Peak-to-Average Power Ratio Reduction in Long Haul Coherent Optical OFDM Systems

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Abstract. Recently, Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) has been seen as a potential candidate for long haul optical transmission. It is due to OFDM technique that was proved as an effective solution for mitigating chromatic dispersion (CD) effects in optical communication systems. However, a very basic drawback of OFDM technique is large peak-to-average power ratio (PAPR) problem which requires large scale linear power amplifier and optical external modulator. The large PAPR leads to the increase of nonlinearity of optical fiber which depends on instantaneous signal power. So, the performance of CO-OFDM system is degraded. Several approaches were studied and applied in wireless communication. Among all techniques of Partial Transmit Sequence (PTS) is considered as the good method because of its distortionless characteristics. But the efficiency of this algorithm in long haul optical communication application is still an open issue. In this paper, we study PTS technique to reduce the influence of optics nonlinear effects. The Simulink simulation results are presented and discussed.

Keywords: Orthogonal Frequency Division Multiplexing, CO-OFDM, PAPR, PTS.

1 Introduction

Optical communication has been advanced to deliver the highest bit rates ever imagined, up to several hundred Gbits/s per optical wavelength channel [1] [2]. This is possible due to the significant progresses in the use of coherent detection, orthogonal frequency division multiplexing (OFDM) technique, multiplexing of polarization modes of guided optical waves in single mode optical fibers, and the employment of ultra-high speed processing in the electronic domain. OFDM technique has been demonstrated to combat fiber impairments such as fiber chromatic dispersion (CD) and polarization-mode dispersion (PMD) by splitting one high data rate stream into many lower data rate streams and then modulating each of them on corresponding subcarriers. Thus, OFDM can tolerate inter-symbol interference (ISI) caused by fiber chromatic dispersion [3], therefore, it seems quite a potential technique in high data rate optical communication. However, this technique exist

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some drawbacks. One of them is a high PAPR since many subcarrier components are added via IFFT operation. The high PAPR gives rise to signal impairments which are caused by nonlinear devices' characteristics such as Analog/Digital (A/D) converter, Mach-Zehnder Modulator (MZM) as well as fiber cable[4]. In addition, the Kerr effect also makes distortions known as four-wave mixing (FWM) phenomenon between OFDM subcarriers. It makes subcarriers become dis-orthogonal. It is worth noticing that the influences of these nonlinear phenomena depend on the signal power which is measured before launching into fiber [5]. Therefore, various PAPR reduction techniques have been researched and proposed in wireless communications and recently for optical OFDM systems[3][6]-[8]. In wireless communication field, researchers already carried out many PAPR reduction methods such as filtering, clipping, coding, partial transmission sequences (PTS), selected mapping (SLM), etc[4][9]. Among these methods, the PTS scheme is considered as more efficient for PAPR reduction. The idea is to scramble an input data block of the OFDM symbols in time domain (PTS) and multiply them by a set of phase factor. Finally, the one with the minimum PAPR is transmitted. So, the probability of occurring high PAPR could be reduced before taking into Mach-Zehnder external modulation module.

In our work we use PTS reduction method applying to optical communication employing OFDM technique to reduce fiber nonlinear effects. The Simulink model is built and the experimental results are discussed. After a short introduction, the fundamental PAPR theory in CO-OFDM systems is revealed in section two. In section three, the PTS algorithm is illustrated in detail, CO-OFDM system set-up with this algorithm is discussed and showed in next part. The last one is some of the numerical simulation results and discussion.

2 PAPR of the OFDM Signal

In OFDM system with N subcarriers, if M signal are added with the same phase, they produce a peak power that is M times the average power.

Generally, even linear amplifier can cause nonlinear distortion on the output signals. It happens because of saturation characteristics of high power amplifier (HPA), external modulation MZM. In this case, the input signal power is much larger than its nominal value. However, the high input power level also causes several serious effects due to fiber nonlinearity[10] such as four-wave mixing (FWM) or self-phase modulation (SPM).

The performance of PAPR reduction algorithms could be evaluated in the following ways: (1) In-band ripple or out of band radiation which can be seen through power spectral density, (2) distribution of PAPR which is given by complementary cumulative distribution function (CCDF), and (3) is coded and un-coded BER performance. In our work, we use (2) and (3) to evaluate system's performance since PTS is a distortionless PAPR reduction method. The formula of CCDF is as follows[8]:

$$P\{PAPR > z\} = 1 - P\{PAPR \le z\} \\ = 1 - (1 - e^{-z})^N \quad (1)$$

3 PTS Algorithm Illustration

PTS is the most efficient approach and a distortionless scheme for PAPR reduction by optimally combining signal sub-blocks. In PTS technique, the input data block is broken up into disjoint sub-blocks in time domain. The sub-blocks are transformed into frequency domain by using IFFT, and after that they are weighted by a phase weighting factor before adding together to produce alternative transmit containing the same information (Fig. 1). However, when we have a large number of sub-blocks, finding out a best weighting factor is a complex and difficult problem [11].

