

# On the efficiency of RF-Pilot-based nonlinearity compensation for CO-OFDM

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**Abstract:** We investigate the efficiency of RF-pilot based phase noise compensation for mitigation of nonlinear impairments in CO-OFDM transmission. We show that the efficiency scales with the effective dispersion difference between the nonlinear regions.

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## 1. Introduction

Coherent detection optical orthogonal frequency division multiplexing (CO-OFDM) is a promising modulation format that is extensively used in the wireless community and has been recently proposed for optical systems [1, 2]. One of the main advantages of OFDM is that it has a well-defined signal shape, allowing multiple bands to be transmitted with a minimal guard band [3]. The main challenges of coherent detected are its sensitivity for laser phase noise (PN) and nonlinear impairments [4].

RF-pilot-based (RFP) PN compensation is an effective compensation technique for the compensation of laser phase noise [4]. This compensation technique uses a pilot tone or RFP, which is placed in the middle of the transmitted OFDM spectrum to revert the distortions caused by PN. As the pilot tone is affected by phase noise in the same way as the OFDM signal, it monitors all phase distortions and can be used at the receiver for phase noise compensation. Recently, it has been shown that RFP-based phase noise compensation is an effective method as well for the compensation of nonlinearities [5]. In this work, RFP-based PN compensation was used for the compensating of phase distortion caused by nonlinearities with 62.2-Gb/s, 8-QAM CO-OFDM. In a 2000-km transmission link, an increase in tolerable launch power of up to 0.5 dB was observed.

In this paper the efficiency of RFP-based nonlinearity compensation is studied for different fiber types, dispersion maps and constellation sizes. It is found that the efficiency of RFP-based nonlinearity compensation is dependent on the correlation of the nonlinear perturbations. For fiber types with a low dispersion coefficient or for transmission systems with in-line dispersion compensation, the nonlinear distortions are correlated resulting in a reduction of the RFP-based compensation efficiency whereas the highest RFP-based nonlinear improvement is obtained for fibers with a high dispersion coefficient on a transmission link without in-line dispersion compensation. Additionally, it is observed that on an unmanaged dispersion link the efficiency of RFP-based nonlinearity compensation is inversely proportional to the constellation size.

## 2. Simulation setup

In this work the nonlinear mitigation of RFP-based nonlinearity compensation is investigated for standard single mode fiber (SSMF) and large effective area fiber (LEAF). The transmission line consists of 10 spans of 100 km length resulting in a total transmission distance of 1000 km. Table 1 summarizes the main parameters of the used fiber types. A single polarization is simulated with 7 co-propagating co-polarized WDM channels at 50-GHz channel spacing. The nominal data rate is 124.4 Gb/s (one polarization of 62.2-Gb/s PDM-OFDM). Taking 4% overhead for training symbols, 6.8 % overhead for cyclic prefix and 13 % overhead for FEC into account the net data rate is 50 Gb/s. In order to focus on the impact and mitigation of nonlinear effects ideal lasers without phase noise are used at the transmitter and receiver. The fast Fourier transform (FFT) size is 2048, from which 11.5 % was utilized for zero-padding, 2 % for the spectral gap around the RFP and 86.5 % for the modulated data subcarriers. Further details of the OFDM transmitter, receiver and the optical link can be found in [5].

**Table 1.** Fiber simulation parameters

Type of fiber	$D$ [ps/km/nm]	$S$ [ps/nm <sup>2</sup> /km]	$\gamma$ [1/W/km]	$\alpha$ [dB/km]
SSMF	17	0.021	1.14	0.2
LEAF	4.2	0.086	1.3	0.21

### 3. RFP-based compensation for SSMF and LEAF

In this section the nonlinear tolerance with and without RFP is investigated for SSMF and LEAF on a transmission link without in-line dispersion compensation. Fig. 1a and 1b show the required optical signal-to-noise ratio (OSNR) for a target bit-error-ratio (BER) of  $10^{-3}$  as a function of the launch power for SSMF and LEAF, respectively. In this simulation 4-QAM is used as the constellation size and the nonlinear tolerance with and without RFP-based compensation is depicted. For single channel transmission the maximum tolerable launch power for a required OSNR of 15 dB is 4.4 dBm and 1.6 dBm for SSMF and LEAF, respectively. As expected the nonlinear tolerance for transmission over SSMF is significantly larger than that of LEAF fiber [7]. With the use of RFP-based compensation, the maximum launch power is increased by 0.7 dB for SSMF and 0.3 dB for LEAF. With 7 co-propagating WDM channels the maximum launch power improvement through RFP is 0.9 dB and 0.6 dB for SSMF and LEAF, respectively. It can be concluded that for both single channel and WDM transmission, the mitigation of nonlinearities of RFP-based compensation is more effective for SSMF than for LEAF. We conjecture that the main reason for the difference in the RFP-based compensation efficiency is that the lower dispersion of the LEAF fiber leads to a higher coherence between nonlinear regions. This will be further investigated in the next section by looking at an SSMF-based transmission system with and without in-line dispersion compensation.

