# Optical OFDM for ultra-high capacity long-haul transmission applications

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***Abstract*—Optical OFDM is a promising modulation format for next generation fiber-optic transmission systems. The main challenges for optical OFDM are its sensitivity to laser phase noise and high PAPR. In this paper the phase noise tolerance is investigated for the two main phase noise compensation algorithms: carrier phase estimation (CPE) and RF-pilot (RFP) compensation. Furthermore, the nonlinear tolerance of OFDM is addressed for SSMF and LEAF, where it is shown that using RFP-based phase noise compensation a nonlinear improvement of up to 1 dB can be obtained.**

***Index Terms*—Wavelength division multiplexing, orthogonal frequency division multiplexing, modulation formats, digital transmission systems**

## I. Introduction

Over the last four years, Orthogonal frequency division multiplexing (OFDM) has gained significant research interest in the fiber-optic community [1, 2]. Even though most of the reported experiments so far have been done with off-line signal processing, some real-time realizations of OFDM transmitters [3-5] and receivers [6, 7] have been reported over the last few years, demonstrating the feasibility of the technology. Many different realizations and applications of optical OFDM have been proposed, spanning from access networks [6] to long-haul transmission systems [4-5].

Optical OFDM is a modulation format, adapted from the wireless community that can potentially enhance the flexibility and scalability of fiber-optic transmission systems. The negligible out of band signal power of OFDM allows passive multiplexing of multiple bands without the need for optical filters and the training based equalization is ideally suited for dynamically scaling of the constellation size. In addition, optical OFDM is easily scalable to higher modulation formats [2] and is ideally suited for parallel integration in an ASIC or FPGA [3-7]. The main drawback of OFDM is that it has a relatively high Peak-to-Average Power Ratio (PAPR) at low chromatic dispersion (CD) compared to single carrier modulation formats. This poses a challenge for the use of optical OFDM on legacy transmission systems with dispersion compensating fiber. Because of the high PAPR, the nonlinear tolerance of the OFDM signal itself is relatively low [9]. In addition, the OFDM signal impairs its neighboring channels through cross phase modulation (XPM) [10]. In modern transmission systems the inline dispersion compensation is removed in order to reduce the coherence of the nonlinearity from span to span. In such a system, the influence of the PAPR is less detrimental [9]: Already after 300 km of SSMF transmission, the PAPR of OFDM and single channel are comparable and as such the nonlinear tolerance as well. Therefore, OFDM has mainly been considered for transmission links without in-line dispersion compensation [2, 8, 9, 12]. In such long-haul transmission systems, coherent optical detection is used in order to achieve high robustness against noise from optical amplifiers. For all coherent detection algorithms that use a local oscillator laser phase noise can represent a major performance impairment that must be compensated for [11], [12]. In particular because of its long symbol size, OFDM requires an effective compensation mechanism.

In this paper design aspects for optical OFDM are discussed focusing on phase noise compensation and the nonlinear tolerance. In section II the phase noise tolerance of OFDM is investigated as a function of the FFT size. Two phase noise compensation schemes are compared: carrier phase estimation (CPE) and RF-pilot (RFP) compensation. Subsequently, section III covers the nonlinear tolerance of OFDM with and without RFP-based phase noise compensation.

## II. Phase noise compensation

In a coherent transmission system, a relatively high power local oscillator is mixed with the received signal and the sum is detected by a photodiode thereby downmixing the received optical signal. The phase noise of the lasers used in a coherent optical system can have a big impact on the performance and therefore must be compensated for. In several coherent fiber-optic transmission systems carrier phase estimation is performed by using the 4$^{th}$ order nonlinearity [13], [14]. However, for CO-OFDM it has been

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shown that such a data-aided carrier phase estimation results in a poor performance [11]. Phase noise compensation requirements are more stringent in an OFDM system as the symbol rate (at the same data rate) is significantly lower than that of conventional fiber-optic systems. More effective methods to compensate for phase noise in OFDM systems have been proposed, namely CPE [11] or RFP [12].

The influence of phase noise in OFDM systems is twofold, i.e., it generates a common phase rotation (CPR) of all the subcarriers in one symbol and a cross-leakage between the subcarriers named inter-carrier interference (ICI). The former effect is commonly solved in wireless systems using CPE [15], aided by inserting dedicated pilot subcarriers. At the receiver these are used to rotate back the received symbols. This method has been used as well in several fiber-optic transmission experiments, see e.g. [2]. The main drawback of CPE, however, is that it does not correct for the ICI, since it inherently assumes the phase of the transmitter (TX) and local oscillator (LO) laser to be constant during one OFDM symbol. Consequently, the OFDM symbol must be short and the laser linewidths must be small to limit the impact of ICI. However, shorter OFDM symbols require larger cyclic-prefix overheads in order to compensate for CD and small linewidths require costly lasers.

