RF-Pilot-based Nonlinearity Compensation in Frequency Domain for CO-OFDM Transmission

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ABSTRACT

The effects of fiber nonlinearity in Coherent Optical Orthogonal Frequency-Division Multiplexing (CO-OFDM) transmission, such as self-phase modulation (SPM) and cross-phase modulation (XPM), are a major concern. In this paper, we investigate the use of RF-Pilot (RFP) based nonlinearity compensation scheme in frequency domain to compensate for fiber nonlinearity in a coherent OFDM optical system. It shows that the RFP-based compensation scheme has superiority over a conventional pilot-based compensation scheme at FEC threshold.

Keywords: fiber optics communications, coherent OFDM system, nonlinear fibers

1. INTRODUCTION

CO-OFDM that allows the merits of both a coherent system and an OFDM system is considered as a high spectral efficiency technology for the next generation of optical communication systems. The tolerance towards CD and PMD is a major advantage of CO-OFDM. OFDM has however a specifically high PAPR compared to signal carrier system so that the effects of fiber nonlinearity induced by Kerr effect are a major concern [1, 2]. This can be explained as the refractive index of the fiber is affected by the intensity of light; therefore a high electrical peak would result in high variance in the refractive index. Nonlinear Schrödinger equation [3] is usually used to model the effects of fiber nonlinearity.

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i\gamma(\omega_0)\left|A\right|^2 A \tag{1}$$

where $A(t,z)$ represents the complex envelope of the signal in the fiber at the position z and time t, γ is the nonlinear parameter defined as:

$$\gamma(\omega_o) = \frac{n_2(\omega_0)\omega_0}{cA_{eff}} \tag{2}$$

where n_2 is the nonlinear index of the fiber and the effective core area of the fiber is A_{eff}.

To mitigate the effects of fiber nonlinearity, several methods have been proposed to reduce the PAPR of the CO-OFDM systems [4, 5]. Nevertheless, the PAPR reduction in high-rate transmission system becomes unsuitable because the cumulated chromatic dispersion in such system causing fast walk-off between subcarriers, hence the PAPR will quickly enlarge again [6, 7]. In single-channel transmission, SPM dominates the nonlinear distortion of OFDM signal, while in multi-channel transmission, as in wavelength division multiplexing (WDM), the XPM between the WDM channels can severely degrade the system performance. In this paper, we investigate the use of RFP-based nonlinearity compensation scheme in frequency domain to compensate for the fiber nonlinearity in a CO-OFDM optical system.

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Nonlinear Optics and Applications VI, edited by Benjamin J. Eggleton, Alexander L Gaeta, Neil G. Broderick, Proc. of SPIE Vol. 8434, 84340J · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.922336

2. RF-PILOT BASED NONLINEARITY COMPENSATION METHOD

It has been shown that RFP compensation scheme is effective to compensate for laser phase noise [8, 9]. As the SPM and XPM induce a phase distortion in optical system, RFP scheme allows compensating for fiber nonlinearity as well [10]. In this scheme, a pilot tone is placed in the middle of the transmitted OFDM signal that called RFP. An easy way to insert the RFP is by turn off the first OFDM subcarrier and setting a DC offset by driving the V_{bias} at the IQ-modulator. This RFP is distorted by the laser phase noise and effects of fiber nonlinearity as a same fashion of OFDM signal.

In conventional RFP, a digital filter is required at the receiver to extract the RFP. Then, the filtered RFP is inverted and multiplied with OFDM symbol at the time domain. Consequently, the digital filter plays a critical role of the efficiency of this compensation scheme. Additionally it adds a complexity to implementation as it requires certain complex multiplications per one sample [9]. In contrast, we proposed the use of RFP-based nonlinearity compensation scheme in frequency domain so that no need to digital filer anymore. Moreover, a second major influence on the compensation efficiency of RFP is the pilot-to-signal ratio (PSR) value, as shown in Fig. 1, which it defines as:

$$PSR(dB) = 10 * \log(\frac{P_{RFP}}{P_{OFDM}}) \tag{3}$$

where P_{RFP} and P_{OFDM} stand for the electrical power of the RFP and the OFDM signal, respectively

