Chromatic dispersion and PMD mitigation at 10 Gb/s using Viterbi equalization for DPSK and DQPSK modulation formats

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Abstract: We explore the potential of chromatic dispersion and polarization-mode dispersion (PMD) mitigation using Viterbi equalization in 10 Gb/s nonreturn-to-zero differential phase-shift keying (NRZ-DPSK) and differential quadrature phase-shift keying (NRZ-DQPSK) systems. We show through Monte Carlo simulations that using Viterbi equalization improves the performance of NRZ-OOK, NRZ-DPSK and NRZ-DQPSK receivers. For NRZ-DQPSK receiver with a Viterbi equalizer, the chromatic dispersion tolerance is about 5000 ps/nm and the 1st order PMD tolerance is about 160 ps at 3 dB OSNR penalty.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2360) Fiber optics links and subsystems; (060.5060) Phase modulation

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1. Introduction

Optical fiber communication systems are subject to intersymbol interference caused by chromatic dispersion (CD) and polarization-mode dispersion (PMD) [1]. In high bit rate fiber optical systems operating at 10 Gb/s or beyond, chromatic dispersion and PMD in the fiber can be troublesome [2,3]. Electronic equalization of distorted data signals at 10 Gb/s is an alternative to optical techniques to mitigate penalties due to transmission impairments [4,5], because electronic signal processing techniques offer great potential in reducing the cost. Analog equalizers have been investigated by simulations and integrated chip realizations [6-8]. Digital equalizers based on maximum likelihood sequence estimation (MLSE) for on-off keying (OOK) systems have been simulated [9] and experimental results showed good performance [10]. In Ref. [4], MLSE was applied in simulation to improve the chromatic dispersion tolerance for data with differential phase-shift keying (DPSK) and differential quadrature phase-shift keying (DQPSK) modulation formats, which are currently being considered as a competitive upgrade to OOK for long-haul transmission [11]. In Ref. [12], the performance of feed-forward equalizers (FFEs) and decision-feedback equalizers (DFEs) was studied in compensating chromatic dispersion and the first-order PMD in optically amplified nonreturn-to-zero (NRZ) OOK and NRZ-DPSK systems at 10 Gb/s. In this paper, we report on Monte Carlo simulations for chromatic dispersion and PMD mitigation in NRZ-DPSK and NRZ-DQPSK optical transmission systems at 10 Gb/s using Viterbi equalization. We compare the calculated performance of Viterbi equalizers with analogue equalizers (FFEs and DFEs) in 10 Gb/s NRZ-OOK, NRZ-DPSK and NRZ-DQPSK optical transmission systems.

