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Regular Articles

Nonlinear ISI cancellation in Nyquist-SCM direct detection PON downstream scheme with Volterra pre-equalizer

Na Liu*, Cheng Ju, Changhong Li

College of Electronic Information, Qingdao University, Qingdao 266071, China

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ABSTRACT

We propose and experimentally demonstrate a 40-Gbps vestigial-sideband (VSB) Nyquist subcarrier modulation (SCM) direct detection (DD) passive optical network (PON) downstream scheme with Volterra pre-equalizer at optical line terminal (OLT). Volterra pre-equalizer is used to mitigate the fiber dispersion- and square-law detection-induced nonlinear inter-symbol interference (ISI), and thereby improve the receiver sensitivity and reduce the computational complexity of optical network unit (ONU). The 60-km standard single mode fiber (SSMF) transmission experiment results show that 2.1 and 2.8-dB receiver sensitivity improvements are obtained by using the second- and third-order Volterra pre-equalizers, respectively.

1. Introduction

There has been an increasing interest in using advanced multilevel modulation formats in combination with digital signal processing (DSP) to increase the system capacity and the spectral efficiency in long-reach passive optical network (PON). To reduce the device cost of ONU, direct detection is preferred, such as Nyquist subcarrier modulation (Nyquist-SCM) scheme [1,2]. However, nonlinear inter-symbol interference (ISI) resulting from fiber dispersion and square-law detection causes a significant degradation of receiver sensitivity [3]. By modeling nonlinear ISI, it could be mitigated by using iteration cancellation technique in receiver [4,5]. The channel parameters, such as modulator nonlinearity [6], modulator transient and adiabatic chirp [7], self-phase modulation [8] and vestigial sideband (VSB) filter [5], are considered in the model to precisely estimate and eliminate nonlinear ISI. Our previous works have demonstrated that nonlinear ISI could be mitigated by using symbol pre-distortion in transmitter [9]. The performances of iteration and symbol pre-distortion techniques depend on the accuracy of channel estimation. The Volterra equalizer is a well-known nonlinear interference cancellation technique, which does not need the detailed model of nonlinearity [10]. Previous contributions mainly focus on nonlinear ISI cancellation in receiver, which due to a high hardware implementation complexity for ONU [11,12]. However, to the best of our knowledge, very few system demonstrations and performance evaluations of nonlinear ISI cancellation in transmitter have been reported, particularly for high data rate PON downstream scenarios. It is attractive to mitigate nonlinear ISI at OLT side and reduce the computational complexity of ONU.

In this work, Volterra pre-equalizer is introduced into VSB Nyquist-SCM DD PON downstream scheme to mitigate nonlinear ISI, which greatly reduces the device cost and DSP complexity of ONU. For each ONU, a software-based Volterra post-equalizer connected in tandem of first- and higher-order Volterra system operators is designed to obtain the tap coefficients of Volterra post-equalizer at system initialization stage. To accelerate convergence speed and improve the steady-state performance, the update rule used in this scenario is implemented based on the training symbol-assisted least-mean-square (LMS) algorithm. Only the second- and higher-order tap coefficients are fed back to OLT as initial tap coefficients of Volterra pre-equalizer. The feasibility of the proposed algorithm is demonstrated in a 40-Gbps data rate, 16-QAM formatted, fiber Bragg grating (FBG)-based VSB Nyquist-SCM direct detection system over 60-km SSMF transmission. The effect of central frequency offset of the FBG filter on Volterra pre-equalizer is discussed in the following. Finally, we evaluate the algorithm performance of second- and third-order Volterra pre-equalizers, and the results show that the receiver sensitivities are improved by 2.1 and 2.8 dB, respectively.

2. The principle of Volterra pre-equalizer

The input-output relationship of the intensity modulation DD system could be represented and modeled as a high-order nonlinear kernel function by using the theory of Volterra series [12]. As shown in Fig. 1(a), the input and output electrical signal are defined in frequency domain by a high-order Volterra series transfer functions as $I(\omega) = \sum_{i=1}^{\infty} H_i[D(\omega)]$, where $D(\omega)$ and $I(\omega)$ are the transmitted signal

* Corresponding author.
E-mail address: liunana@bupt.edu.cn (N. Liu).

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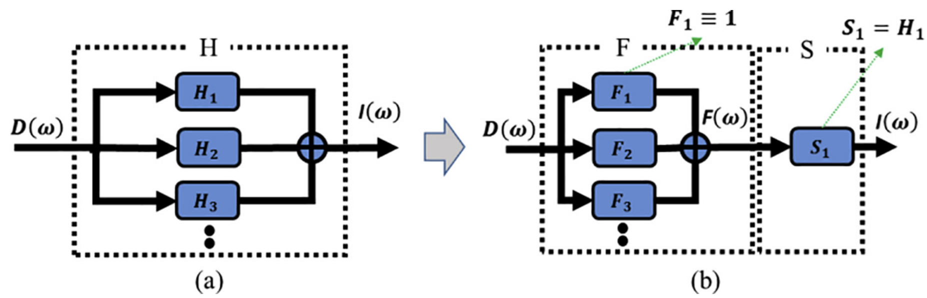

Fig. 1. (a) Intensity modulation DD system operator, H, formed by parallel connection of H_i. H_i: the ith-order Volterra operator. (b) Conversion of system operator, H, formed by tandem connection of system operator F and S.