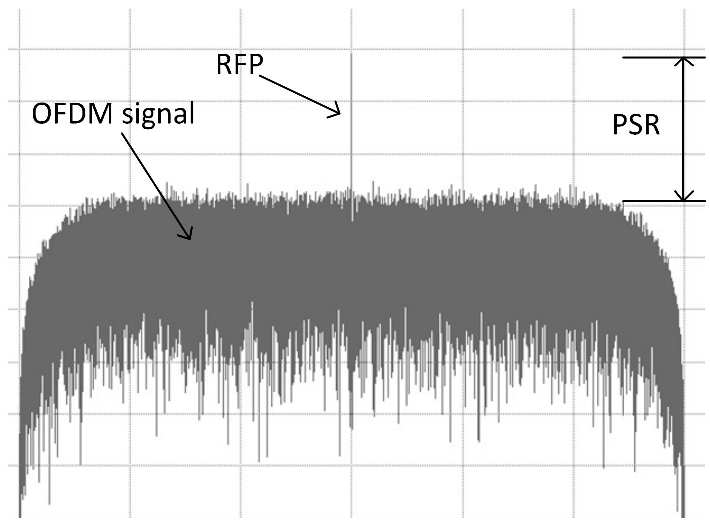

Figure 1. OFDM signal with RF-Pilot, PSR is the power of pilot to power of signal ration

3. SYSTEM SETUP AND RESULTS

Fig. 2 shows the setup for the homodyne coherent optical OFDM transmission system used in our simulation. Electrical OFDM baseband signal is generated through MATLAB. A PRBS bit streams are mapped into 16-QAM, then a different point value of iFFT size with 12% cyclic prefix is considered to evaluate the RFP compensation performance. Several training symbols are used for channel estimation before conversing to time domain. Then the electrical signal is converted onto the optical signal through an optical IQ Mach-Zehnder Modulator. VPItransmissionMaker 8.6 [11] is used to model the optical system transmission on 10 Gbit/s data rate. The optical signal is transmitted over 800 Km of SSMF which consist of 6x80 km span. The erbium doped fiber amplifiers (EDFAs) among the fiber are used to compensate the span loss with gain of 16 dB and noise figure of 6 dB. The fiber chromatic dispersion of 16 ps/nm/km, 0.2dB/km loss, and a nonlinear coefficient of 6×10^{-20} m2/W are used. 5 channels WDM with 5 GHz channel spacing are transmitted to model the effect of XPM and one polarization is considered. To evaluate the performance of RFP nonlinearity compensation, the SPM and XPM effects are enabled without phase noise, i.e. ideal lasers. At the coherent receiver, a coherent detection is used that consist of 90° optical hybrid and balanced detectors. Then the electrical signal is passed to OFDM decoder where the RFP is filtered, inverted and then multiplied by its OFDM symbols.