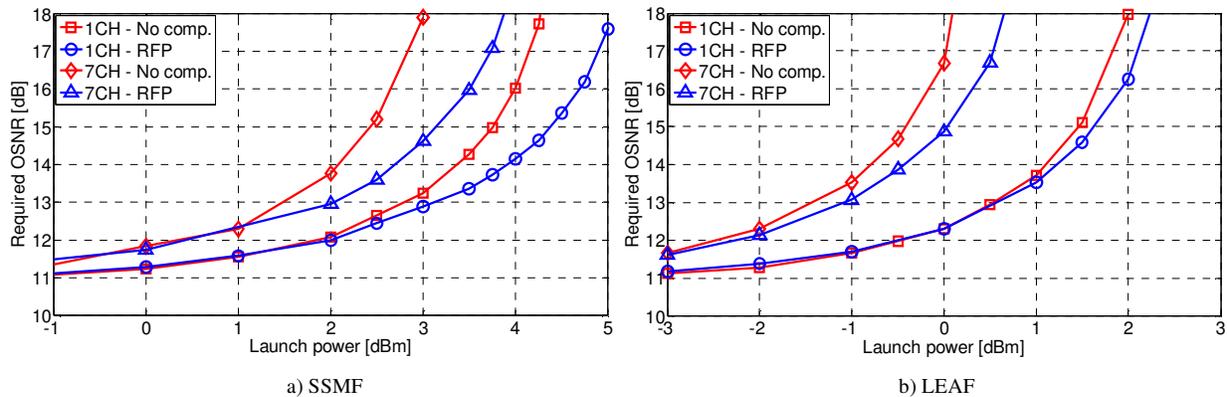


Fig. 1. Required OSNR as a function of the launch power for a BER of  $10^{-3}$  with 4-QAM CO-OFDM after 1000 km transmission for single channel and 7 WDM channels.

### 4. Simulation results for SSMF with and without in-line dispersion compensation

In this section the nonlinear tolerance with and without RFP is investigated on SSMF fiber with either an uncompensated or a fully periodically compensated dispersion map. The constellation size in this section is varied by keeping the nominal data rate at 62.2 Gb/s. As such the bandwidth of 16-QAM is for instance half the bandwidth of the 4-QAM constellation. Fig. 2a and 2b depict the required OSNR as a function of the launch power without and with in-line dispersion compensation, respectively. The squares represent the RFP-based compensation and the circles the no compensation case. Similar to the observations done in [7], the use of in-line dispersion compensation results in a reduction of the nonlinear tolerance by about 3 dB. This reduction of  $\sim 3$  dB is observed independent of the constellation size. Without in-line dispersion compensation (Fig. 2a), the largest nonlinear improvement through RFP is observed for 4-QAM. For higher constellation sizes the impact of RFP decreases. This can be shown through the nonlinear tolerance improvement for a 2 dB OSNR penalty, which ranges from 0,1 dB to 0,5 dB for 32-QAM and 4-QAM, respectively.

In Fig. 2b it can be observed that when in-line dispersion compensation is used, the RFP-based compensation is scarcely effective for any of the evaluated constellation sizes. By fully compensating for the chromatic dispersion after every span, all first-order nonlinear distortions are identical. Similar to the results for LEAF fiber that were observed in the previous section, the RFP-based nonlinearity compensation is less effective when there is a high correlation of the nonlinear perturbations.

In order to investigate the effectiveness of the RFP-based compensation the error vector magnitude (EVM) is calculated per modulated data subcarrier (for the definition of the EVM, see [8,9]). OSNR is set to 30 dB and the curves obtained are low-pass-filtered. Fig. 3 shows the EVM for two scenarios. Plot a) shows the EVM for the back-to-back configuration. Plot b) shows the simulations results for 7 channels after 2000 km transmission.

