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Mitigating Sampling Phase Sensitivity of the MLSE by Overlapping Branch Metrics

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Abstract *A new method, which applies overlapping branch metrics of adjacent symbols, mitigates sampling phase sensitivity towards a large window without performance loss and without increasing the sampling rate.*

Introduction

Recently electrical signal processing (ESP) has been investigated into for different modulation formats [1][2] to relax system penalties induced by optical linear and nonlinear distortions. In addition electrical equalization can adaptively compensate for optical and electrical distortions at a low cost. There is common consensus that electrical low-pass filtering with over-sampled Maximum Likelihood Sequence Estimation (MLSE) yields near-optimum performance compared to feed-forward (FFE) or decision feedback equalizers (DFE) [3]. Most investigations and experiments focus on optical impairment mitigation avoiding challenges of clock recovery implementation and sampling phase sensitivity.

The implementation of an electrical MLSE for a 10Gbit/s transmission system has already been demonstrated experimentally [4]. It implies a four-state Viterbi decoder using a non-parametric channel estimation based on histograms to compute the branch metrics, which are stored in lookup tables. At a sampling rate of 20Gsamples/s (2 samples/symbol), an enhanced clock recovery controls the sampling phase in the ADC.

From [3] we know that over-sampling is less sensitive to sampling phase variations and the choice of the sampling phase than classical Nyquist sampling. In addition it was shown in [5] that an MLSE with oversampling performs better in terms of required OSNR.

In the following we propose an alternative computation of the branch metrics with overlapping branch metrics for adjacent sampling instants. This allows sampling phase variations within the duration of two symbols or more without decreasing the performance. At the same time we improve the back-to-back performance.

Metric Robust to the Sampling Phase

With a j-fold oversampling we receive j samples $r_{\varphi(x,j)}(i)$, $x=1,\dots,j$ for every symbol slot i, which lasts one symbol duration T. We define the sampling phase φ as the deviation from the open eye located at $T/2$ for undistorted transmission. A negative φ refers to a sampling phase preceding to $T/2$, a positive φ refers to a sampling phase succeeding $T/2$. The sampling instants refer to $\varphi(1,1)=\varphi$ in case of classical Nyquist sampling, to $\varphi(1,2)=\varphi-T/4$ and $\varphi(2,2)=\varphi+T/4$ for 2-fold over-sampling and to $\varphi(1,3)=\varphi-T/3$, $\varphi(2,3)=\varphi$ and $\varphi(3,3)=\varphi+T/3$ for 3-fold over-sampling.

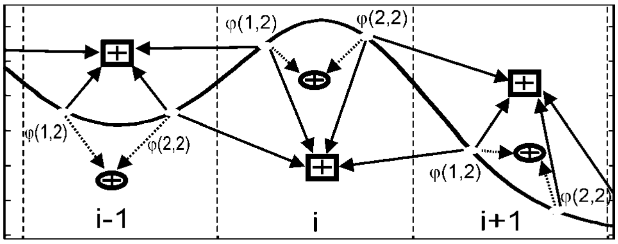

Figure 1: Schematic contribution to branch metrics for 2s2PDF (circle) and 2s4PDF (box)

The Viterbi-Algorithm (VA), as an implementation of the MLSE principle, applies a state probabilistic model with conditioned probability density functions (PDF) $p(r(i)|S)$ stored in a lookup table. The state transition S is composed of O leading symbols and P trailing symbols interfering with the actual symbol. Typically we build one lookup table for every sampling instant $r_{\varphi(x,j)}$. In the following, we will refer to these cases as "1s1PDF" for j=1, "2s2PDF" for j=2 and "3s3PDF" for j=3. The VA estimates the most likely digital sequence $\hat{D}$ maximizing the path metric. For $j=2$ the path metric is exemplarily shown in Eq. (1) as it is known from [2]. The path metrics for j=1 and j=3 can be derived similarly.

Fig.1 makes clear that for one step i in the branch metric classical schemes only apply j samples within the same symbol duration. However, the grouping is arbitrary and could be shifted by one sampling instant as well.