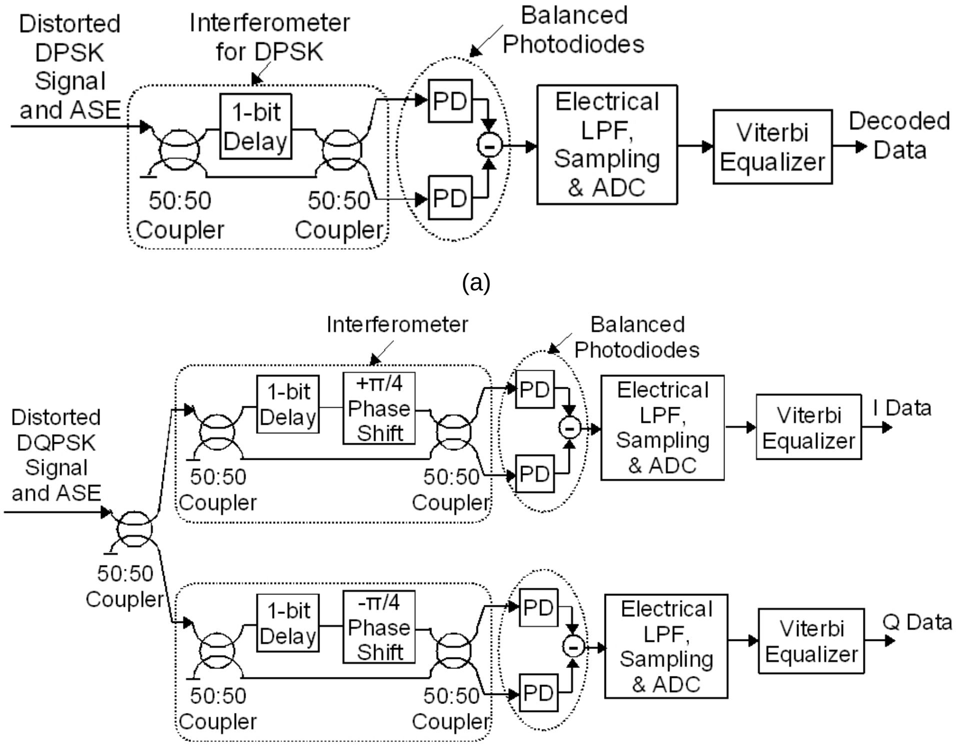
2. Technique principle

One of the applications of the Viterbi algorithm [13, 14] as a realization of MLSE is to decode convolutional codes. The signal distortion within an optical channel can be treated as a kind of coding of the signal, which is very similar to convolutional codes. Thus, using an estimation of the channel model by the Viterbi equalizer, the true transmitted bit stream can be recovered. In a simple receiver, the decision on each bit is immediate. But in an MLSE, the decision is performed by searching through a whole sequence of bits and selecting the "most likely" sequence, which means that the probability of all bit combinations for the whole sequence is considered and the combination with the highest probability is assumed as the transmitted bit combination.

The Viterbi algorithm can be used in different ways according to the modulation formats. Figure 1(a) shows the receiver structure for DPSK data. In the DPSK receiver with a Viterbi equalizer, the distorted optical DPSK signal and amplified spontaneous emission (ASE) noise pass through an interferometer, a pair of balanced photodiodes (PD) followed by an electrical low pass filter (LPF), and sampled by A/D converters (ADC). Then a Viterbi equalizer is used to decode the data. For 10 Gb/s data, we may have 1 sample/bit or 2 samples/bit. Mathematically, operation of the MLSE is expressed as [4]

$$\max_S \log p(x \mid S) = \max_S \left[\sum_k \log p(x_k \mid S)|_T + \sum_k \log p(x_k \mid S)|_{\frac{T}{2}} \right] \qquad (1)$$

where S is the selecting sequence, x is the received sequence, x_k represents the k the sample of x, and T is the bit period. When the sample rate is 1 sample/bit, the second summation is omitted.



(a)

(b)

Fig. 1. Viterbi receiver structure for (a) NRZ-DPSK and (b) NRZ-DQPSK data.

Figure 1(b) shows the Viterbi receiver structure for a DQPSK signal. The DQPSK data has two independent channels (channel I and channel Q), therefore the receiver consists of two interferometers and two pairs of balanced photodiodes. To the output of each balanced photodiode, we apply a separate Viterbi equalizer, which processes the I data and Q data separately, according to Eq. (1).

3. Simulation setup and results

We have carried out Monte Carlo simulations to assess the performance of the Viterbi equalizer in DPSK and DQPSK systems. Figure 2 shows the optical transmission system for the simulations. The transmitter generates 10 Gb/s NRZ DPSK signal or 5 GBaud DQPSK signal with a nonreturn to zero (NRZ) pseudo-random binary sequence (PRBS) of pattern length 2^7. A CD/PMD emulator generates variable chromatic dispersions and the 1st order PMD. Then the Gaussian noise is added to simulate the ASE noise. After optical band pass filtering (BPF), the Viterbi receiver structures in Figs. 1(a) and 1(b) are applied to equalize the DPSK and DQPSK signals. A DPSK or DQPSK receiver performs opto-electronic conversion. Then electrical 5th order Bessel low pass filters (LPF) are applied with a 3 dB bandwidth of about 5 GHz for DPSK and 2.5 GHz for DQPSK, which are the optimum electrical bandwidths we find through optimizing the receivers. The filtered received data signal is sampled at the center of eye with 1 sample/bit. It has been reported that using 2 samples/bit and joint symbol maximum likelihood estimator will further improve the equalizers [1, 4]. We calculated with infinite ADC resolution to determine the ultimate performance of Viterbi equalizer and it has been shown that for the case of NRZ signal the application of 3 or 4 bit analog to digital conversion will lead to a low additional penalty of 0.2 dB [9]. The data signal is fed into the 4 state Viterbi equalizer and the 1st 20480 bits are used to calculate the probability density functions of each symbol for Viterbi decoding.