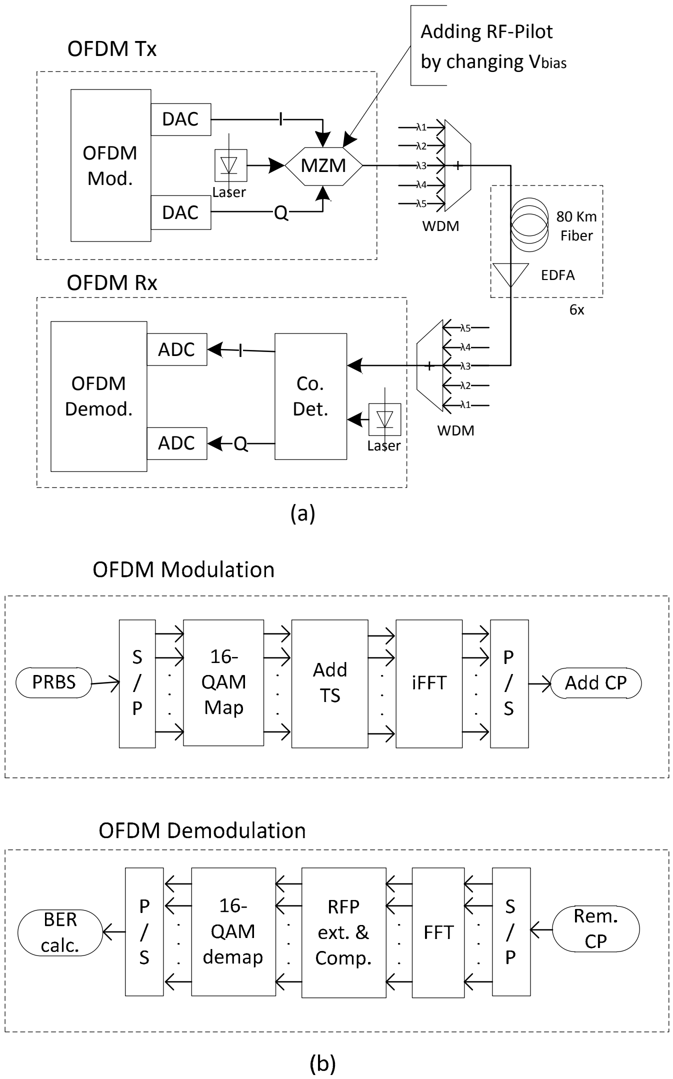

Figure 2. (a) System setup of CO-OFDM, DAC: digital to analog, MZM: mach-zehnder modulator, EDFA: erbium-doped fiber amplifier. (b) OFDM coder and decoder, S/P: serial to Parallel, P/S: parallel to serial, TS: Training Symbols, CP: cyclic prefix, FFT/iFFT: (invers) Fast Fourier Transform, RFP ext. & comp.:RFP extraction and compensation, Co. Det.: Coherent Detection., WDM: Wavelength-Division Multiplexing.

Fig.3 shows the influence of PSR on the BER, the optimal PSR for 256 FFT size is -6.1 dB and -4.4 dB for 1024 FFT size. When the OFDM symbol gets longer by increasing the FFT size, the optimal PSR required is decreased. It is important to find the optimal value of PSR. This is because the total power of the system is the power of pilot plus the OFDM power. Therefore if the PSR is too high causing the power of the OFDM signal become too low which leads to worse performance due to ASE noise. While if the RFP power is too low, the ASE noise affects the performance of the RFP compensation because the RFP becomes too noisy to compensate the phase distortion.

The conventional RFP compensation [10] requires a bandwidth of the guard band around the RFP; this guard band decreases the spectral efficiency. On the other hand, this could reduce the effective of the compensation because the noise within the guard band around the pilot is multiplied with the OFDM symbols. Therefore, our scheme avoids the noise within the guard band and save the bandwidth efficiency by performs it in frequency domain.

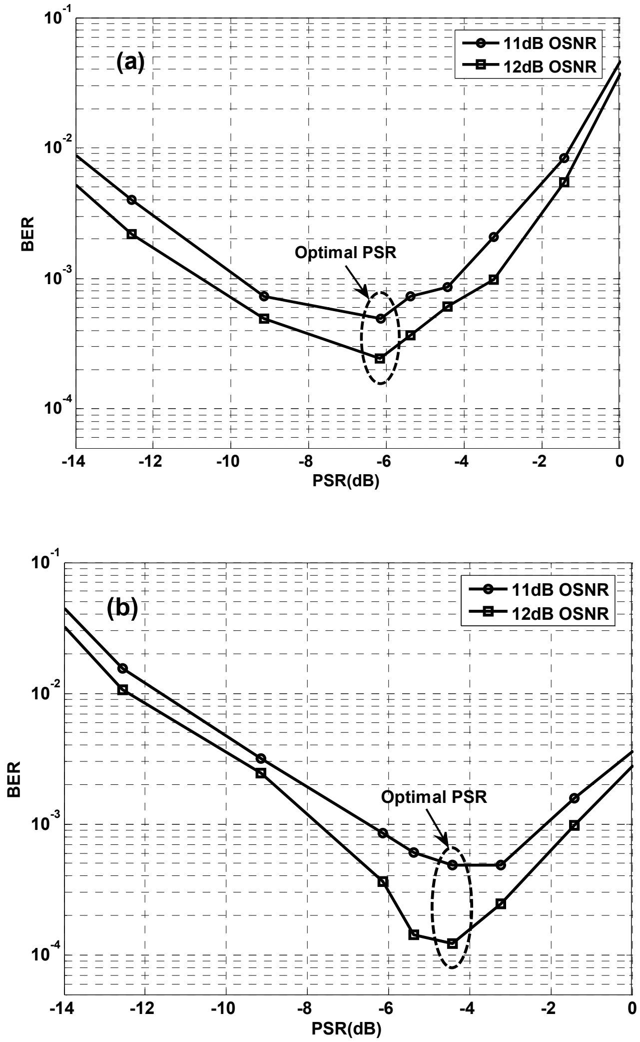

Figure 3. BER as a function of the PSR, the optimal PSR value is around -6 dBm and -4.4 dBm for (a) 256 FFT size (b) 1024 FFT size, respectively.