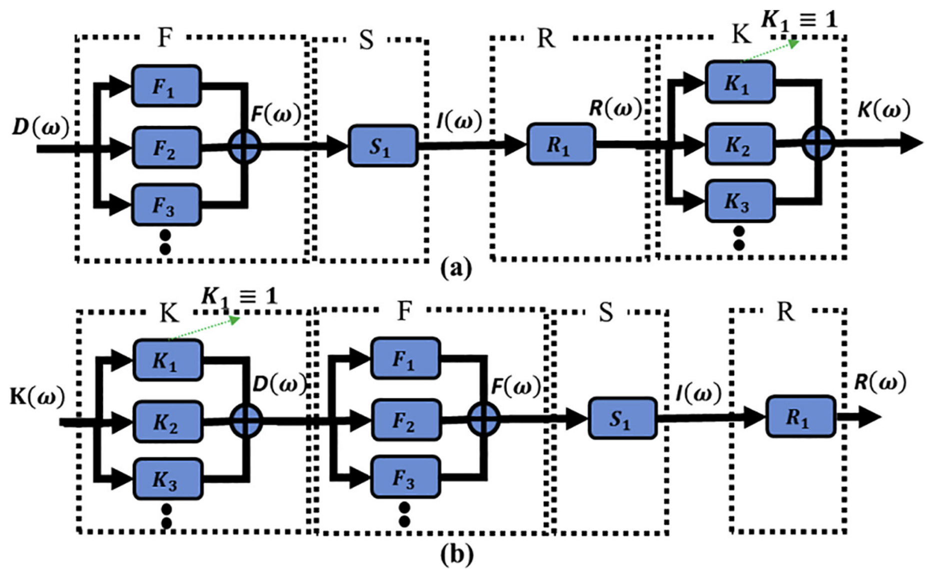

Fig. 2. (a) Cascaded system operator formed by generalized channel, F and S, first-order post-inverse system operator R, and high-order post-inverse system operator K. (b) The Volterra pre-inverse system operator K.

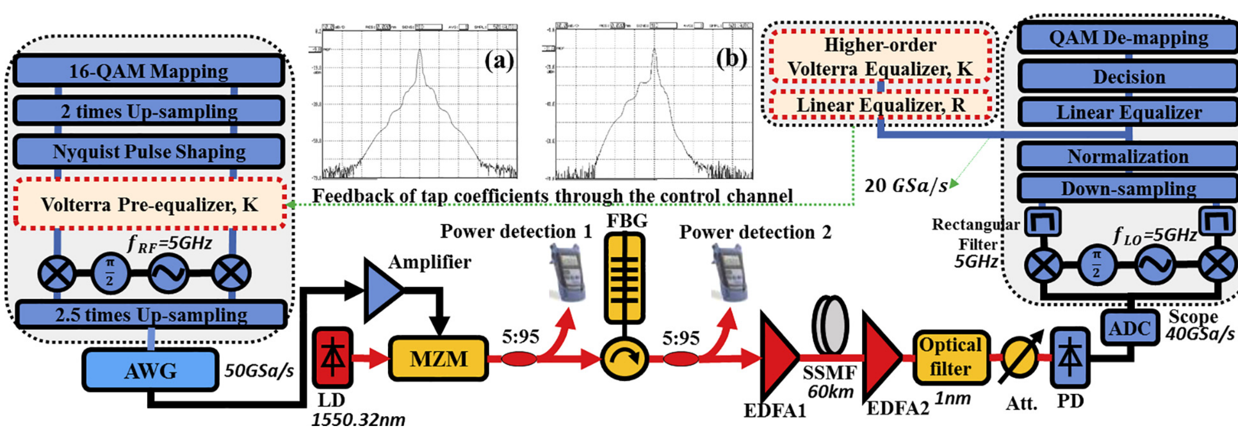

Fig. 3. Experimental setup of FBG-based VSB IMDD Nyquist-SCM transmission system with Volterra pre-equalizer. The spectrums (a) before and (b) after FBG filter.

and the received signal in frequency domain, H is called the system operator of generalized channel, H_i is the ith-order Volterra operator. $H_1[D(\omega)]$ is the valid signal with linear distortion, and $\sum_{i=2}^{\infty} H_i[D(\omega)]$ is the nonlinear terms, which introduce nonlinear ISI. According to the theory of Volterra series [10], the parallel connected system operator, H, can be converted to a tandem connected model formed by F and S, as shown in Fig. 1(b). In this form of representation, the first and higher-order Volterra operators of system operator F are $F_1 \equiv 1$ and $F_i = H_i/H_1$. S is a first-order Volterra system operator, and its first-order Volterra operator is $S_1 = H_1$. It is clear that the signal, $F(\omega)$, after system operator F only suffers from nonlinear interference, $F(\omega) = D(\omega) + \sum_{i=2}^{\infty} F_i[D(\omega)]$. The linear interference is induced by system operator S. The tandem connected model indicates that the nonlinear and linear ISI could be compensated, respectively.

The conventional Volterra post-equalizer is a parallel arrangement [8,13], which is derived based on the parallel channel model as shown in Fig. 1(a). Based on the Volterra series theory, a pth-order Volterra post-inverse is also a pth-order Volterra pre-inverse. However, for a fading channel where the power dip point is depend on fiber length [5], Volterra pre-equalizer including first-order Volterra pre-inverse