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Iterative nonlinear ISI cancellation in optical tilted filter-based Nyquist 4-PAM system

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ABSTRACT

The conventional double sideband (DSB) modulation and direct detection scheme suffers from severer power fading, linear and nonlinear inter-symbol interference (ISI) caused by fiber dispersion and square-law direct detection. The system's frequency response deteriorates at high frequencies owing to the limited device bandwidth. Moreover, the linear and nonlinear ISI is enhanced induced by the bandwidth limited effect. In this paper, an optical tilted filter is used to mitigate the effect of power fading, and improve the high frequency response of bandwidth limited device in Nyquist 4-ary pulse amplitude modulation (4-PAM) system. Furtherly, iterative technique is introduced to mitigate the nonlinear ISI caused by the combined effects of electrical Nyquist filter, limited device bandwidth, optical tilted filter, dispersion, and square-law photo-detection. Thus, the system's frequency response is greatly improved and the delivery distance can be extended.

1. Introduction

The increasing demand to achieve both higher bit rates and spectral efficiency using cost-effective systems is especially strong in short-range communication. Intensity modulation and direct detection (IMDD) based optical communication systems with high-order modulation formats have continued to attract attention because of the low cost and simple implementation. Several advanced modulation schemes have been researched, such as Nyquist subcarrier modulation (Nyquist-SCM), [1] pulse amplitude modulation (PAM), [2,3] carrierless amplitude/phase modulation (CAP), [4] orthogonal frequency division multiplexing (OFDM), [5] and etc. PAM offers the lowest implementation complexity of all the advanced modulation formats and simultaneously maintains high spectral efficiency [3,6]. However, two main problems exist in the 4-PAM direct detection system. The first one is that the frequency response of optical modulator tend to drop when the frequency go high, hence the gain of signal power decreases at high frequency region [7,8]. This unevenness of the frequency response in the optical links is undoubtedly deleterious. Chromatic dispersion effect is the other problem in long distance direct detection system when conventional double sideband (DSB) intensity modulation is adopted. The signal after fiber transmission suffers from periodic power fading and nonlinear ISI caused by the dispersion and square-law photo-detection [3,8]. The bandwidth limited effect is the major bottleneck at back-to-back (B2B) scenario. With the increasing of transmission distance, the effects of limited device bandwidth, power fading and nonlinear ISI, become dramatically serous and degrade the transmission performance.

The theory presented earlier indicates that digital pre-emphasis technique [9] and optical equalization [3,7,8] can eliminate the impacts of device bandwidth limitation. The tilted filter, acting as an optical equalizer, is used to improve the high frequency response in single carrier system without using digital-to-analog converter (DAC). Moreover, the dip point caused by power fading is also eliminated by suppressing one sideband of the DSB signal. Therefore, the effects of bandwidth limitation and power fading could both be mitigated by using optical tilted simultaneously. The principle and explicit analysis of linear and nonlinear distortion caused by vestigial sideband (VSB) filter, and dispersion in IMDD system have been given in our previous works [10,11]. Nonlinear ISI becomes the main bottleneck of VSB-IMDD system, which is enhanced after fiber transmission.

Compared with conventional 4-PAM, the Nyquist 4-PAM signal has been demonstrated to have a stronger resistance to nonlinear ISI [3]. The spectral components outside Nyquist band are invalid for signal demodulation, but they increase the nonlinear ISI inside the Nyquist band. An iterative distortion cancellation method [12–14] used in orthogonal frequency division multiplexing (OFDM)

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system is introduced to mitigate the nonlinear ISI in subcarrier modulation (SCM) system [10,15]. In this paper, iterative interference cancellation method is introduced into Nyquist 4-PAM system to eliminate nonlinear ISI caused by the electrical Nyquist filter, device bandwidth limitation, optical tilted filter, dispersion, and square-law photo-detection for the first time. Furthermore, we have experimentally demonstrated a 10 GBaud Nyquist 4-PAM system transmission over 100-km uncompensated standard single-mode fiber (SSMF) with iterative nonlinear ISI cancellation, which is achieved by employing a bandwidth limited MZM with 3-dB bandwidth of 2 GHz. An electrical filter is used to realize Nyquist pulse-shaping, and an interleaver with 50-GHz intervals is used as a tilted filter to realize VSB filter and improve the high-frequency response of bandwidth limited MZM. The experimental results show that 0.8-dB receiver sensitivity is improved at the forward error correction (FEC) limit. The iterative nonlinear ISI cancellation method in Nyquist 4-PAM system can effectively suppress the destructive effect of the nonlinear ISI.

