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Improved fiber nonlinearity mitigation in dispersion managed optical OFDM links

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ABSTRACT

Fiber nonlinearity is seen as a capacity limiting factor in OFDM based dispersion managed links since the Four Wave Mixing effects become enhanced due to the high PAPR. In this paper, the authors have compared the linear and nonlinear PAPR reduction techniques for fiber nonlinearity mitigation in OFDM based dispersion managed links. In the existing optical systems, linear transform techniques such as SLM and PTS have been implemented to reduce nonlinear effects. In the proposed study, superior performance of the L_2-by-3 nonlinear transform technique is demonstrated for PAPR reduction to mitigate fiber nonlinearities. The performance evaluation is carried out by interfacing multiple simulators. The results of both linear and nonlinear transform techniques have been compared and the results show that nonlinear transform technique outperforms the linear transform in terms of nonlinearity mitigation and improved BER performance.

1. Introduction

The OFDM technique is highly desirable for designing flexible and energy efficient backbone (BB) and backhaul (BH) links in cognitive optical networks (CON) [1]. An adaptive impairments assessment scheme is necessary to evaluate the impact of various effects in BB & BH links. Based on the assessed impairments, an adaptive compensation is required to improve the performance of system. In optical OFDM (OOFDM) systems, peak power increases the fiber nonlinear effects such as SPM, XPM and FWM [2,3]. By applying suitable PAPR reduction scheme, peak power of the OFDM signal can be reduced, which results in reduction of fiber nonlinear effects [2,3,11]. The PAPR is also a major limitation in non-orthogonal modulation formats like FBMC and GFDM [4], that are envisaged for next generation 5 G wireless standards. Hence PAPR reduction and thereby fiber nonlinearity mitigation becomes essential for next generation fiber transport networks.

The effect of FWM is dominant in OOFDM systems, due to the compact distribution of large number of subcarriers [5]. Most of the commercial backbone links are installed with necessary dispersion compensating systems which enhances the phase matching conditions for FWM. Therefore, it is necessary to use a FWM mitigation scheme to improve the overall performance of the system.

The FWM efficiency depends on laser power and phase match conditions. The incorporation of suitable PAPR reduction technique will reduce the correlation among subcarriers and thereby increase the phase mismatch. In OOFDM systems, for peak power reduction, several techniques have been proposed which includes conventional linear transform techniques such as SLM and PTS [6,7]. In this paper, authors have implemented an L_2-by-3 nonlinear transform technique to mitigate fiber nonlinear effects in the OFDM based BB & BH links. Complexity analysis and results of both transformation techniques have been compared in detail.

2. Theoretical analysis

2.1. OFDM signals with PAPR

In discrete-time domain, the complex base band OFDM signal can be represented as [6]

$$s[n] = \sum_{l=-N/2}^{N/2-1} u_l e^{\frac{j2\pi ln}{NL}}, \quad n = 0, 1, \ldots NL - 1 \tag{1}$$

where u_l is lth information symbol, N is number of subcarriers and L is the oversampling factor. The discrete time signal $s[n]$ is interpreted as IFFT of u_l with (L-1)N zero padding. The PAPR of the continuous time signal cannot be precisely obtained at L=1. However, L=4 can provide sufficiently accurate PAPR results and it is implemented in most of the reduction techniques. The PAPR of the signal defined in (1) is given as

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$$PAPR = \frac{\max_{0\le n\le NL-1}[|s[n]|^2]}{E[|s[n]|^2]} \quad (2)$$

where E[.] denotes the statistical expectation. To evaluate PAPR reduction performance of employed schemes, the Complementary Cumulative Distribution Function (CCDF) is plotted to calculate the probability that the PAPR of an OFDM frame exceeds the defined threshold value [8].

$$p(PAPR > PAPR_{th}) = 1 - (1 - e^{-PAPR_{th}})^N \quad (3)$$

2.2. Nonlinear phase noise variance of SPM/XPM/FWM

The fiber nonlinear effects are highly dependent on the input signal power. The increase in peak power of OFDM signals will increase the variance of nonlinear phase noises due to SPM, XPM and FWM which in turn results BER performance degradation. So, the reduction in peak power of the OFDM signal is necessary to reduce the nonlinear phase noise variance and improve the BER. The variance of nonlinear phase noise due to SPM and XPM reported in [9] can be modified as

$$\langle\delta\phi_{SX,l}\rangle^2 = \frac{N_a(N_a-1)(2N_a-1)\gamma^2L_{eff}^2(2N_e-1)P_{sc}}{3} \quad (4)$$

where N_a is the number of amplifiers, γ is the nonlinear parameter, L_{eff} is the effective fiber length, N_e is the number of data carrying subcarriers and P_{sc} is the power per subcarrier. The FWM induced deterministic distortion can be mathematically represented as [10]

$$\xi_{F,l} = i\gamma N_a L_{eff}\sum_{i+j-k=l}^{i\neq l,j\neq k} u_i u_j u_k^* \quad (5)$$

where $\sum_{i+j-k=l}^{i\neq l,j\neq k} u_i u_j u_k^*$ represents the serial correlation among the subcarriers which increases the FWM induced phase noise.