To verify the performance of RFP-based nonlinearity compensation, a comparison with pilot-based nonlinearity compensation is considered. An averaging of multiple pilot subcarriers is used to compensate the phase distortion. Fig. 4 (a) shows BER as a function of launched power for 256 FFT size. As we see for BER of 10^{-3}, the RFP compensation at -6.1 dB PSR shows a 1.75 dBm of launched power improvement compared to 2 pilot subcarriers compensation. Even at -3.2 dB PSR, the improvement is better of pilot-based compensation around 0.5 dBm of power launch. The improvement of launched power at 10^{-3} BER is 0.5 dBm for -6.1 dB PSR compared to 6 pilot subcarriers compensation. the efficiency of RFP-based nonlinearity compensation scheme shows the same effective for 1024 FFT size as shown in Fig. 4 (b).

From both Fig. 4(a) and (b), at launched power -1 dBm, the RFP with -6.1 dB PSR performs better than the RFP with 3.2 dB in FFT size of 256, while RFP with -5.3 dB is better than RFP with -6.1 in FFT size of 1024. This shows that the required PSR is decreased as the length of OFDM symbols is getting longer. In addition to the efficiency of RFP-based nonlinearity compensation, the spectral efficiency is saved from using extra pilot subcarriers to improve the performance of the system.

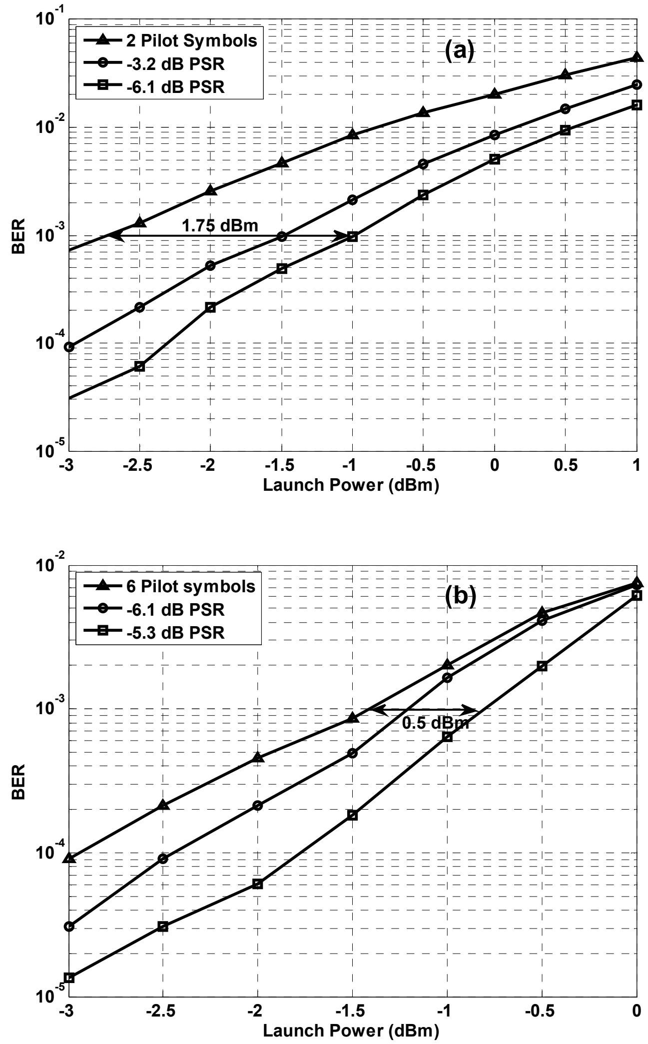

Figure 4. BER as a function of the launched power, an improvement of 1.75 dBm and 0.5 dBm are achieved for both (a) 256 FFT size (b) 1024 FFT size, respectively.

4. CONCLUSION

In this paper, we studied the ability to compensation for fiber nonlinearity in long-haul CO-OFDM. We proposed to use RFP-based nonlinearity in frequency domain. Thereby, the guard band around the pilot is avoided and the performance of RFP-based nonlinearity compensation is improved by avoiding the noise falls inside the guard band. Simulation results of a 10 Gbit/s with several FFT sizes show the capability and simplicity of RFP-based nonlinearity compensation in frequency domain. The fiber nonlinear penalty is improved by 1.75 dBm and 0.5 dBm for 256 FFT size and 1024 FFT size, respectively. In addition, numerical simulation shows the optimal value of pilot to signal power ratio, the value for 256 FFT size is -6.1 dB and -4.4 dB for 1024 FFT size. It is observed that on a large FFT size the required PSR is decreased and the efficiency of the RFP-based nonlinearity compensation scheme is increased. To our knowledge, this is more applicable scheme than others in terms of hardware implementation.

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