Dynamic PMD Mitigation at 10 Gb/s Using Viterbi Equalization in DPSK Systems

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Abstract—**Compensating dynamically changing polarization-mode dispersion (PMD) is important for optical fiber transmission systems. We present simulations of a Viterbi equalization for dynamic PMD mitigation in 10-Gb/s nonreturn-to-zero differential phase-shift keying systems. The equalizer can dynamically track fast varying differential group delay (DGD) and achieve similar performance to static DGD.**

Index Terms—**Differential modulation format, polarization-mode-dispersion (PMD) mitigation, Viterbi equalizer.**

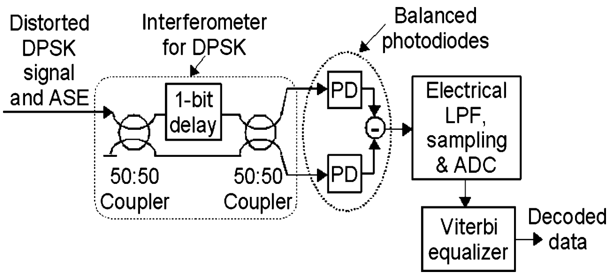

Fig. 1. Viterbi receiver structure for NRZ-DPSK data.

I. INTRODUCTION

POLARIZATION-MODE dispersion (PMD) is one of the barriers to upgrade the current per-channel data rates to 10 Gb/s and beyond in optical-fiber transmission systems. In recent years, a number of techniques have been developed to mitigate PMD and chromatic dispersion (CD) by electronic compensators [1]–[3]. Digital equalizers based on maximum likelihood sequence estimation (MLSE) for CD and PMD mitigation have been simulated and experimentally demonstrated, and the results showed very good performance for on–off keying (OOK) and differential phase-shift keying (DPSK) and differential quadrature phase-shift keying systems [4]–[6]. Experimental comparison of the MLSE performance in the presence of CD and PMD has been presented [7]. In [5], the simulation results are based on static CD and PMD. It is important to track and compensate the dynamically varying PMD [8] because the performance of the optical transmission systems may be affected by fast changing PMD. Therefore, PMD equalizers are required to track PMD variation. Dynamic PMD compensation in OOK systems using MLSE equalizers has been reported in [9]. To the best of our knowledge, the performance of Viterbi equalization (VE) for dynamic PMD mitigation for differential phase modulation formats has not been reported before.

In this letter, we present dynamic PMD mitigation in non-return-to-zero (NRZ) DPSK optical transmission systems at 10 Gb/s using fast tracking VE with an adaptation speed of about 2 ms and we assess the performance of Viterbi equalizers through Monte Carlo simulations.

II. EQUALIZATION TECHNIQUES

Electronic equalization is a well-known technology in wireless communications. Since 2000, there has been a growing interest in using electronic signal processing techniques for the compensation of optical transmission impairments because electronic techniques offer the potential for significant cost savings and enhanced performance and flexibility.

The Viterbi algorithm [7] as a realization of MLSE is commonly used to decode convolutional codes. The signal distortion within an optical channel can be treated as one kind of coding of the signal, which is very similar to convolutional codes. Thus, channel estimation and the true transmitted bit stream can be obtained by VE. In a simple receiver, the decision on each bit is immediate. 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. Fig. 1 shows the receiver structure for DPSK data.

In the Viterbi DPSK receiver, the distorted optical DPSK signal and amplified spontaneous emission (ASE) noise pass through an interferometer, a pair of balanced photodiodes followed by an electrical low-pass filter (LPF), sampling and analog-to-digital converters (ADCs). 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, the principle of the MLSE is expressed by [6]

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

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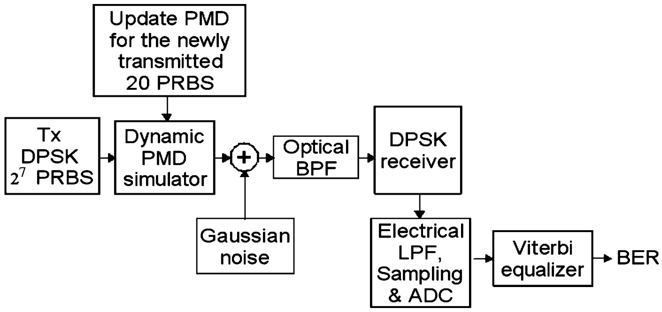


Fig. 2. Optical transmission system for the simulations.

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

When the channel characteristics change, the Viterbi equalizer performs channel estimation and updates the probability density functions. In this way, dynamic PMD mitigation will be obtained with the updated channel characteristics.