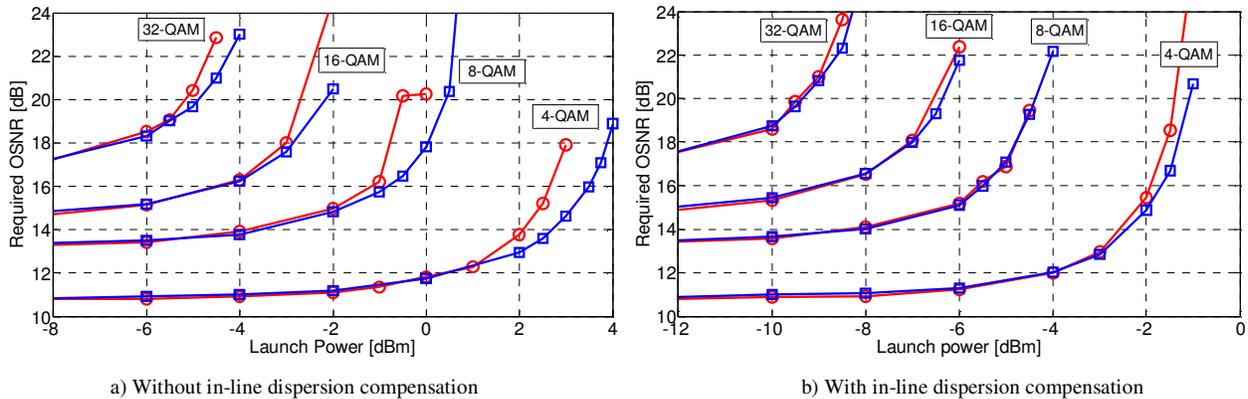


Fig. 2. Required OSNR for a target BER of  $10^{-3}$  for 7 WDM channels and different constellation sizes after 1000 km transmission for SSMF link.

The results in Fig. 3a show a flat EVM shape, meaning that the subcarrier are affected in a similar way by the noise and the RFP-based compensation works uniformly for all the subcarriers. Fig. 3b shows a higher EVM for the subcarriers at the center compared to the rest. The XPM impact in the center of the spectrum is more severe than in the sides. Furthermore, it can also be seen that for plot b) the RFP-based compensation compensates in the same proportion for all the subcarriers, since the EVM curves are separated by an approximately constant EVM distance.

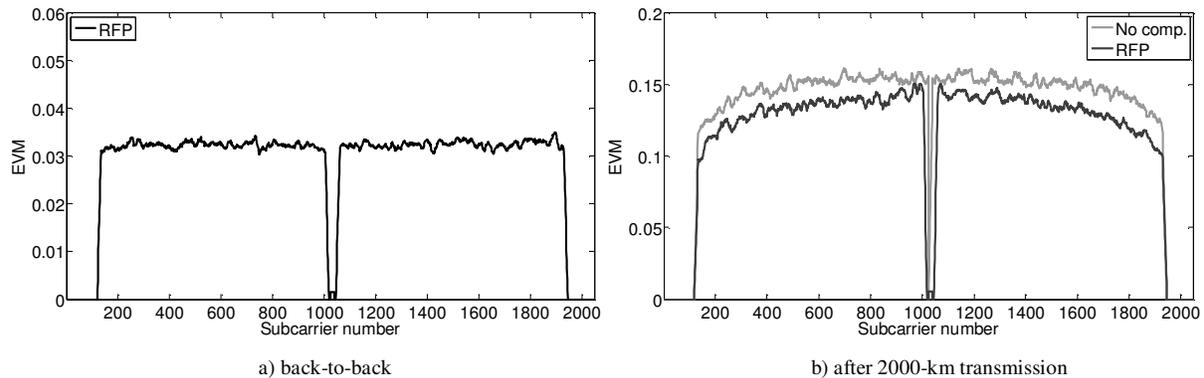


Fig. 3. EVM averaged over 15 subcarriers as a function of the subcarrier number for 8-QAM modulation, 7 WDM channels, 30 dB OSNR.

#### 4. Conclusion

In this paper, we investigated the efficiency of RF-pilot (RFP) based phase noise compensation for the mitigation of nonlinear impairments. On a 1000-km link it is shown that the efficiency of RFP nonlinearity mitigation scales with the effective dispersion difference between the nonlinear regions. On fiber with a small dispersion coefficient (i.e. LEAF) and in-line dispersion compensation the nonlinearities from span to span are highly correlated, resulting in a reduction of the RFP efficiency. On an SSMF link without in-line dispersion compensation the efficiency of RFP is significantly higher showing an improvement of maximum launch power of up to 1 dB. Additionally it is observed that on an unmanaged dispersion link the efficiency of the RFP-based nonlinearity compensation is inversely proportional to the constellation size. The EVM performance evaluation for the RFP-based compensation showed that the nonlinear impact is greater at the center of the spectrum and that the RFP-based method for nonlinear effects compensates in a homogeneous way for all the subcarriers.

#### 5. References

- [1] W. Shieh et al., *Electronic letters*, vol. 42, 587-589, (2006).
- [2] A. Lowery et al., *JLT*, vol. 25, No. 1, 131-138, (2007).
- [3] X. Liu, *proc. ECOC 2010*, PD2.6, (2010).
- [4] S. L. Jansen et al., *JLT*, vol. 26, No. 1, 6-15, (2008).
- [5] B. Inan et al., *proc. ECOC*, Tu.4.A.6, (2010).
- [6] P. Winzer et al., *JLT*, vol. 24, No. 12, 4711-4728, (2006).
- [7] K. Forozesh et al., *digest of the LEOSS*, 135-136, (2008).
- [8] J.L. Pinto et al., *proc. LCS*, Plenary 5, 14-15, (2000).
- [9] M.D. McKinley et al., *proc. ARFTG*, 45-52, (2004).