 62.2-Gb/s OFDM signal and the location of the RF-pilot-tone. The electrical digital filter that is used to separate the RF-pilot from the OFDM signal is illustrated in Fig. 1b. Fig. 2 shows how the pilot phase is effected from nonlinearities and also ASE noise. It can clearly be seen that the ASE noise limits the effectiveness of the RFP compensation scheme.

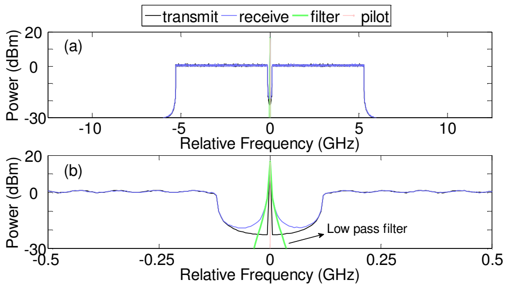

Fig 1: (a) Transmitted and received spectrum of 62.2 Gb/s OFDM system with pilot for RFP together with RFP filter at receiver (b) Zoomed version of (a).

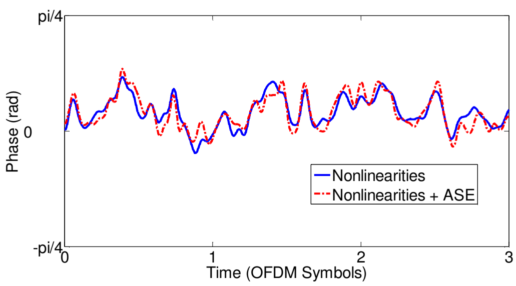

Fig. 2: The received pilot phase with and without ASE noise (at 12dB OSNR).

Optical OFDM System

Fig. 3 depicts the OFDM system used for Monte Carlo simulations. A 2,000-km SSMF link is used with an attenuation coefficient of 0.2 dB/km, a nonlinearity coefficient of 1.14 1/W/km, 17-ps/nm/km chromatic dispersion, and -0.0021-ps/nm^2/km dispersion slope. No dispersion compensation is utilized in optical link; all accumulated dispersion is compensated electrically with the help of a cyclic prefix (required cyclic prefix overhead is 6.8%). The net data rate 56 Gb/s, including FEC; increases to a nominal data rate of 62.2 Gb/s with OFDM overheads. Note that in this work one polarization is simulated of a 100GbE PDM-OFDM signal.

The FFT size is 2048, and data subcarriers are modulated with 8-QAM. 40 subcarriers are reserved for the gap for the simulations with RFP. Consequently, the DAC sampling rate is equal to 24 Gb/s. A Gaussian filter is used at receiver as RFP filter and the ASE noise is added at the receiver. The target BER is 10^{-3} for all the simulations. Ideal lasers without phase noise were assumed in order to be able to compare the performance with and without RFP.

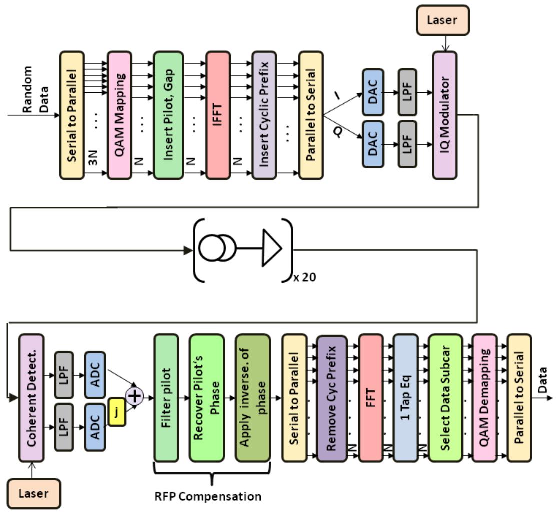

Fig. 3: The OFDM system used in simulations. Transmitter, optical link, and receiver.

Results

Fig. 4 shows the required OSNR as a function of the PSR for the back-to-back and after transmission. In back-to-back configuration an optimum PSR of -18 dB is measured. For the -1 dBm case, on the other hand, the optimal PSR is increased to -12 dB. For all launch powers the optimal PSR is chosen.

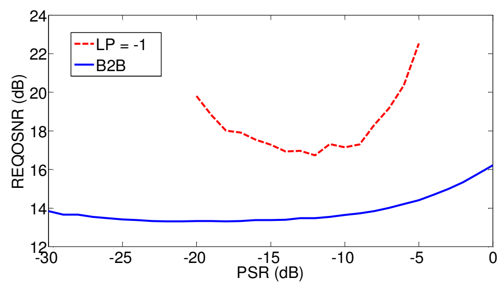

Fig. 4: PSR optimization for B2B and a launch power of -1 dBm. The RFP filter width is optimized for both cases as 5 MHz and 150 MHz respectively.