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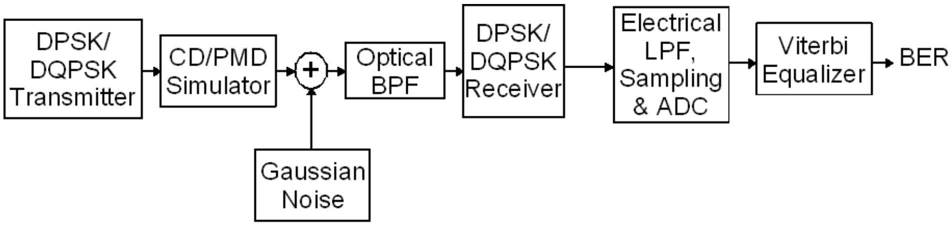

Fig. 2. Optical transmission system for simulations

The performance of Viterbi equalizers is evaluated in terms of OSNR penalty according to different chromatic dispersion and PMDs. The OSNR penalty is defined as the OSNR increment required to achieve a desired BER, with respect to the back-to-back condition [15]. The OSNR penalty in each system is calculated by referring to its own back-to-back condition. A BER of 10^{-3} is sufficient as the desired BER for OSNR penalty because it could be corrected to below 10^{-9} using forward error correction (FEC) [4]. Detailed report on applying FEC with electronic equalizations can be found in Ref. [16].

Figure 3 shows the OSNR penalty for a BER of 10^{-3} vs. the chromatic dispersion in NRZ-OOK, NRZ-DPSK and NRZ-DQPSK systems at a bit rate of 10 Gb/s. We can see that the CD tolerance at 3 dB OSNR penalty for NRZ-OOK receiver without a Viterbi equalizer (VE) is 1000 ps/nm which corresponds to a transmission length of about 60 km for standard single mode fiber with a dispersion of 17 ps/(nm·km). For NRZ-DPSK receiver without a VE, the CD at 3-dB penalty is 1318 ps/nm. For NRZ-OOK receiver with a VE, the CD tolerance at 3 dB penalty increases to 3111 ps/nm which means that the transmission length is extended to 180 km. For NRZ-DPSK receiver with a VE, the CD tolerance is 1635 ps/nm. The CD tolerance at 3 dB OSNR penalty for NRZ-DQPSK receiver without a VE is 4063 ps/nm which corresponds to a transmission length of about 240 km (4 times compared with NRZ-OOK receiver w/o VE). For NRZ-DQPSK receiver with a VE, CD tolerance increases to 5048 ps/nm which means that the transmission length is extended by another 60 km. Comparing NRZ-DQPSK with NRZ-DPSK, the CD tolerance increases to more than 3 times.

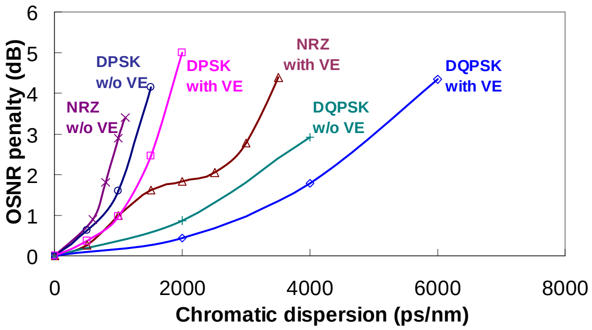

Fig. 3. OSNR penalty for a BER of 10^{-3} vs. chromatic dispersion in 10 Gb/s NRZ-OOK, NRZ-DPSK, and NRZ-DQPSK systems

Figure 4 shows the OSNR penalty for a BER of 10^{-3} vs. the 1st order PMD in NRZ-OOK, NRZ-DPSK and NRZ-DQPSK systems at a bit rate of 10 Gb/s. We can see that the PMD tolerance at 3 dB OSNR penalty for NRZ-OOK receiver without a VE is 48 ps. For NRZ-DPSK receiver without a VE, the PMD tolerance at 3 dB penalty is 59 ps. For NRZ-OOK receiver with a VE, PMD tolerance at 3 dB penalty is 74 ps. For NRZ-DPSK receiver with a VE, the PMD tolerance at 3 dB penalty is 77 ps which is about 1.6 times of the PMD tolerance compared with the NRZ-OOK receiver without a VE. The PMD tolerance at 3 dB OSNR penalty for NRZ-DQPSK receivers without a VE and with a VE are 112 ps and 160 ps respectively. Comparing NRZ-DQPSK with NRZ-DPSK, the symbol rate is half and the PMD tolerance doubles.