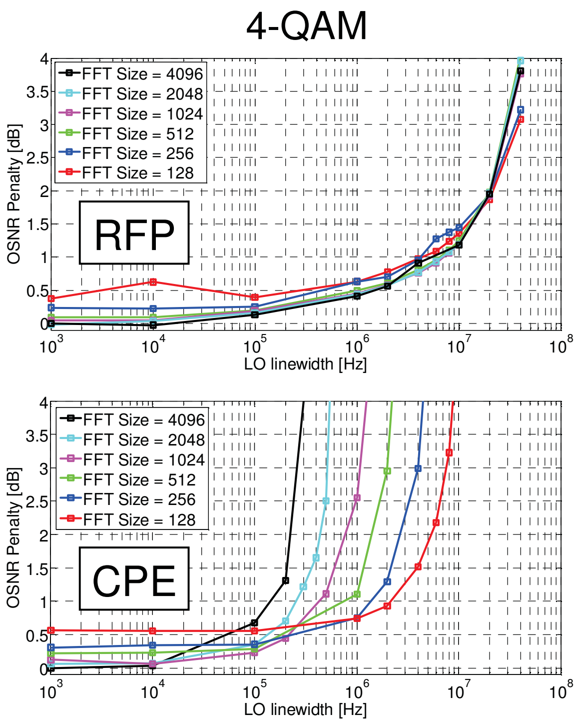


Fig. 1: Phase noise tolerance for RFP and CPE with varying FFT size.

In [12] a new phase noise compensation scheme has been introduced and referred to as RF-pilot-based phase-noise compensation, which effectively compensates for both the common phase error and the ICI. With this technique, phase-noise compensation is realized by placing a RF-pilot (RFP) tone in the center of the OFDM transmit spectrum, which is subsequently used at the receiver in order to undo phase noise impairments.

The performance of these two phase noise compensation schemes (CPE and RFP) will be compared in this section as a function of the FFT size. The OFDM signal used for the evaluation has a nominal data rate of 62.2-Gb/s (one polarization of a 124.4 Gb/s PDM-OFDM signal). 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. Further details of the OFDM transmitter, receiver and the optical link can be found in [17]. Fig. 1 shows phase noise tolerance of CPE and RFP expressed as the required OSNR for a BER of $10^{-3}$ as a function of the laser linewidth of the transmitter and receiver laser. The constellation size in this evaluation was 4-QAM and the FFT size is varied from 128 to 4096.

Allowing a 1-dB penalty in required OSNR, the maximum laser linewidth tolerance for the evaluated configurations is ~7MHz and ~2MHz for RFP and CPE, respectively. This clearly demonstrates that RFP can cope with significantly higher laser phase noise than CPE. In addition it can be observed that with CPE the FFT size has a large impact on the phase noise tolerance: The FFT size inversely scales with the phase noise tolerance. With RFP, however, RFP the phase noise tolerance is practically independent of the FFT size. The principle of RFP-based phase noise compensation is further illustrated in Fig. 2. An example of the temporal evolution of random phase noise is shown for three consecutive OFDM symbols. Furthermore, the phase noise estimates obtained with the CPE-based as well as the RFP-based scheme are shown. Clearly, the CPE compensation accounts for the mean phase noise per OFDM symbol but does not correct for the fast fluctuations. However, these residual phase dynamics can result in considerable ICI.

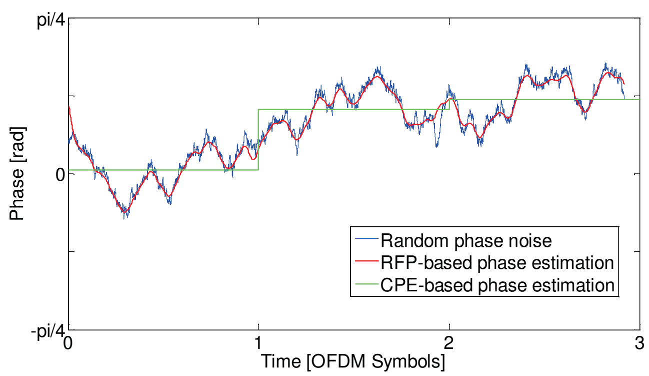


Fig. 2: Example of random phase noise evolution over three OFDM symbols together with results of CPE estimation and RFP phase noise estimation.

For CPE it can be observed as well that for negligible laser phase noise (LO Linewidth = $10^3$ to $10^4$ Hz) a required OSNR penalty of up to 0.6 dB is present for low FFT sizes (128 for instance). This penalty arises from the fact that for low FFT sizes the OFDM symbol is shorter. As a result, the phase estimation of the OFDM subcarriers has less power per OFDM symbol and becomes less accurate at low OSNR values.

