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40-Gb/s PAM4 with low-complexity equalizers for next-generation PON systems

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ABSTRACT

In this paper, we demonstrate 40-Gb/s four-level pulse amplitude modulation (PAM4) transmission with 10 GHz devices and low-complexity equalizers for next-generation passive optical network (PON) systems. Simple feed-forward equalizer (FFE) and decision feedback equalizer (DFE) enable 20 km fiber transmission while high-complexity Volterra algorithm in combination with FFE and DFE can extend the transmission distance to 40 km. A simplified Volterra algorithm is proposed for reducing computational complexity. Simulation results show that the simplified Volterra algorithm reduces up to ∼75% computational complexity at a relatively low cost of only 0.4 dB power budget. At a forward error correction (FEC) threshold of 10^{-3}, we achieve 31.2 dB and 30.8 dB power budget over 40 km fiber transmission using traditional FFE-DFE-Volterra and our simplified FFE-DFE-Volterra, respectively.

1. Introduction

Next-generation passive optical network (PON) mainly faces two kinds of demand [1]. On one hand, with the rapid growth of bandwidth-thirsty services such as 4 k/8 k high-definition video, cloud computing and virtual reality, higher capacity of optical access networks will be needed [2,3]. On the other hand, there is also significant requirement of mobile front-haul network for the 5-th generation (5G) of mobile communication systems [4]. The typical front-haul distance is 10 km to 40 km and this can be ideally implemented by PON systems. Low-cost mobile front-haul will become one of the major drivers for PON rates exceeding 10 Gb/s. As a result, the research for single-wavelength 25 Gb/s, 40 Gb/s even 50 Gb/s PON based on low-cost devices has become a hot issue recently [5,6]. In order to achieve high-speed transmission using low-cost devices, spectrally efficient modulation formats such as direct-detection orthogonal frequency division multiplexing (DD-OFDM) modulation, carrier-less amplitude and phase (CAP) modulation and four-level pulse amplitude modulation (PAM4) have been widely studied [7–12]. Among these advanced modulations, PAM4 offers the lowest implementation complexity and can be used in cost-sensitive and power-sensitive PON systems [13–15]. However, advanced modulations are more sensitive to channel impairments compared to traditional non-return to zero (NRZ) modulation. Electronic equalizers based on digital signal processing (DSP) for advanced modulations can efficiently mitigate channel distortion without changing the optical infrastructure, which enables a practical low-cost realization of next-generation PON systems [16,17].

In recent years, electronic equalizers for PON systems have been extensively studied. Feed-forward equalizer (FFE) and decision feedback equalizer (DFE) are two kinds of simple equalizers which have been widely investigated in PON systems. For instance, a 29 dB power budget of 25-Gb/s PAM4-PON system without optical amplifier using low-complexity FFE with least mean square algorithm (LMS-FFE) was successfully demonstrated [18]. 40-Gb/s PAM4/Duobinary time division multiplexed PON (TDM-PON) over 10 km standard single-mode fiber (SSMF) using FFE and DFE was experimentally studied [19]. However, in intensity-modulation/direct-detection (IM/DD) systems, the performance of FFE and DFE are fundamentally limited by the decreased fiber dispersion tolerance and the nonlinear distortion [20]. As a result, FFE and DFE can hardly support 40 km transmission in 40-Gb/s PAM4-PON systems. DSP-based signal-signal beat interference (SSBI) mitigation technique was proposed for reducing nonlinear distortions in DD-OFDM systems while Volterra algorithm combined with FFE and DFE has been proved to be a good solution to mitigate nonlinear distortions for single-carrier systems [21,22]. A 40-Gb/s PAM4/Duobinary system using linear and nonlinear equalizers has been deeply studied [23]. The results show that nonlinear equalizers based on Volterra algorithm achieve better performance than simple FFE and DFE.

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However, the Volterra algorithm possesses a relatively high computational complexity. By using the modified Gram-Schmidt method with reorthogonalization techniques, sparse-Volterra was proposed to reduce computational complexity [25,24]. This is a mathematical transformation method to determine the importance of Volterra kernels. In our study, we concentrate on the square terms of Volterra kernels and we find that square terms are the most significant impacting indicators of Volterra kernels.

In this paper, we propose a simplified Volterra algorithm in combination with FFE and DFE which has extremely similar performance optimization and only ~25% computational complexity compared to traditional Volterra algorithm. In addition, we discuss different optimum equalizers for 40-Gb/s PAM4-PON systems over different transmission distances. For 20 km SSMF transmission, we achieve 34.2 dB power budget using simple FFE. For 40 km SSMF transmission, we achieve 31.2 dB and 30.8 dB power budget using traditional FFE-DFE-Volterra and our simplified FFE-DFE-Volterra, respectively.

2. Principle of equalization

2.1. The structure of low-complexity equalizers

The blue part of Fig. 1 is a schematic of a symbol-spaced FFE structure. An FFE is the simplest structure which can be used in low-cost PON systems. It consists of several delay line filters with corresponding coefficients which are usually updated according to adaptive algorithms, such as least mean square (LMS) algorithm and recursive least square (RLS) algorithm. The FFE with M taps can be expressed as follows

$$Y(n) = \sum_{k=0}^{M-1} a(k)X(n-k) \tag{1}$$

where X(n) represent input signals, Y(n) represent output signals, a(k) represent tap coefficients, M represents the number of taps.