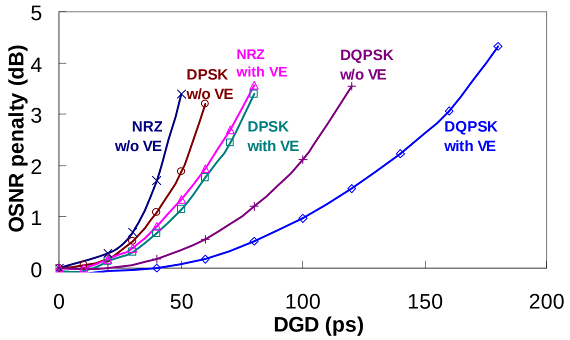

Fig. 4. OSNR penalty for a BER of 10^{-3} vs. the 1st order PMD in 10 Gb/s NRZ-OOK, NRZ-DPSK, and NRZ-DQPSK systems

From the results in Fig. 3 and Fig. 4, we can see that in general the receivers with Viterbi equalizers perform better than the receivers without Viterbi equalizers in NRZ-OOK, NRZ-DPSK and NRZ-DQPSK systems. The NRZ-DPSK receiver without a VE has more CD tolerance than NRZ-OOK receiver without a VE. NRZ-DPSK receiver with a VE has less CD tolerance than NRZ-OOK receiver with a VE. For NRZ-DQPSK receiver with a VE, the CD tolerance increases. In terms of the first order PMD tolerance, NRZ-DPSK receiver without a VE has more PMD tolerance than NRZ-OOK receiver without a VE. NRZ-DPSK receiver with a VE has the similar PMD tolerance as NRZ-OOK receiver with a VE. For NRZ-DQPSK receiver with a VE, the PMD tolerance is doubled.

To obtain a better understanding of the performance of VE, we carried out simulations for the comparison of analog equalizers (FFE and FFE+DFE) and VE in 10 Gb/s NRZ-OOK and NRZ-DPSK systems. We use 7 taps half-bit delay FFE and 1-bit feedback DFE with least mean square (LMS) algorithm for adaptation.

Figure 5 shows the comparison of FFE, FFE+DFE and VE in terms of OSNR penalty for a BER of 10^{-3} according to different chromatic dispersion and PMDs. Figure 5(a) plots the OSNR penalty vs. chromatic dispersion in 10 Gb/s NRZ-OOK systems without equalization (w/o EQ), with FFE, FFE+DFE and VE. When the chromatic dispersion is less than 1500 ps/nm, FFE, FFE+DFE and VE have similar CD tolerance, and with equalizers the OSNR penalty is improved by 1 to 2 dB compared to the receiver without EQ. For chromatic dispersion larger than 1500 ps/nm, VE outperforms the analog equalizers.

Figure 5(b) shows the OSNR penalty vs. chromatic dispersion in 10 Gb/s NRZ-DPSK systems. For the chromatic dispersion of 1000 ps/nm or less, FFE, FFE+DFE and VE have similar CD tolerance. For chromatic dispersion larger than 1000 ps/nm, FFE+DFE has less OSNR penalty than FFE and VE has less penalty than FFE+DFE. At 1500 ps/nm or beyond, VE has about 0.7 dB OSNR penalty less than FFE+DFE and at least 1 dB penalty less than FFE.

Figure 5(c) plots the OSNR penalty vs. the 1st order PMD in 10 Gb/s NRZ-OOK systems. We can see that at 3 dB OSNR penalty, VE and FFE+DFE have about 75 ps and 70 ps PMD tolerance respectively. At 80 ps PMD, VE has about 1.8 dB less penalty than FFE, and FFE+DFE has about 0.8 dB less penalty than FFE.

