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A novel high precision adaptive equalizer in digital coherent optical receivers

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ABSTRACT

A novel high precision adaptive equalization method is introduced and applied to dynamic equalization for quadrature phase shift keying (QPSK) coherent optical communication system in this paper. A frequency-domain constant modulus algorithm (CMA) method is used to equalize the received signal roughly. Then, some non-ideal output signals will be picked out through the error measurement, and they will be equalized accurately further in a fixed time-domain CMA equalizer. This high precision equalization method can decrease the equalization error, then it can reduce the bit error ratio (BER) of coherent communication system. Simulation results show that there is a 6% decrease for computation complexity by proposed scheme when compared with time-domain CMA. Furthermore, compared with time-domain CMA and frequency-domain CMA, about 2 dB and 2.2 dB in OSNR improvement can be obtained by proposed scheme at the BER value of 1e – 3, respectively.

1. Introduction

Polarization diversity optical coherent receivers, which combine a polarization-division multiplexing (PDM) and an *M*-ary modulation formats, were a promising solution for high-capacity optical communication systems. A superiority of coherent receiver was the equalization of linear distortions and the demultiplexing of the two PDM signals could be done in the electronic equalizer. The butterfly-structure multiple-input/multiple-output adaptive electronic equalizer was usually employed to accomplish the equalization procedure [1–3].

The sampling rate of received signals was always set as twice symbol rate for the sake of reduction in aliasing effect [4]. Under the condition of twofold oversampling, time-domain equalizer (TDE) with constant modulus algorithm (CMA) was adapted two samples per step in order to adjust the initial sampling phase [5,6]. The butterfly equalizer in optical coherent communication system was implemented in the time-domain generally. However, it was recently shown in [7] that, frequency-domain equalizers (FDE) could bring significant computational savings in the adaptive equalization than TDE. In [7,8], FDE was realized by using pilot-symbol sequence, but such approaches generally decreased the spectral efficiency of transmission systems. Another attractive solution for FDE was equalization in frequency domain based on the overlap-save technique (OS-FDE) [9], this scheme was apt to implement and any cyclic prefix were not required.

A fractionally spaced overlap-save FDE was proposed in [10]. This implementation was mathematically equivalent to the block-adaptive TDE, but offered substantial complexity reduction. What's more, Ref. [11] proposed another FDE using CMA, it could work on the double oversampling rate by introducing even and odd sub-equalizers. As a result, the polarization demultiplexing and sampling-phase adjustment could achieve together in FDE. However, only the sampling phase adjustment and reduction of the computation complexity were considered both in Ref. [10] and Ref. [11], no obvious improvement was shown in FDE performance compared with the TDE.

A novel high precision adaptive equalizer (FAT) was proposed in this paper, which consisted of a FDE, an error measurement stage and a TDE. Firstly, the linear impairments could be equalized roughly through the FDE in frequency-domain, the sampling phase also would be adjusted to best position simultaneously. Then some undesirable equalized signals would be picked out by error measurement. The thresholds of error measurement are for computation complexity and final performance to decide. At last, a fixed tap weights TDE was proposed and implemented, giving the more precise equalization to the picked out signals. Simulation results showed that there was a 6% decrease for computation complexity by FAT when compared with TDE. Moreover, a remarkable

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decrease with 5.25 dB and 4.36 dB was founded for BER by the FAT compared with the FDE and the TDE.

2. System description

The simulated QPSK coherent optical communication system is shown in Fig. 1. In the transmitter, two branches of QPSK signals were modulated by 40 Gb/s PRBS of length $2^{15}-1$; the lasers of the transmitter and the local oscillator had a line-width which were both equal to 100 kHz. Then, two orthogonal branches were polarization-multiplexed by a polarization beam combiner (PBC) in transmission channel. In the SSMF channel, the setting of chromatic dispersion (CD) and first-order polarization-mode dispersion (PMD) was determined. Linear polarization controllers (PCs) were placed at 45° and $-45°$ on both sides of SSMF. After detecting by the coherent receiver, the received signals were sampled by free-running analog-to-digital converters (ADCs) which operated at the twice symbol rate. Such oversampling significantly reduced the aliasing effect. Then, the sampled signal sequences were sent into the signal processing stage which consisted of an electric equalizer and a carrier recovery stage. At last, the signal sequence would be disposed in the data recovery stage to extract the original data and calculate the BER.

3. Electronic equalizer

3.1. Equalization by FDE

The equalization scheme in FDE was same as in Ref. [11]. As shown in Fig. 2, the structure of FDE consisted of a CD compensation stage and an adaptive FDE. In the CD equalization stage, the CD was compensated in the frequency-domain firstly. Then, the PMD and the residual CD would be equalized in FDE roughly.

