Viterbi equalizer for mitigation of distortions from chromatic dispersion and PMD at 10 Gb/s

Fred Buchali, Gunter Thielecke, Henning Bülow
Alcatel Research & Innovation, Holderaeckerstr. 35, D-70499 Stuttgart, Germany
phone: +49 711 821 42891, fax: +49 711 821 32457, e-mail: fred.buchali@alcatel.de

Abstract: Electrical distortion mitigation simulations at 10Gb/s using 2 and 4 state Viterbi equalizers exhibit a 3dB penalty limit for a DGD of 80ps and for a chromatic dispersion of 3100ps/nm, which outperforms analog equalizers.
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1. Introduction

Electronic equalization of distorted data signals at 10 Gb/s is a hot topic since half a decade in research as an alternative to optical techniques to mitigate penalties due to transmission impairments [1]. Up to now analog equalizers have been investigated by simulations and integrated chip realizations proofed feasibility of this concept. Digital equalizers based on analog to digital conversion and subsequent digital signal processing have been applied at lower data rates in cable and radio transmission systems, at 10 Gb/s only few papers report on simulation results demonstrating very high efficiency [2,3], but realizations have not been reported up to now. The progress in microelectronics enables the realization of analog to digital converters at 10 Gb/s with 3 bit resolution [4] and very complex digital signal processing chips with moderate power dissipation [5]. Digital equalizers based on maximum likelihood sequence estimation (MLSE) are regarded as most efficient electronic equalization leading to lowest penalties. In this paper we report on Monte Carlo simulations for MLSE applied to optical fiber transmission systems including the most important signal distortions chromatic dispersion and polarization mode dispersion.

2. Viterbi equalizers in optical transmission systems

In difference to simple receivers, where each bit is deceided immediately, in a MLSE the decision is performed by calculating the transmitted bitstream with the highest probability. That means, that the probability for all bit combinations for the whole sequence is considered and the combination with highest probability is assumed as the transmitted bit combination. The overall probability of a transmitted bit combination is given by the product of all single bit probabilities. Instead of probability its logarithmic value is used and all separated logarithmic probabilities can be added which is easyer for hardware realization.

The Viterbi algorithm as a realization of MLSE is used commonly to decode convolutional codes. The signal distortion within an optical channel can be assumed as coding of signal, which is very similar to convolutional codes. At a differential group delay of 1 bit period and a power splitting ratio of γ=½ a single isolated "1" bit is distorted or "coded" to a "½" "½" combination. By using an estimation of the channel model within the Viterbi equalizer the true transmitted bitstream can be recovered. In a 2 state Viterbi we have 2 states "0" and "1" assumed as previous bits (cf. Fig. 1.). Dependent on the present bits "0" and "1" we have 4 branches with 4 probabilities dependent on received signal and expected amplitudes.

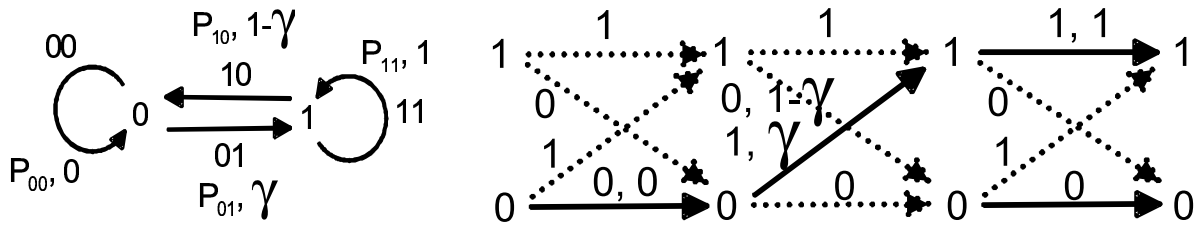


Fig. 1. State diagram for 2 states with 4 branches. Each branch is characterized by a magnitude, the probability is calculated from the normalized deviation of the sample from magnitude (left), corresponding trellis diagram.

The sequence of levels is given by the state diagram or the trellis and the channel model, e.g. 0-γ-1 or 0-γ-(1-γ), whereas 0-γ-0 is not allowed, the magnitude of levels is given by the distortion. For each sequence the logarithmic probabilities have to be calculated. At each state the branch with the higher probability is selected resulting the best estimation for the transmitted bit. For calculation of probabilities a good estimation of channel model is required and

a good estimation of the noise behavior. In Gaussian noise limited systems the probability is inverse to the quadratic deviation from the expected values. The noise of optical fields before o/e conversion is Gaussian, but due to squaring at photodiode the noise is determined by the χ^2-distribution. This leads to a signal dependent noise and non-symmetric distribution functions as demonstrated in Fig. 2. We calculated the probabilities by normalizing the deviations using single side adaptation to a Gaussian distribution function.