2. Principle of nonlinear ISI cancellation in Nyquist 4-PAM system

The principle of the iterative nonlinear ISI cancellation method in Nyquist 4-PAM system using bandwidth limited modulator and tilted filter is shown in Fig. 1. An electrical low pass filter (LPF) with a 3-dB bandwidth equal or greater than B/2 is used to cut off the signal outside the Nyquist frequency band and realize Nyquist pulse shaping, where B is the baud rate. The electrical spectrum of 4-PAM signal before and after LPF is shown in Fig. 1(i) and (ii). The 4-PAM signal at frequency of B/2 after LPF has more than a 6-dB power reduction relative to zero frequency. The optical spectrum after intensity modulator is shown in Fig. 1(iii). The signal power at high frequency drop seriously due to the bandwidth limited effect. The Nyquist 4-PAM signal at frequency of B/2 has a power dip point and be easily buried in noise. The tilted filter is used to offer different suppression for optical carrier and the two sidebands. The optical spectrum after tilted filter is shown in Fig. 1(iv). As the signal frequency increasing, one sideband of the Nyquist 4-PAM signal is more and more suppressed while the other one is just the contrary. The optical tilted filter exhibits high-pass filter characteristics and helps to increase the power of the high frequency components of the Nyquist 4-PAM signal. Moreover, the symmetry of DSB optical spectrum is destroyed by tilted filter. Therefore, the effects of bandwidth limitation and power fading are mitigated simultaneously.

The Nyquist 4-PAM signal suffers from ISI after direct detection. In more detail, the ISI can be divided into two parts [10], namely the linear part and the nonlinear part. The linear ISI could be compensated by using the overlap FDE [16] (O-FDE). The FFT and IFFT size used in O-FDE is 2N, where N is the number of symbols used in one block. The signal processing after O-FDE consists of discarding the overlap symbols, two times down-sampling, and symbol decision.

The detected symbols are used to calculate the nonlinear ISI based on the theoretical model [10] and the calculated results are further fed back to carry out the nonlinear ISI cancellation in the time domain with respect to each block. The N detected symbols after two times zero filled up-sampling are transformed to frequency domain using 2N points FFT. Then the detected signal is multiplied with the frequency response of optical transmitter. The frequency response measurement of optical transmitter will be discussed in the following experiment. The nonlinear ISI is composed of the beating and intermixing terms. As shown in Fig. 1, the processes of lower and upper branches are the reconstruction of beating and intermixing terms, respectively. The signal is multiplied with the response of dispersion and tilted filter, then transforms to time domain using 2N points IFFT. The square of the absolute value of signal is the reconstructed beating term. The second-order term of optical field after intensity modulator is a quadratic component of the desired signal [5,10]. To simplify the computational complexity, the reconstruction of second-order term could be expressed by using two times zero filled up-sampling, 4N points IFFT, square of the absolute value, 4N points FFT and two times down-sampling. This process uses 4 times oversampling, because the spectral bandwidth of the second-order term is double that of the desired signal. The second-order signal adds optical carrier [10], and is multiplied with the response of dispersion and tilted filter, then transforms to time domain using 2N points IFFT. The square of the absolute value of signal is the reconstructed intermixing term. The calculated nonlinear ISI is the product of the weighting factor and the sum of beating and intermixing terms, where the weighting factor is obtained by using least squares error [17]. Then the received data after the nonlinear ISI cancellation are demodulated again to get the more accurate detected data.

Although the nonlinear ISI could be mitigated by using iterative technique, the nonlinear equalizer involves FFT/IFFT processing to assist reconstruct nonlinear ISI. Compared with O-FDE, which needs only two 2N points FFT/IFFT processing, the nonlinear ISI reconstruction for each iteration needs three 2N points FFT/IFFT processing and two 4N points FFT/IFFT processing. Note that the

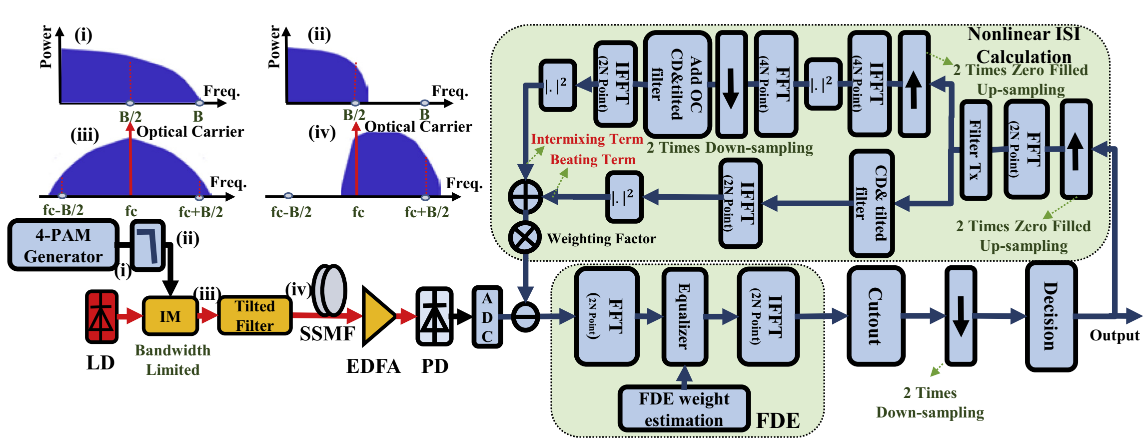

Fig. 1. Principle of iterative ISI cancellation technique in Nyquist 4-PAM system with bandwidth limited modulator and optical tilted filter. B: baud rate; f_c: frequency of optical carrier.