In the FDE, eight frequency-domain filters consisted of even sub-equalizers and odd sub-equalizers. Four even sub-equalizers $H^{\prime e}_{xx}$, $H^{\prime e}_{xy}$, $H^{\prime e}_{yx}$, $H^{\prime e}_{yy}$ were connected in a two-by-two butterfly configuration. In the same way, four odd sub-equalizers $H^{\prime o}_{xx}$, $H^{\prime o}_{xy}$, $H^{\prime o}_{yx}$, $H^{\prime o}_{yy}$ were placed in another two-by-two butterfly configuration. The input sequences were represented as $[x(n),y(n)]^T$ and the output signal sequence were represented as $[x_1(n),y_1(n)]^T$. Before the process of equalizing, the input sequences $[x(n),y(n)]^T$ were divided into $[x^e(m),x^o(m),y^e(m),y^o(m)]^T$ by serial–parallel converter for sub-equalizers. Where, $n=2m-1$. After FFT transforming and overlapping, the input sequence of FDE could be expressed as $[X^e(K),X^o(K),Y^e(K),Y^o(K)]^T$ and the equalization output in frequency-domain could be expressed as $[X_1(K),Y_1(K)]^T$. The equalization procedure was same as in Ref. [11]. The length of signal block was set as P, so the tap weights length of every sub-equalizer was $2P$. Moreover, all the sub-equalizers were updated one symbol per step without down-sampling output sequence. The equalized signals can be expressed as [11]

$$\begin{aligned}X'(K) &= H'^{e}{}_{xx}(K)\cdot X^{e}(K) + H'^{o}{}_{xx}(K)\cdot X^{o}(K) + H'^{e}{}_{xy}(K)\cdot Y^{e}(K) + H'^{o}{}_{xy}(K)\cdot Y^{o}(K)\\ Y'(K) &= H'^{e}{}_{yx}(K)\cdot X^{e}(K) + H'^{o}{}_{yx}(K)\cdot X^{o}(K) + H'^{e}{}_{yy}(K)\cdot Y^{e}(K) + H'^{o}{}_{yy}(K)\cdot Y^{o}(K)\end{aligned} \tag{1}$$

where $H'(K)$ represented the tap weights in frequency-domain. Thus, after IFFT transforming, the time-domain outputs are expressed by

$$\begin{aligned}x_1(K) &= \text{last } p \text{ elements of IFFT } \left(X'(K)\right)\\ y_1(K) &= \text{last } p \text{ elements of IFFT } \left(Y'(K)\right)\end{aligned} \tag{2}$$

At last, the outputs of FDE $[x_1(n),y_1(n)]^T$ could be achieved from $[x_1(K),y_1(K)]^T$ by parallel–serial converter.

3.2. Error measurement of FDE

After equalization in FDE, a measurement for error function would be executed. Those signals still with larger error would be picked out and equalized refined in the TDE. The constellations of equalized signals by FDE and TDE are shown in Fig. 3. As shown in

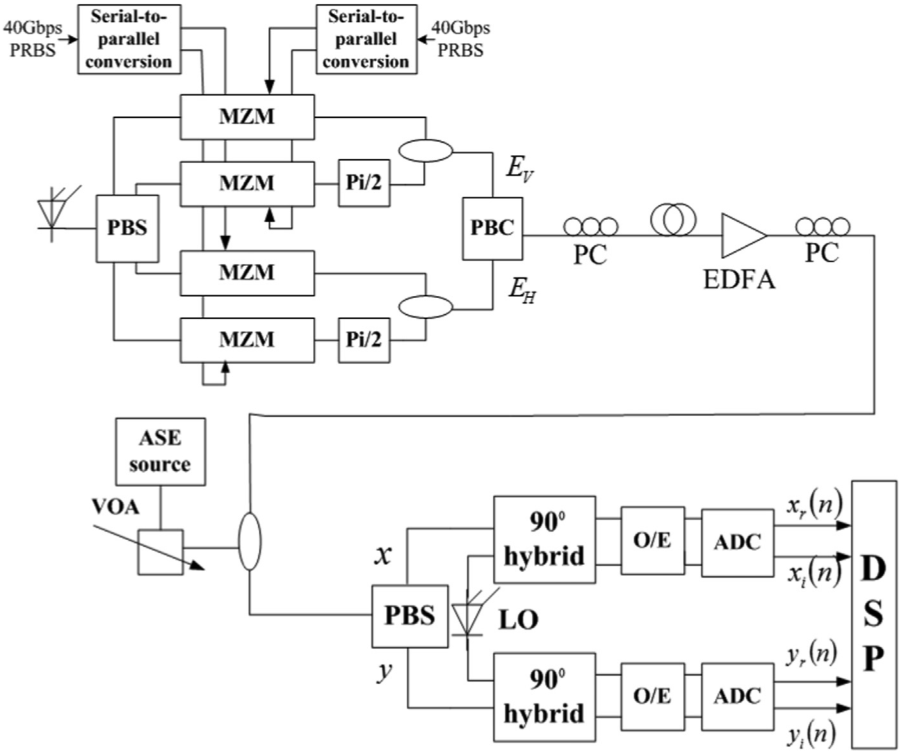

Fig. 1. Setup for 80 Gbps QPSK coherent system.