FFE is usually combined with DFE (FFE-DFE) to mitigate the pre-interference and post-interference simultaneously. The blue part and red part of Fig. 1 depict a schematic of FFE-DFE with three forward taps and three feedback taps. Thanks to the introduction of the feedback

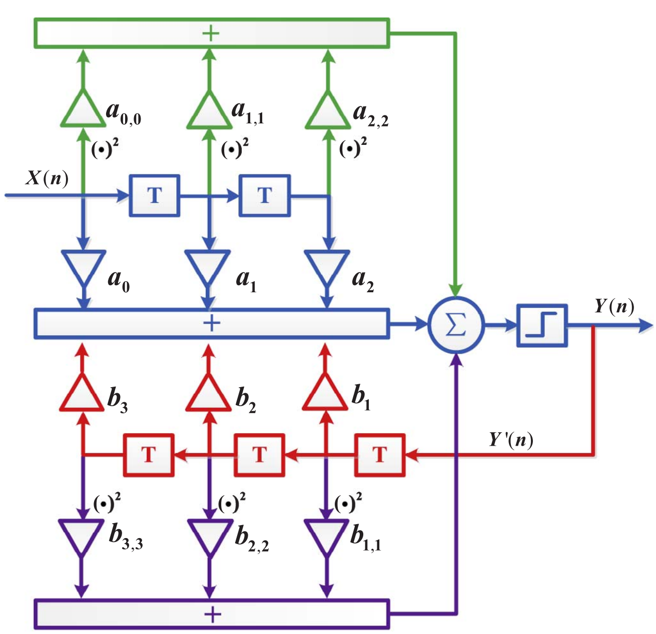

Fig. 1. Illustrative diagram of an example FFE/FFE-DFE/simplified FFE-Volterra/simplified FFE-DFE-Volterra with three (M) feedforward taps and three (N) feedback taps.

information of the determined symbols, FFE-DFE generally has a better performance than FFE to eliminate inter-symbol interference (ISI). The FFE-DFE with M forward taps and N feedback taps can be described as follows

$$Y(n) = \sum_{k_1=0}^{M-1} a(k_1)X(n-k_1) + \sum_{k_2=1}^{N} b(k_2)Y'(n-k_2) \tag{2}$$

where M and N are the numbers of FFE and DFE taps, respectively. a(k) and b(k) are feed-forward tap coefficients and feed-back tap coefficients, respectively. X(n) and Y(n) represent input and output signals, respectively. Y'(n) represent decision feedback output signals.

Volterra algorithm comes from nonlinear Volterra model which has been widely used in coherent optical communication to mitigate nonlinear distortion [24]. Volterra model can be expressed as

$$Y(n) = \sum_{p=1}^{P} \sum_{k_1=0}^{N-1} \dots \sum_{k_p=0}^{N-1} h_p(k_1,\dots,k_p)X(n-k_1)\dots X(n-k_p) \tag{3}$$

where X(n) and Y(n) are input and output signals, respectively. h_p is pth-order Volterra kernel. P represents the order of Volterra kernels and N is the memory length. It is noted that nonlinear Volterra equalizer actually becomes linear FFE when P is set to 1. For PON systems, the order of Volterra kernels is usually set to 2 in consideration of computational complexity [23,26]. Thus, the second-order Volterra model can be rewritten as

$$Y(n) = \sum_{k_1=0}^{N-1} \sum_{k_2=0}^{N-1} a(k_1,k_2)X(n-k_1)X(n-k_2) \tag{4}$$

Based on (4), we propose a simplified Volterra algorithm by only considering the square terms of Volterra kernels. The simplified Volterra algorithm combined with FFE can mitigate linear and nonlinear distortion simultaneously. The blue part and green part of Fig. 1 depict an example schematic of simplified Volterra algorithm combined with FFE (simplified FFE-Volterra). The simplified FFE-Volterra can be described as

$$Y(n) = \sum_{k_1=0}^{M-1} a(k_1)X(n-k_1) + \sum_{k_1=0}^{M-1} a(k_1,k_1)X(n-k_1)^2 \tag{5}$$

Similarly, we can also combine the simplified Volterra algorithm with FFE-DFE. All parts of Fig. 1 depict an example schematic of simplified Volterra algorithm with FFE-DFE (simplified FFE-DFE-Volterra). The simplified FFE-DFE-Volterra can be described as

$$Y(n) = \sum_{k_1=0}^{M-1} a(k_1)X(n-k_1) + \sum_{k_2=1}^{N} b(k_2)Y'(n-k_2) + \sum_{k_1=0}^{M-1} a(k_1,k_1)X(n-k_1)^2 + \sum_{k_2=1}^{N} b(k_2,k_2)Y'(n-k_2)^2 \tag{6}$$

2.2. The computational complexity comparison of equalizers

Table I shows the comparison of computational complexity among various equalizers. *M* and *N* are the numbers of FFE and DFE taps (also

Table I
Computational complexity comparison among different equalizers.

Equalizers	Additions	Multiplications
FFE	M-1	M
FFE-Volterra	$M + M^2-1$	$M + 2M^2$
Simplified FFE-Volterra	$2M-1$	$3M$
FFE-DFE	M + N-1	M + N
FFE-DFE-Volterra	$M + M^2 + N + N^2-1$	$M + N + 2(M^2 + N^2)$
Simplified FFE-DFE-Volterra	2 M + 2 N-1	3 M + 3 N