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Adaptive compensation of multiple distortions with only pilot tones for flexible coherent transmission systems

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ABSTRACT

In this paper an adaptive multiple distortions compensation method based on amplitude modulated pilot tones (AM-PTs) is proposed for flexible single carrier optical coherent transmission systems. At the transmitter a pair of AM-PTs are generated from the optical carrier and inserted at the double sidebands of the optical signal. At the receiver the field of the AM-PT is recovered with the main signal and fully utilized for the estimation of both linear and ultra-fast nonlinear distortions including chromatic dispersion (CD), laser phase noise (LPN), local oscillator frequency offset (LFO) and cross phase modulation (XPM), thus avoiding the spectral efficiency and complexity cost due to the insertion of different pilots for the estimation of different distortions. The four distortions can be estimate from a simple analytical procedure or directly from the AM-PT fields. Thus the distortion estimation and XPM compensation process can be greatly simplified compared to the non-pilot-aided compensation algorithms. Furthermore the distortion estimation accuracy is not compromised and in inhomogeneous networks the XPM estimation accuracy is even better compared to the previous pilot-aided methods. Numerical simulations are then used to demonstrate the effectiveness and efficiency of this method.

1. Introduction

Coherent optical communications based on digital signal processing (DSP) has been considered as the most efficient method to fulfill a set of different requirements for future optical networks, such as high capacity, better spectral efficiency and long-haul transmission [1]. The main advantage of the DSP-based coherent reception is its capability to compensate various linear and nonlinear distortions, such as CD, PMD (polarization mode dispersion), LPN, LFO, SPM (self-phase modulation) and XPM which have serious impacts on system performance [2]. As we know these distortions are generally time-variant [3] and according to the variation speed, these distortions can be classified into two main categories: (1) The ultrafast nonlinear SPM and XPM distortions changing at the speed equal to the signal rate. (2) The linear distortions like CD, PMD, LPN and LFO changing at a much lower speed due to environmental variations, device defect, flexible switching and wavelength routing. Thus adaptive compensation methods for such distortions are indispensable and have been intensively studied recently [4–14].

By now various schemes have been proposed. For CD estimation (CDE) gradient algorithm or algorithm based on scanning through the possible CD values are often used, which is slow to converge and computation expensive [2,4]. For LPN and LFO estimation M-th power operation is often used which is not transparent to modulation formats and sensitive to the thresholds of partitioning the symbols into QPSK subsets [1,5]. For SPM and XPM compensation computation expensive backward propagation based on coupled nonlinear Schrödinger equations (NLSEs) was used [2]. In contrast the pilot-aided methods are more robust and simpler because the distortion can be estimated by an analytical procedure [6–8] or directly from the pilot field [9–14], which is desirous for real time processing and timely response to fast distortion variations.

According to the way the pilot is inserted, they can be classified into two main categories: (1) Methods based on pilot-tone (PT) inserted into the signal spectrum by frequency multiplexing, which can be applied to both slow time variant distortions like LPN and ultrafast nonlinear XPM distortions [9–14] as the PT always accompanies the signal in the propagation. (2) Methods based on pilot-sequence (PS) inserted into the signal symbols by time multiplexing, which can only be applied to relatively slow time-variant distortions like CD [6–8] and LFO [15,16] as the PS only appears at specific time intervals. Recently PS is also used

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for the estimation of PMD changing much fast than CD [17,18]. As the PT-aided methods can compensate ultrafast distortions, while PS-aided methods are only suitable for slow time-variant distortions, by now no pilot-aided methods can deal with all of the four main distortions including CD, XPM, LPN and LFO using one kind of pilot. Apparently it is not desirous to insert different pilots to deal with the different distortions because this will make the system less spectrally efficient and more complicated for adding, recognition and removing of the different pilots.

In this paper we propose a method to compensate the all of the four distortions adaptively using only PT. A pair of AM-PTs generated from the optical carrier is inserted into the signal spectrum at the transmitter. At coherent receiver the field information of the AM-PT, including the amplitude, phase and frequency are fully utilized for the estimation of the four different distortions, thus avoiding the spectral efficiency and complexity cost due to using different pilots for different distortions. By our method the four distortions can be estimated from an analytical procedure or directly from the AM-PT field. So the distortion estimation and XPM compensation process can be greatly simplified compared to non-pilot-aided algorithms, which is desirous for real time processing and fast response to optical link reconfiguration. It is demonstrated that the distortion estimation accuracy is not compromised and in inhomogeneous networks the estimation of XPM phase shift is even more accurate compared to previous PT-aided methods [11].