The FWM induced nonlinear phase noise variance of the lth subcarrier can be obtained from [9,11] as

$$\langle\delta\phi_{F,l}\rangle^2 = \frac{N_a(N_a-1)(2N_a-1)\gamma^2L_{eff}^2P_{sc}^2}{12} \times \left[3 - \frac{9}{N_e} - \left(\frac{2l+1-N_e}{N_e}\right)^2\right] \quad (6)$$

The implementation of suitable peak power reduction scheme will reduce the correlation among subcarriers and therefore reduction in FWM noises is achieved.

2.3. Linear transform based nonlinearity mitigation

Nonlinear effects in OOFDM system is reduced by applying conventional linear transform techniques such as SLM and PTS. In SLM, the input data is duplicated D times and it is multiplied by a suitable phase factor $\phi_l^{(d)}$ that can be represented as [7]

$$u_l^{(d)} = u_l e^{j\phi_l^{(d)}}, \quad d = 0, 1, \ldots, D-1 \quad (7)$$

The different phase factor multiplied data sequences are then analyzed to find the sequence which offers lowest PAPR for transmission. To recover the original data sequence at the receiver, side information (SI) need to be transmitted along with the data sequence which increase the link rate and bandwidth requirements.

In PTS, the input data sequence is divided into V disjoint subblocks and multiplied by the phase factor suitable for that subblock. The IFFT is applied to generate the time domain discrete signal and it is represented as [7]

$$s[n] = F^{-1}\left\{\sum_{v=0}^{v-1} b_v u_v\right\} \quad (8)$$

$$s[n] = \sum_{v=0}^{v-1} b_v F^{-1}\{u_v\} \quad (9)$$

This scheme also requires side information transmission for data recovery. As the number of subcarriers increases the required number of subblocks and corresponding phase factors also increases. Due to higher computational complexity and SI transmission, these techniques are not well adopted in recent technologies.

2.4. Nonlinear transform based nonlinearity mitigation

The nonlinear transform technique which avoids transmission of SI and has reduced computational complexity is required for PAPR reduction in OOFDM systems. Therefore in the proposed optical system, authors have implemented the L_2-by-3 transformation to mitigate various fiber nonlinear effects through PAPR reduction. In this transformation, the term L_2 indicates the metric and 3 indicates the norm of samples per sliding operation. The L_2-by-3 transformed sequence r_n with the input signal sequence s_n is represented as [12]

$$r_n = \frac{s_{(n)N}}{\sqrt{\alpha + s_{(n-1)N}^2 + s_{(n)N}^2 + s_{(n+1)N}^2}} \quad (10)$$

Where N is the number of samples, $()_N$ is the modulo N operation for the index of samples, α is the parametric constant to adjust the PAPR of the output signal. In (10), the term (n) is the present sample, (n−1) is the past sample and (n+1) is the future sample. For example if n=1, s(n−1)=s(0) and s(n+1)=s(2).

The selection of parametric constant α decides the amount of peak power reduction in an OFDM signal. The value of this constant usually ranges from 0 to 1. The PAPR reduction performance of the L_2-by-3 scheme in OOFDM system for varying α is shown in Fig. 1. The increase in value of α from 0, decreases the quantum of PAPR reduction. The value of α is optimized based on PAPR reduction and corresponding BER performance obtained at the OOFDM receiver. From the results, the optimized value of α is identified as 0.1 because it satisfies the required PAPR reduction with better BER performance. Therefore, the various performance analysis in this work is carried out using the optimized α value of 0.1. The inverse transformation is applied at the receiver to recover the original transmitted signal.

3. Simulation setup

The simulation setup of the OOFDM system with PAPR reduction based fiber nonlinearity mitigation scheme is shown in Fig. 2. In the proposed high level simulation, authors have interfaced Matlab simulator with VPI simulator to demonstrate the nonlinearity mitigation. The impact of fiber channel impairments and their mitigation schemes is similar for DD-OFDM and CO-OFDM systems. However, in this paper, the simulation is performed using DD-OFDM to avoid the

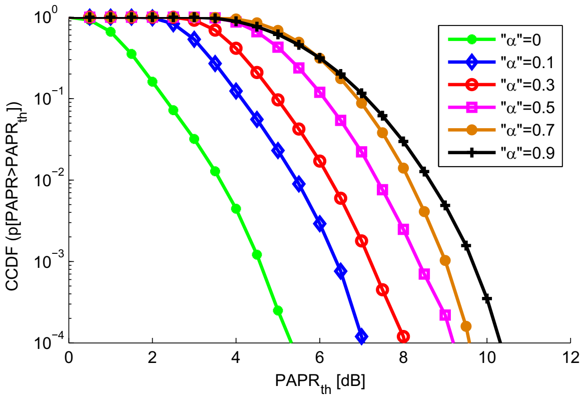

Fig. 1. Performance of PAPR reduction for varying α.