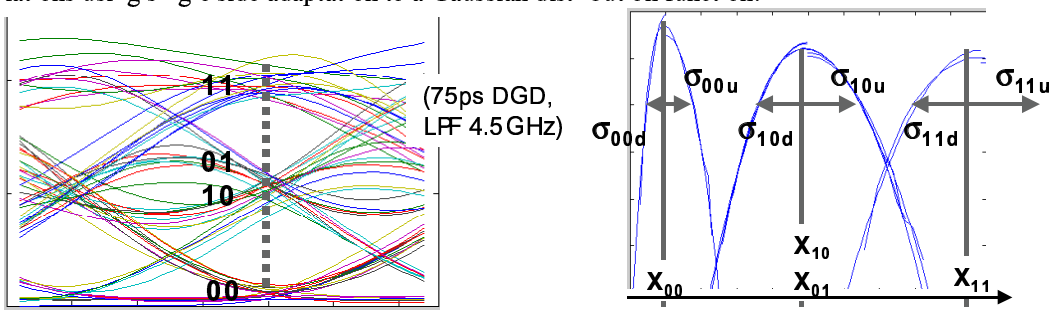


Fig. 2. Eye diagram of data signal at a DGD of 75 ps with indicated sampling time for determination of PDF (left), probability distribution function of data signal showing 4 separate functions for 4 symbols (10 and 01 are equal at this distortion, right).

The transmission system consists of a 10 Gb/s NRZ transmitter and an extinction ratio of 13 dB for optical data modulator, a distortion emulator generating variable chromatic dispersion or variable 1st order PMD and a following statistical Gaussian noise addition sample by sample by chance. After optical filtering with 20 GHz bandwidth opto-electronic conversion was simulated by signal squaring. The subsequent electrical 5th order Bessel low pass filter with variable cut-off frequency was adjusted for each distortion. After electrical filtering with 5 to 3.5 GHz bandwidth the data signal was sampled with variable phase and 1 sample per bit. In order to find out ultimate performance of VE we calculated with infinite ADC resolution and determined penalties due to limitation of resolution later. The data signal is fed to the Viterbi equalizer and the 1st 200.000 bit sequence has been used to calculate the probability density functions of each symbol.

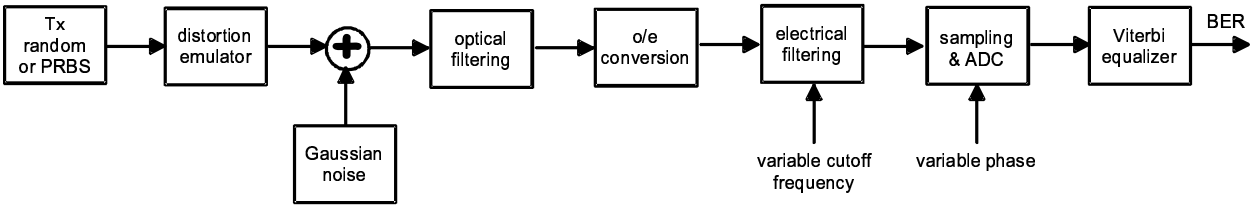


Fig. 3. Optical transmission system for simulations.

3. Performance of Viterbi equalizer

The performance of VE was simulated using a 1st order PMD distortion and a 2 state as well as 4 state equalizer. The 2 state VE has a memory of 1 bit leading to the capability to cope with ISI, the maximum pulse broadening is 1 bit period. This ISI is given by the whole optical channel including o/e conversion and variable electrical filtering and can be used for further bandwidth limitation. The 4 state Viterbi has a memory of 3 bit leading to an increased maximum ISI up to 2 bits. In general the VE is capable to equalize the signal at variable phase. We considered 2 fixed phase positions of the sampler at center of eye and between 2 eyes for variable DGD (cf. Fig. 2.).