Figure 5(d) shows the OSNR penalty vs. the 1st order PMD in 10 Gb/s NRZ-DPSK systems. We can see that when the DGD is larger than 70 ps, VE and FFE+DFE have similar performance and both have better PMD tolerance than FFE. In the presence of higher-order PMD, it has been reported that electronic equalizers improve the performance of receivers and VE outperforms the analog equalizers [16].

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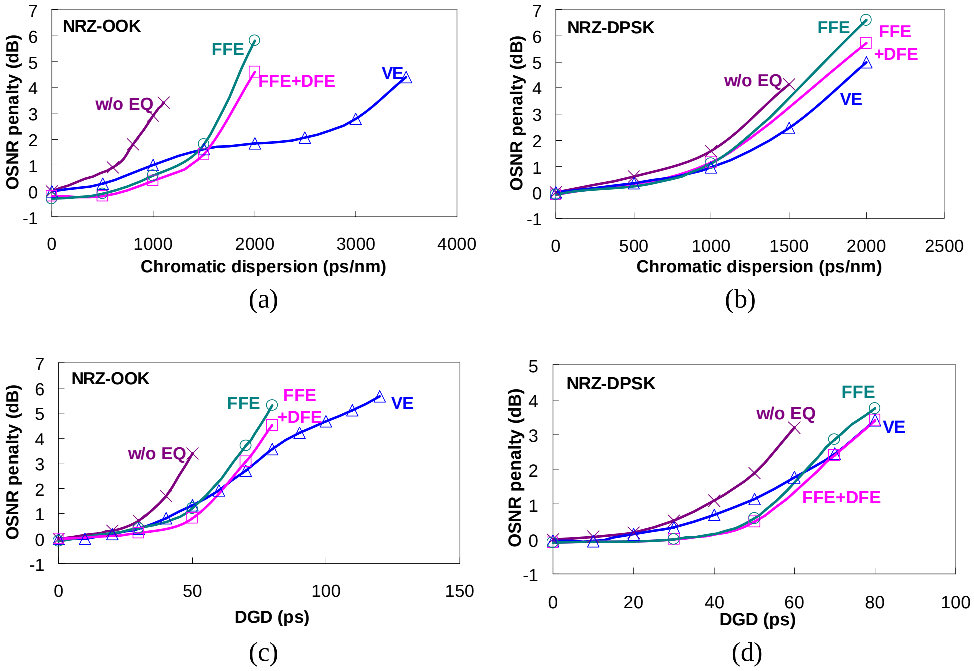

(a) (b)

(c) (d)

Fig. 5. Comparison of FFE, FFE+DFE and VE: OSNR penalty for a BER of 10^{-3} vs. chromatic dispersion in 10 Gb/s (a) NRZ-OOK and (b) NRZ-DPSK systems, and OSNR penalty vs. 1st order PMD in 10 Gb/s (c) NRZ-OOK and (d) NRZ-DPSK systems.

The simulation results in Fig. 5 show that both analog and digital equalizers improve the CD and PMD tolerance in 10 Gb/s systems with OOK and differential modulation formats. For mitigation of PMD, the FFE+DFE and VE outperform FFE and have similar tolerance of up to 80 ps DGD. For mitigation of chromatic dispersion up to 1500 ps/nm, FFE, FFE+DFE, and VE have similar performance. For large PMD and large CD compensation, VE clearly outperforms the analog equalizers (FFE and FFE+DFE).

4. Conclusions

We carried out Monte-Carlo simulations at 10 Gb/s to assess the performance of Viterbi equalizers in NRZ-OOK, NRZ-DPSK and NRZ-DQPSK systems. Simulation results demonstrate that Viterbi equalization are capable of compensating both chromatic dispersion and PMD, and have better performance than analog equalizers. We show through simulations that using Viterbi equalizers improves the performance of NRZ-OOK, NRZ-DPSK and NRZ-DQPSK receivers. At 3 dB OSNR penalty, the chromatic dispersion tolerance is about 5000 ps/nm and the 1^{st} order PMD tolerance is about 160 ps for NRZ-DQPSK receiver with Viterbi equalization. The performance comparison between Viterbi equalizer and analog equalizer has also been discussed.

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