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Volterra series based blind equalization for nonlinear distortions in short reach optical CAP system

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ABSTRACT

In this paper, we propose a blind Volterra series based nonlinear equalization (VNLE) with low complexity for the nonlinear distortion mitigation in short reach optical carrierless amplitude and phase (CAP) modulation system. The principle of the blind VNLE is presented and the performance of its blind adaptive algorithms including the modified cascaded multi-mode algorithm (MCMMA) and direct detection LMS (DD-LMS) are investigated experimentally. Compared to the conventional VNLE using training symbols before demodulation, it is performed after matched filtering and downsampling, so shorter memory length is required but similar performance improvement is observed. About 1 dB improvement is observed at BER of 3.8×10^{-3} for 40 Gb/s CAP32 signal over 40 km standard single mode fiber.

1. Introduction

Bandwidth demands have driven the development of cost-effective short reach optical transmissions with higher data rate. Digital signal process have been widely used and proved to be an effective way to compensate the linear distortion in high baud rate and high modulation order with low cost direct detection in short reach system[1–6]. However, after the linear distortion mitigation, nonlinear distortions becomes serious and hard to estimate and compensate, such as the modulation chirp in DML, saturated power amplification and square law detection after fiber link. As the phase information is lost after direct detection in short reach system, Volterra series theory offers a feasible way to design an equalizer and compensate the nonlinear distortion [7–9]. These Volterra series based nonlinear equalizers (VNLE) employed training symbols and are performed before signal demodulation [7–9] for orthogonal frequency division multiplexing (OFDM) system. Recursive least square (RLS) [7] and least mean square (LMS) [8,9] adaptive algorithms are often used. Carrierless amplitude and phase (CAP) modulation is an alternative modulation scheme for short reach optical transmission and blind linear equalizations are usually utilized, which is different from OFDM system. We have presented different linear compensation schemes for high order CAP signal [10–12]. In this paper, blind VNLEs are proposed for the nonlinear distortion mitigation in optical CAP32 system, which is a simple development of the presented linear equalizers by the additional Volterra series based nonlinear terms. The performance of the blind adaptive algorithms based VNLE including the modified cascaded multi-mode algorithm (MCMMA) and direct detection LMS (DD-LMS) and the TS based VNLE are investigated through 30 Gb/s and 40 Gb/s CAP32 experiment system over 40 km standard single mode fiber (SSMF).

2. Operating principle

Unlike the nonlinear compensation in coherent systems, digital backward propagation algorithm may not be suitable in short reach systems because of the lost phase information after directed detection. Volterra series offer an alternative way to describe the system's nonlinear response. It is expressed as below.

$$y(i) = \sum_{k=0}^{N-1} h_k(i)\cdot x(i-k) + \sum_{k=0}^{N-1}\sum_{l=k}^{N-1} h_{kl}(i)\cdot x(i-k)\cdot x(i-l) + \sum_{k=0}^{N-1}\sum_{l=k}^{N-1}\sum_{m=l}^{N-1} h_{klm}(i)\cdot x(i-k)\cdot x(i-l)\cdot x(i-m) + \dots \quad (1)$$

It is observed that the output of system's response $y(i)$ is the sum of multiple polynomials. The terms on the right side of Eq. (1) represent the first order, the second order and higher order respectively. Hk, hkl and hklm are the coefficients for each polynomial term with different orders. N is the memory length of Volterra series.

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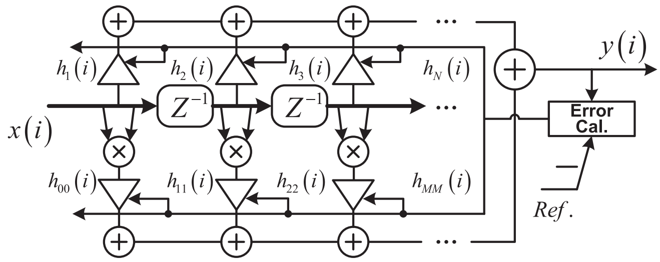

Fig. 1. Structure of Volterra based nonlinear equalization.

The conventional Volterra based nonlinear equalization (VNLE) is usually performed before signal demodulation. Training symbols (TS) are necessary because there is no or not obvious statistical law of symbols before demodulation. However, blind equalization scheme is preferred in CAP system to reduce the overhead. In addition, the sampling rate is often over 2 times of signal baud rate, which means more data need to be processed compared the blind scheme that VNLE is performed after matched filtering and downsampling in CAP system. So we propose a blind VNLE scheme, which the nonlinear compensation is embedded in the presented linear hybrid equalization structure in [11] for the sake of low cost. It has the same structure to the VNLE using TSs, as shown in Fig. 1. Considering the high baud rate CAP signal after fiber link is affected by the chromatic dispersion and square law detection [15], the Volterra series is simplified to first order and second order form, and the product terms between the adjacent bits are also ignored. So Eq. (1) is simplified as follows.