The 2 state VE exhibits 0 penalty at 0 dispersion if sampling was performed at center of eye. The performance is comparable to a standard receiver. With increasing DGD the opening of inner eye is reduced. Hence the PDF of different symbols are shifted closer together and the differences in probability for different symbols drop down. The penalty rises up to 5 dB at a DGD of 75 ps. If sampling was performed between 2 eyes we found a penalty of 1.8 dB at 0 disperion, but the penalty rises slower with a 3 dB penalty DGD of about 75 ps and a penalty of 4.8 dB at 100 ps. If applying the 4 state VE at 0 distortion an additional gain of 0.2 dB was found and an increased 3 dB penalty of more than 80 ps for sampling at eye center. If sampling between 2 eye the 4 state VE is comparable to the 2 state VE up to 50 ps DGD, beyond a slight improvement was found of 0.3 dB at 100 ps. If increasing the DGD above 1 bit period the 4 state VE is able to cope with. The penalties rise up to 6 dB at 125 ps, at 150 and 175 ps DGD 4.7 dB were found, only.

If considering FEC supported transmission with 7% overhead the transmitted data rate is 10.7 Gb/s and a reduced PMD limit of 75 ps DGD has to be taken into account. The application of 3 or 4 bit analog to digital conversion leads to a low additional penalty of 0.2 dB.

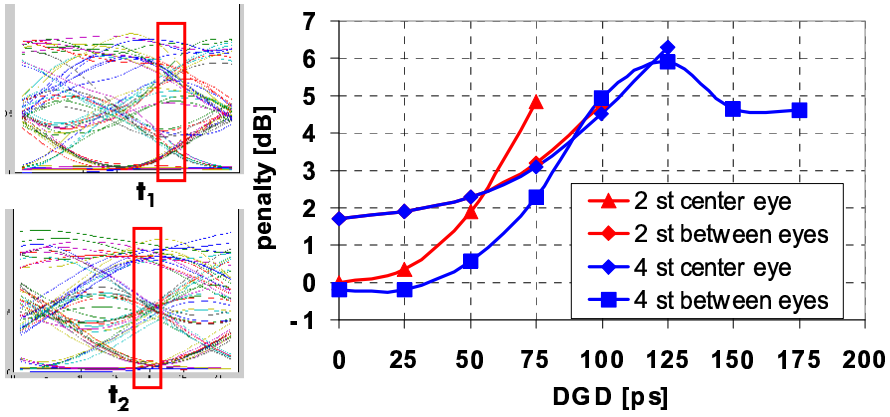


Fig. 4. Eye diagram of a PMD distorted signal indicating 2 differant sampling phases (left) and sensitivity of Viterbi equalizer with 2 and 4 state for 1st order PMD (right).

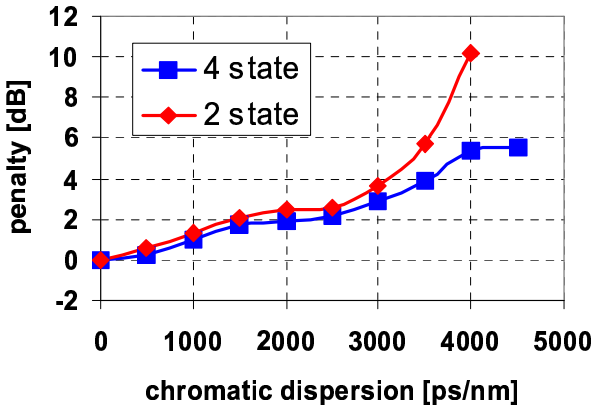


Fig. 5. Sensitivity of 2 and 4 state VE for variable chromatic dispersion, the sampling phase was optimized for each CD.

If applying a chromatic dispersion to the 2 state Viterbi the penalty increases to 2.5 dB at 1500 ps/nm and remains at this penalty up to 2500 ps/nm. A 3 dB limit for chromatic dispersion was found at 2700 ps/nm. The 4 state VE has reduced penalties in the whole dispersion range with a 3 dB penalty limit of 3100 ps/nm corresponding to a maximum transmission length of 180 km for standard single mode fiber with a dispersion of 17 ps/nm.km. If considering FEC overhead the CD limit will be reduced to 2720 ps/nm leading to reduced maximum length of fiber.

4. Conclusions

Simulations of the Viterbi equalizer for distorted optical channels exhibit a 3 dB PMD limit of about 80 ps and a chromatic dispersion limit of 3100 ps/nm. The penalty increase to higher distortions is moderate. In comparison to analog equalizers the VE outperforms the compound equalizer consisting of a FFE and a DFE. At a DGD of 1 bit period the Viterbi reduces the penalty by about 3.5 dB and the influence of non-ideal phase is very low. Contrary to previous publications we expect higher penalties for PMD distortions. The performance of VE was found to be optimum at high error rates typical for FEC supported systems. In conclusion the application of Viterbi equalizers is a good choice for distortion mitigation leading to low penalties, multi distortion mitigation ability and a good suitability for integration into the receiver.

5. References

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