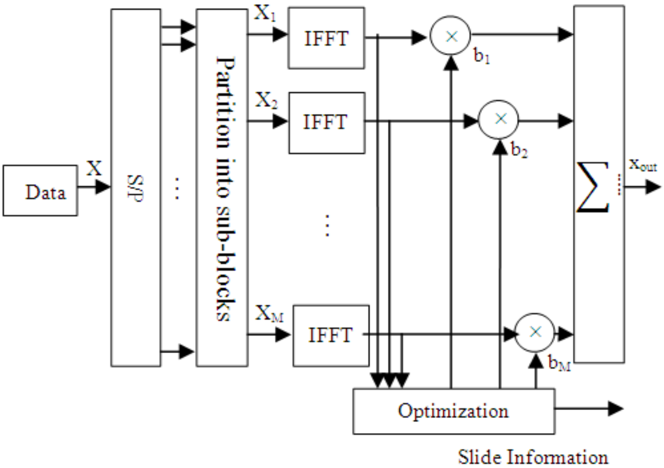

Fig. 1. The structure of transmitter site with PTS

The input data vector X in PTS algorithm is firstly partitioned into M disjointed sub-blocks $X_m = [X_{m,0}, X_{m,1}, \ldots X_{m,N-1}]^T$ such that:

$$X = \sum_{m=0}^{M-1} X^{(m)}, 0 \le m \le M-1 \quad (2)$$

The sub-blocks are combined to minimize the PAPR. After performing the Inverse Fast Fourier Transform of X_m, we have $x_m = [x_{m,0}, x_{m,1}, \ldots x_{m,NL-1}]^T$, $0 \le m \le M-1$ with L is oversampling factor.

Each sub-block in time domain after that is rotated by a phase factor set $b_m = e^{j\phi m}$. In general, the phase factor set is limited with a finite number of elements to reduce the complexity. In this paper, we chose $\phi \in \{0, \pi/2, \pi, 3\pi/2\}$, this means $b_m \in \{\pm j, \pm 1\}$. Finally, the sub-blocks are summed up. After the PTS operation, the OFDM signal becomes [12]

$$x = \sum_{m=0}^{M-1} b_m x_m \tag{3}$$

Where x and x_m are the signal in the time domain.

The aim in the PTS is to find the optimal phase factors. In the phase optimization, because the phase factor of the first sub-block is taken as $b_0 = 1$, there are W^{M-1} alternative b combinations, where $b = [b_1 ... b_{M-1}]$ and W is the number of the phase factors. In sequence b, b_m values are as follows:

$$b_m = \begin{cases} \{\pm 1\} & if \; W = 2 \\ \{\pm 1, \pm j\}, & if \; W = 4 \end{cases} \tag{4}$$

Therefore, the side information (SI) consists of the length of the SI is $R = (M-1)\log_2(W)$ bits.

4 Long-Haul Optics Fiber Communication Setup

A single fiber transmission span consists of a Single Mode Fiber (SMF), an optical amplifier EDFA. We simulate an optical communications link over several hundred kilometers by cascading these spans from one end of the transmission link to another. The loss of each span is compensated by an EDFA.

The simulation of the optical signal which is propagated is based on the solution of the nonlinear Schrödinger equation (NES)[12].

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2} A - \beta_1 \frac{\partial A}{\partial t} - \frac{j}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} + \frac{1}{6} \beta_3 \frac{\partial^3 A}{\partial t3} - j\gamma |A|^2 A \tag{5}$$

Where β_1 correspond to the various dispersion components of the fiber; β_2, β_3 are the chromatic dispersion parameters respectively; Losses over the fiber are considered through the attenuation α parameter, and fiber non-linearity are showed by the γ term.

The parameters of a single fiber link and EDFA are shown in Table 1.

Table 1. Fiber and EDFA parameters for single span

SMF	EDFA
Loss factor: $\alpha = 0.2dB$ Dispersion coeff.: D = 17 (ps/nm.km) Nonlinear coeff.: $\gamma = 1.4e^{-4}(m^{-1}.W^{-1})$ Fibre length: L = 80 km	Gain: G_dB = 16(dB) Noise figure: NF = 5

The block diagram of CO-OFDM is shown in Fig. 2. A very high speed data is firstly modulated by using 4-QAM. After serial to parallel conversion, IFFT algorithm is performed to convert signal from frequency domain to time domain. They are then added CP, performed DAC converter and finally converted to optical domain via external modulation MZM.