The digital RFP filter that is used to separate the pilot tone from the OFDM signal must be optimized for each launch power. The RFP filter must be as narrow as possible in order to minimize the influence of the ASE noise, but sufficiently wide to encompass the complete pilot signal. Fig. 5 shows the optimal RFP filter bandwidth as a function of the launch power. A sweep of launch powers between -8 dBm and 0 dBm for one channel is made with optimized PSRs. In the linear region (from -8dBm to -4 dBm) the optimal RFP filter bandwidth is relatively constant at around 10 MHz. For powers higher than -4 dBm optimal RFP filter bandwidth increases abruptly indicating that the pilot tone is significantly broadened by SPM.

Fig. 6 shows the single channel required OSNR for the target BER of 10^{-3} as a function of the launch powers with and without RFP compensation. In this simulation the PSR and RFP filter bandwidth are optimized for each launch power. Until a launch power of -2 dBm, the required OSNR for both scenarios are almost the same. For higher launch powers where nonlinearities limit the system performance, the RFP method shows an improvement, allowing a launch power increase of up to 0.4 dB.

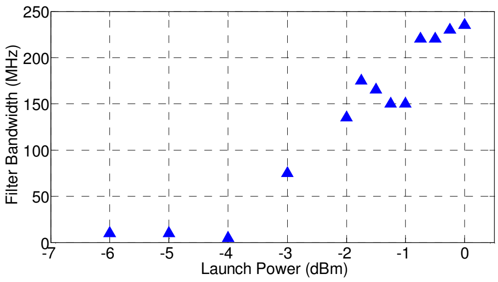

Fig. 5: Gaussian RFP filter bandwidth optimization for different launch powers for single channel case.

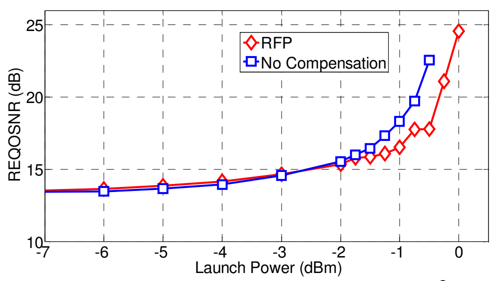

Fig. 6: The required OSNR for a BER of 10^{-3} with and without RFP compensation for the single channel case.

For the WDM case, the bandwidth optimization of the RFP filter and the required OSNR as a function of the launch power are shown in Fig. 7 and Fig. 8, respectively. Compared to the single channel results (Fig. 5 and 6) it can be observed that due to the impact of XPM the nonlinear tolerance is reduced by 1 dB. With the RFP method an improvement in nonlinear tolerance is observed up to 0.5 dB for powers -3dBm and higher.

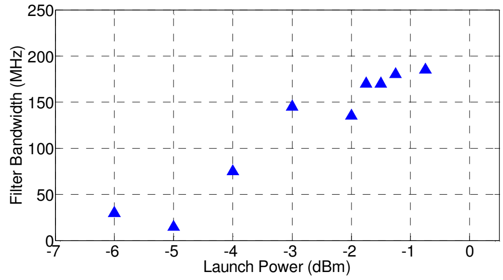

Fig. 7: RFP filter bandwidth optimization for different launch powers for 7 WDM channels case

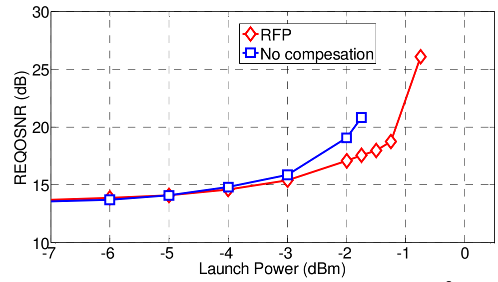

Fig. 8: The required OSNR for a BER of 10^{-3} with and without RFP compensation for 7 WDM channels case

Conclusion

In this paper, we propose the use of RF-pilot-tone based method for the compensation of both SPM and XPM-induced transmission impairments without direct knowledge of the optical field of the co-propagating channels.

References

1 S. L. Jansen et al., Proc. Summer Topicals MA1.2 (2007).
2 T. Schenk, RF Imperfections In High-Rate Wireless Systems, Springer-Verlag, (2008).
3 W. Shieh, Optics Express, 16, 2, (2008)
4 Y. Tang et al., Proc. OFC'10, JThA6 (2010)
5 A. J. Lowery, Optics Express, 15, 20, (2007)
6 E. Ip et al. Nonlinear Impairment Comp. Using Backpropagation", In-Tech (to be published).
7 S. L. Jansen et al., J. Lightwave Technol., 26, 1, (2008).
8 S. Randel et al., Photonics Technol. Letters, submitted, (2010).