Similar to CPE, for RFP a small required OSNR penalty of up to 0.6 dB is observed for short FFT sizes as well in the regime with negligible laser phase noise. In case of RFP, the OSNR penalty is caused by spectral leakage of the OFDM signal into the RF carrier. This concept is illustrated in Fig. 3. In this plot four neighboring OFDM subcarriers are shown with an RF carrier for a large and a small FFT size. In case of the large FFT size the OFDM subcarriers are very small causing negligible power leakage into the RF carrier whereas in case of a small FFT size the wide OFDM subcarriers spectrally overlap with the tails of the RF-carrier. Because of the spectral leakage of the OFDM subcarriers the phase noise compensation becomes less accurate and a small penalty arises.

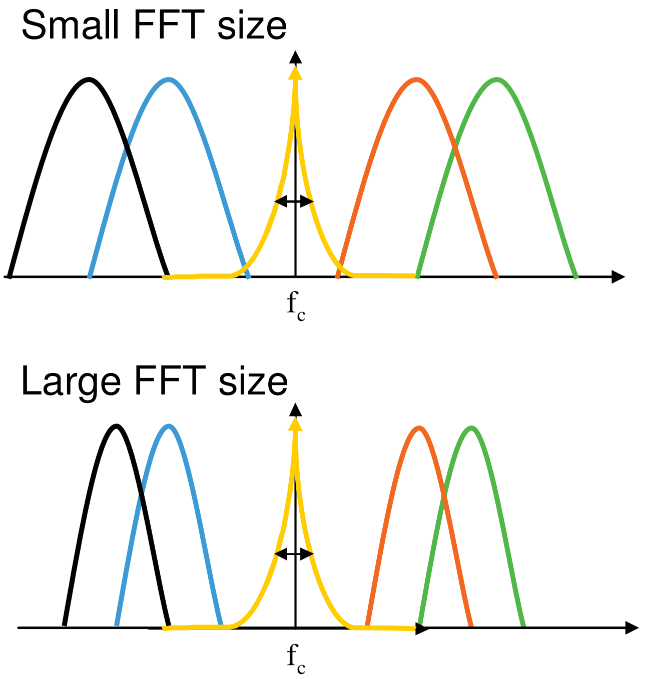


Fig. 3: Illustration of RFP with small and large FFT size

## III. Nonlinear Performance of RFP

Recently, it has been shown that using RFP for phase noise compensation, the nonlinear tolerance can be improved [16, 17]. This section summarizes the results published in [17] where the nonlinear performance of RFP is evaluated for standard single mode fiber (SSMF) and large effective area fiber (LEAF) on a 1000-km transmission line. In this simulation, single channel and 7 co-propagating co-polarized WDM channels are evaluated at 50-GHz channel spacing. The OFDM parameters are identical as the ones presented in section II. 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 FFT size is set to 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 [16] and in [17]. Fig. 4 shows the required optical signal-to-noise ratio (OSNR) for a bit-error-ratio (BER) of $10^{-3}$ as a function of the launch power for SSMF and LEAF. 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 [9]. 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.

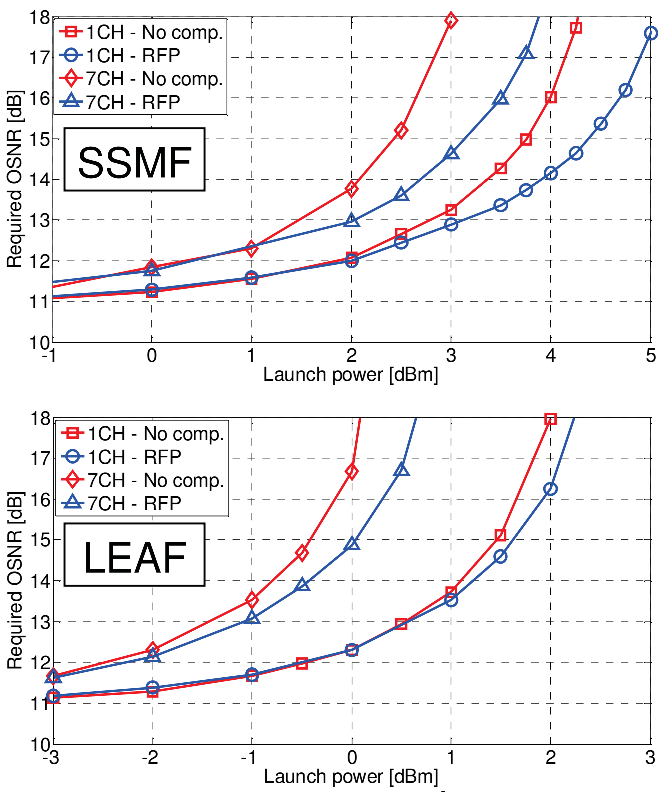


Fig. 4: Required OSNR for a BER of $10^{-3}$ as a function of the launch power.

## IV. CONCLUSION

In this paper we have reviewed the influence of the FFT size on the phase noise tolerance of optical OFDM. We have shown that the phase noise tolerance for RFP is significantly higher than that of CPE. In addition the nonlinear tolerance of RFP is reviewed for SSMF and LEAF. 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 an SSMF link without in-line dispersion compensation up to 1 dB improvement in nonlinear tolerance is observed.

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