2. Operation principles

The setup of the AM-PT aided coherent transmission system is demonstrated in Fig. 1. At the transmitter the optical source (ω_c) is split into two optical paths and input to the IQ and MZ modulator respectively to generate the main signal and double sideband AM-PTs. The AM-PT insertion, enabled by external double sideband modulation can be written as

$$E_p(t) = A_p(t,0)\exp\left[i(\omega_c - \omega_p)t + i\phi_{pn}\right] + A_p(t,0)\exp[i(\omega_c + \omega_p)t + i\phi_{pn}], \quad (1)$$

where ω_p and $A_p(t, 0)$ are respectively the radio carrier frequency and amplitude of the AM-PTs, and ϕ_{pn} represents the LPN sharing also by the main signal [13,14]. Here $A_p(t)$ is a periodic pulse signal as shown in the inset of Fig. 1, where MI, τ_w and T are respectively the amplitude modulation index, pulse width and period. When the signal propagates in the fiber CD will introduce a relative time delay ($\Delta\tau$) between the two line spectra of the AM-PTs which is related to CD as follows

$$\Delta\tau = 2\frac{CD \cdot f_p c}{f_c^2}, \quad (2)$$

where $f_{c,p} = \omega_{c,p}/2\pi$ and c is the vacuum light speed. Meanwhile, the AM-PTs also acquire nearly the same XPM nonlinear phase shift as the signal [9–13]. The output AM-PT field can be written as

$$E_p(t) = A_{p1}(t,z)\exp\left[i(\omega_c - \omega_p)t + i(\phi_{pn} + \phi_{XPM1})\right] + A_{p2}(t,z)\exp\left[i(\omega_c + \omega_p)t + i(\phi_{pn} + \phi_{XPM2})\right], \quad (3)$$

where $A_{p1,2}(t, z)$ are the output amplitude of the AM-PTs and $\phi_{XPM1,2}$ are the XPM phase shift acquired by the lower and upper sideband PTs, respectively. The optical signal at the input of the coherent receiver is the summation of received main signal, AM-PTs and additive in-band noise. Considering the impact of CD, $A_{p1,2}(t, z)$ are different from $A_p(t, 0)$ and from each other. In [19] it is proved that in a long dispersive fiber the magnitude of the XPM induced phase shift can be approximated by

$$\Delta\Phi \approx \frac{2\gamma P_{2m}\alpha L_{eff}}{\omega D\Delta\lambda_{12}}, \quad (4)$$

where γ, P_{2m}, ω, α, L_{eff}, D and $\Delta\lambda_{12}$ are the fiber nonlinear coefficient, the power variation magnitude and frequency of the neighboring channel, the fiber attenuation coefficient, the effective length and dispersion coefficient of the fiber and the channel wavelength

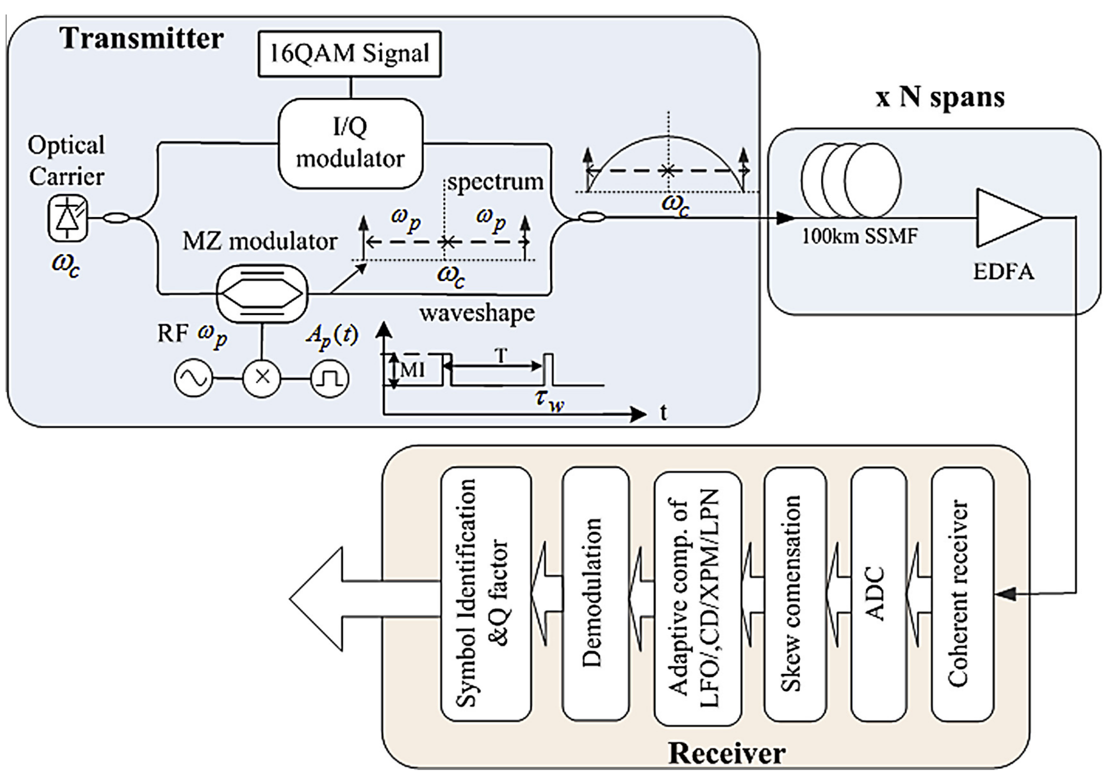

Fig. 1. The setup of AM-PT aided coherent transmission system.