$$y(i) = \sum_{k=0}^{N-1} h_k(i)\cdot x(i-k) + \sum_{l=0}^{NL-1} h_l(i)\cdot x^2(i-l) \tag{2}$$

Similar to linear equalizer, the objective is also to find the coefficient of each filter tap in VNLE. For the conventional TS based VNLE, the least mean square (LMS) is chosen, while MCMMA and direct decision (DD) LMS are investigated in the proposed blind VNLE. The coefficient update equations for LMS and DD-LMS algorithm are expressed as,

$$H(i+1) = H(i) + 2\mu\cdot e(i)X^*(i) \tag{3}$$

The detailed derivation of multimodulus algorithm that taking advantage of the symbol statistics of square constellations can be found in [13], and the cascaded algorithm for high order signal is introduced in [14]. We develop the multimodulus algorithm for the high order signal and proposed a MCMMA algorithm for the linear equalization in [11] and its coefficient update equation is shown as below.

$$\begin{aligned}
\vec{H}_{11}(i+1) &= \vec{H}_{11}(i) + \mu\varepsilon_I M_I \vec{X}_I^*(i)\\
\vec{H}_{12}(i+1) &= \vec{H}_{12}(i) + \mu\varepsilon_I M_I \vec{X}_Q^*(i)\\
\vec{H}_{21}(i+1) &= \vec{H}_{21}(i) + \mu\varepsilon_Q M_Q \vec{X}_I^*(i)\\
\vec{H}_{22}(i+1) &= \vec{H}_{22}(i) + \mu\varepsilon_Q M_Q \vec{X}_Q^*(i)
\end{aligned} \tag{4}$$

Its cost function is expressed as

$$\begin{aligned}
\varepsilon_I &= \Big|\big||y_I(i)| - Am_1\big| - Am_2\Big| - Am_3\\
\varepsilon_Q &= \Big|\big||y_Q(i)| - Am_1\big| - Am_2\Big| - Am_3
\end{aligned} \tag{5}$$

$$\begin{aligned}
y_I(i) &= real(y(i))\\
y_Q(i) &= imag(y(i))\\
Am_1 &= (L_1 + L_2)/2\\
Am_2 &= (L_3 - L_1)/2\\
Am_3 &= (L_3 - L_2)/2
\end{aligned} \tag{6}$$

$$\begin{aligned}
M_I &= sign(|y_I(i) - A_1| - A_2)sign(|y_I(i)| - A_1)sign(y_I(i))\\
M_Q &= sign(|y_Q(i) - A_1| - A_2)sign(|y_Q(i)| - A_1)sign(y_Q(i))
\end{aligned} \tag{7}$$

L1, L2 and L3 the moduli of the real and imaginary parts of QAM32 signal. $\vec{X}_I(i)$, $\vec{X}_Q(i)$ is the real and imaginary part of input signal respectively, $y(i)$ is output of the equalizer. "*" is the Hermitian symbol.

For the MCMMA based VNLE, the cost function is the same to Eq. (5) while $y(i)$ is the sum of the output of linear and nonlinear equalization. Combining Eqs. (5) and (7), the total error for a complex updating equation is $\varepsilon_I M_I + j\varepsilon_Q M_Q$. So the updating equation for the nonlinear equalization is

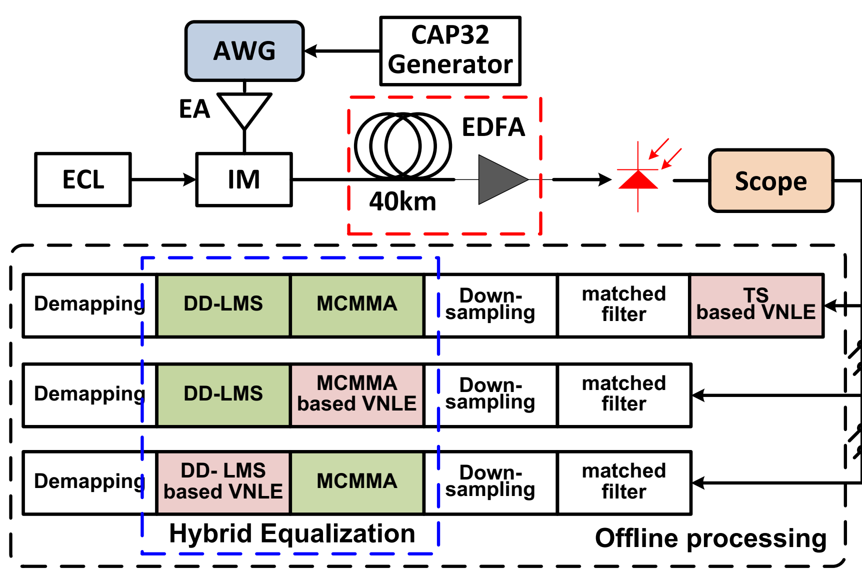

Fig. 2. Experiment setup of CAP32 transmission system using different VNLE schemes, ECL: external cavity laser, IM: intensity modulator, EA: electrical amplifier, AWG: arbitrary waveform generator.