III. SIMULATION SETUP

We have carried out Monte Carlo simulations to assess the performance of the Viterbi equalizer for mitigation of dynamically varying PMD in DPSK systems. Fig. 2 shows the optical transmission system for the simulations.

The transmitter generates a 10-Gb/s NRZ DPSK signal with 2^7 pseudorandom binary sequence (PRBS). A dynamic PMD simulator generates variable first-order PMD. Differential group delay (DGD) and launch angle are dynamically varied for every new 2560 bits (20 PRBS) to change the DGD and power splitting ratio of the two principle states of polarization, respectively. Then the Gaussian noise is added to simulate the ASE noise. The optical signal-to-noise ratio in our simulation is 5.5 dB. After a fifth-order Bessel optical bandpass filter with a 3-dB bandwidth of 50 GHz, a DPSK receiver performs optoelectronic conversion. After the subsequent electrical fifth-order Bessel LPF with a 3-dB bandwidth of 4.5 GHz, the data signal is sampled at the center of eye with 1 sample/bit. We calculated with infinite ADC resolution to determine the ultimate performance of Viterbi equalizer and it has been shown that for the case of the NRZ signal, the application of 3- or 4-bit ADC will lead to a small penalty below 0.2 dB [11]. The data signal is fed into a four-state Viterbi equalizer to calculate the probability density functions of each symbol, conduct VE, and compute the bit-error rate (BER). The probability density functions of each symbol for the dynamic PMD are calculated by processing 20 480 bits (160 PRBS), which is about 2 μs for 10-Gb/s data. For every new 2560 bits (20 PRBS) with new PMD, the probability density functions are updated. In our simulation, we use 140 PRBS with old PMD plus 20 PRBS with new PMD as input for VE.

IV. SIMULATION RESULTS

To study the performance of VE for dynamically varying PMD, we first simulate the evolution of PMD. The dynamic PMD can be reflected by the variation of launch angle and DGD. Therefore, we use the evolution of DGD and launch angle to emulate the dynamically varying PMD and to evaluate the performance of VE. In this letter, we only examine the first-order PMD, which is dominant in 10-Gb/s systems. The evolution of PMD is stochastic. We chose the raised-cosine shape for the evolution of DGD and launch angle in the simulation, and the evolution is designed to vary much faster than the practical statistical PMD evolution in the field, because our focus in this letter is to evaluate the performance of the VE under the fast changing PMD. Fig. 3 plots the evolution of DGD and launch angle for every new 2560 bits (20 PRBS). The DGD varies from 30 to 80 ps and DGD changes every 20 PRBS and follows the half raised cosine shape. The launch angle changes from 45° (i.e., the power splitting ratio of the two principle state of polarization is 1.) to 225° then back to 45°. The evolution of launch angle follows the raised cosine shape.

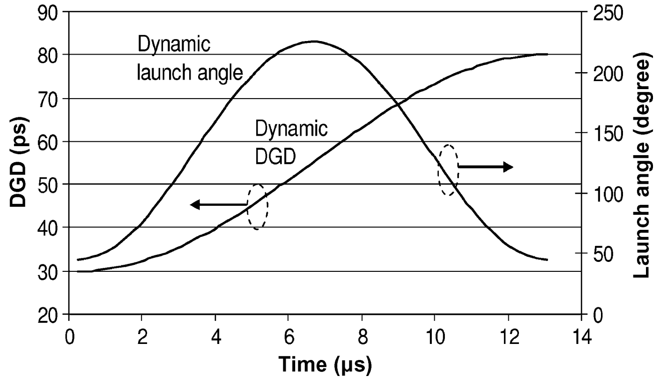
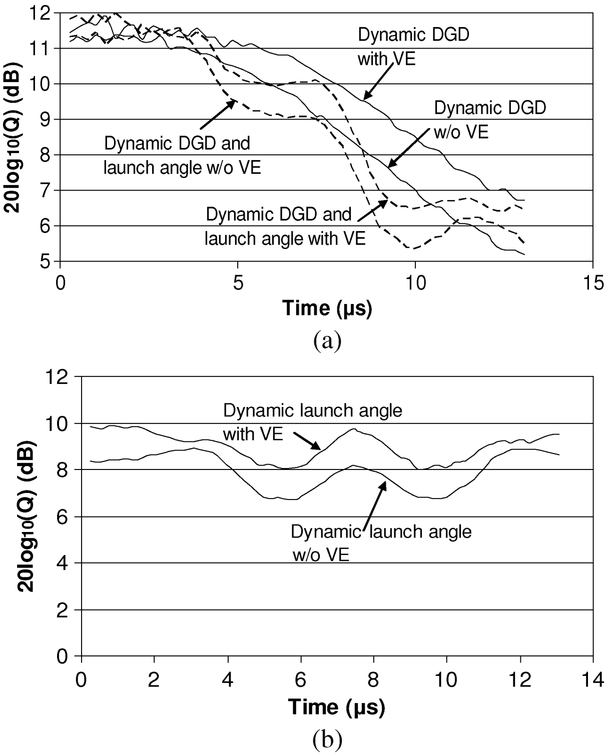