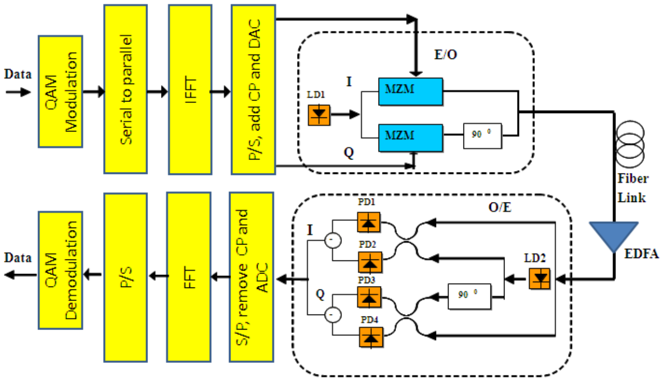

Fig. 2. CO-OFDM system

At the receiver, after converting the signal from optical to electrical domain by using photo-detectors, the electrical signal is processed to give back the data via de-OFDM modulation, and 4-QAM de-modulation.

In our simulation, the data rate is simulated at 10 Gbps and we have totally 256 subcarriers. It means that we use 256 points IFFT/FFT transformation.

5 Simulation Results

This part illustrates the results of Simulink simulations conducted to evaluate the performance of long-haul CO-OFDM system with and without PTS algorithm.

5.1 PTS Efficiency

The PAPR reduction performance of PTS algorithm is evaluated by the CCDF. Fig. 3 show the comparison of PAPR performance in term of CCDF of PTS.

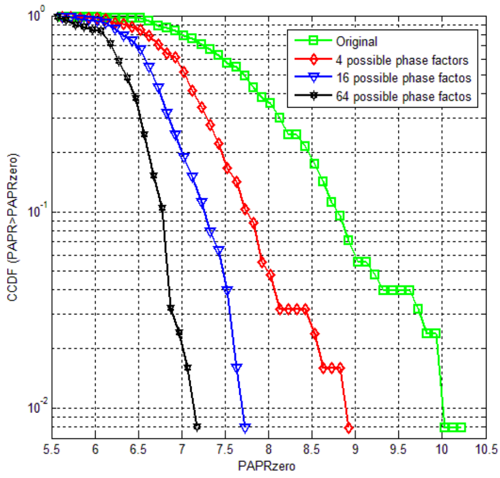

Fig. 3. CCDF comparison of PTS with different number of phase factors

Fig. 3 reveals the performance of PTS in term of number phase factor. We can see that the PTS even gives the better result when the number of combination phase factor increases. However, the system complexity becomes a big trouble as number of phase factor is large. We chose the number of combination at 16. It gave quite good performance as well as reasonable complexity.

5.2 Long Haul Optical Communication Link Experiment Results

The system is demonstrated for a transmission up to 1000 km of standard-single-mode-fiber (SSMF) without dispersion compensation at 10Gb/s. The tolerance of the models to nonlinear effects is tested by increasing the average launched power into the fiber. The nonlinear threshold which is used in this model is 10mW.

In Fig. 4, we can see that at low launched power, the system with and without PAPR reduction algorithms have similar performances. At 2.5 dBm in PTS, the performance of CO-OFDM with and without reduction methods is almost the same. The quality of system could be acceptable for around 1000 km fiber long. BER of this system is still below 10^{-9} for such a long haul optics communication link.

When we increase the launched powers, system performance is now influenced by nonlinear effects. Therefore, the efficiency of PTS is represented clearly. As we can see in Fig. 4, the performance of the system with PAPR reduction algorithm is better than system without this algorithm in nonlinear region. This number is even span to about 200 km with PTS algorithm (Fig. 4).

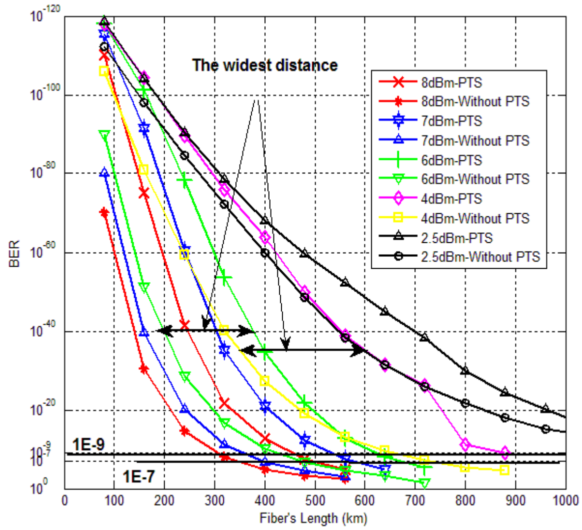

Fig. 4. BER of long haul optics fiber link with and without PTS algorithm in different average launched power values

6 Conclusion

OFDM technique is a very attractive approach for long haul high speed optical transmission system. However, the PAPR problem is one of the important aspects needed to consider. In this article, we have fundamentally simulated the algorithm for PAPR reduction purpose, namely PTS applying for point-to-point long haul coherent optical – CO-OFDM system. As a result, system tolerance of nonlinear effects increases with this algorithm. It is necessary to study some algorithms for reducing the complexity of the both PAPR reduction methods in optical OFDM communication.

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