Fig. 3. Evolution of DGD (left y-axis) and launch angle (right y-axis) in 10-Gb/s NRZ-DPSK systems.

Figs. 4 and 5 demonstrate the performance of a VE in 10-Gb/s NRZ-DPSK systems with dynamically varying DGD and launch angle. The dynamically changing DGD and launch angle in Figs. 4 and 5 are according to the evolution in Fig. 3.

Fig. 4 shows the Q-factor in decibels versus time for the systems with dynamic DGD and launch angle. The solid lines in Fig. 4(a) present Q-factor in decibels versus time when DGD varies, and the launch angle is fixed at 45°. The dashed lines in Fig. 4(a) show Q-factor in decibels versus time when both DGD and launch angle change. For each case, we consider the NRZ-DPSK system with a VE and without a VE. The Q-factor is calculated from BER. We can see that for both cases applying a VE improves the Q-factor of the system. Fig. 4(b) describes the Q-factor in decibels versus time with dynamic launch angle only when the DGD is fixed at 60 ps. We can see that for this case, the receiver with a VE performs better than the receiver without a VE as well.

After we observed that applying a VE in the receiver improved the performance of NRZ-DPSK systems with dynamically varying DGD and launch angle, the next question is: Can the VE achieve comparable improvements on system performance for compensating dynamic PMD and static PMD? We carried out simulations to compare the performance of VE for mitigating dynamically varying PMD and static PMD. Fig. 5 illustrates the Q-factor improvement by VE versus DGD



(a)

(b)

Fig. 4. Performance of VE in 10-Gb/s NRZ-DPSK systems with dynamically varying PMD (a) Q (decibels) versus time for the system with dynamic DGD only (launch angle $= 45°$) and mixed dynamic DGD and launch angle; (b) Q (decibels) versus time for the system with dynamic launch angle only (DGD $=$ 60 ps).

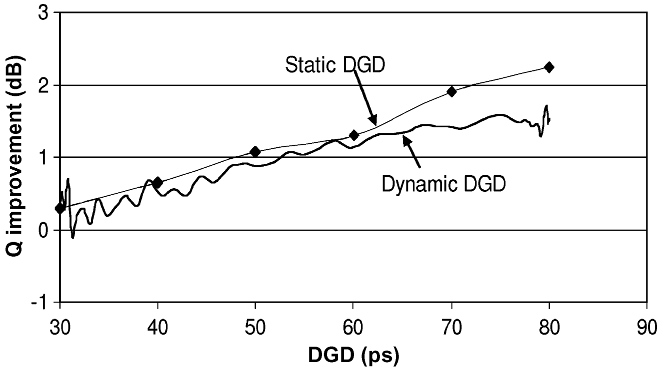


Fig. 5. Q-factor improvement by VE versus DGD for dynamic DGD and static DGD (launch angle $= 45°$) in 10-Gb/s NRZ-DPSK systems.

in 10-Gb/s NRZ-DPSK systems with both dynamic and static DGD.

The dynamic DGD changes according to the evolution in Fig. 3. Static DGD means that each time we process the sequence (160 PRBS) with a fixed DGD. The Q improvement for both dynamic and static DGD is the improvement by using a VE compared to a simple threshold receiver. The Q improvement gained with a VE is equivalent to the reduction of BER. We can see that when the DGD is lower than 60 ps, the Q-factor improvement is similar for dynamic and static DGD; from 60 to 80 ps, the difference of the improvements is less than 0.7 dB for compensating dynamic and static DGD.

V. CONCLUSION

We simulated dynamic PMD mitigation in NRZ-DPSK optical transmission systems at 10 Gb/s using VE with an adaptation speed of about 2 ms. Monte Carlo simulations were carried out to investigate the performance of dynamic PMD compensation using VE. We showed that the fast tracking VE for dynamically varying DGD and launch angel improves the system performance and the VE techniques can achieve similar performance to static DGD compensation. Investigation on the realistic PMD update rate and experimental verification can be interesting future work.

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