To avoid such a hard cutoff, we propose an new scheme, which applies 2-fold over-sampling with 4 PDFs called "2s4PDF". Now every sampling instant $\varphi(1,2)$ and $\varphi(2,2)$ is employed by both adjacent branch metrics $i-1$ and $i+1$ as well, leading to the additional contributions of Eq.(2) and Eq.(3). Yet, the 2 PDFs referring to the overlapping sample look differently and contain different information.

$$\hat{D}=\arg\max_{S}\left[\sum_{i}\sum_{x=1}^{j}\ln p\left(r_{\varphi(x,j)}(i)\middle|S\right)\right] \quad (1)$$

$$+\overbrace{\sum_{i}\sum_{x=j/2+1}^{j}\ln p\left(r_{\varphi(x,j)}(i-1)\middle|S\right)}\quad (2)$$

$$+\overbrace{\sum_{i}\sum_{x=1}^{j/2}\ln p\left(r_{\varphi(x,j)}(i+1)\middle|S\right)}\quad (3)$$

Numerical Results

To evaluate the performance of the four sampling schemes we use Monte-Carlo simulations. A PRBS of 2^7 bit is sent with 10Gbit/s NRZ-OOK modulation (low launch power) over 100km of SSMF and a relevant DCF to adjust residual dispersion, simulated by split-step-Fourier-method, including distortions like chromatic dispersion and SPM. The noise loaded waveforms are fed into the receiver. The optical Gaussian BP filter (1st order, 25GHz), the photo diode and the electrical LP Bessel filter (20th order, 4GHz) are followed by a 4bit A/D-converter. For equalization we applied a 4-state Viterbi-Algorithm leading to 8 state transitions and PDFs represented in the lookup tables.

Fig.2 and Fig.3 show the sampling phase sensitivity for variations of φ in case of three different distortions by residual dispersion. For CD=0ps/nm Nyquist sampling is clearly limited to the open eye for optimum performance. Shifting the sampling phase to adjacent symbols still leads to satisfactory results because the Viterbi-Algorithm partly compensates such offset. Over-sampling clearly opens the window for the optimum sampling instant. 2-fold over-sampling suffers a small penalty if none of the samples is located at the open eye. The scheme of 2s4PDFs proves the widest window in all cases, even outperforming the 3-fold over-sampling.

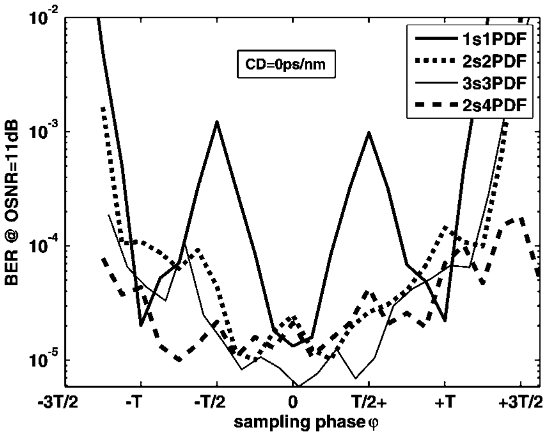

Figure 2: Sampling phase sensitivity for CD=0ps/nm

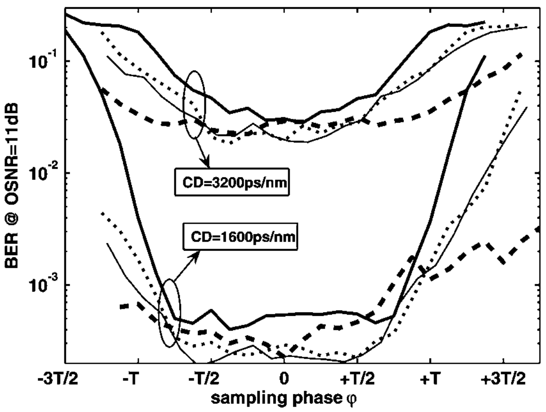

Figure 3: Sampling phase sensitivity for CD=1600ps/nm and CD=3200ps/nm

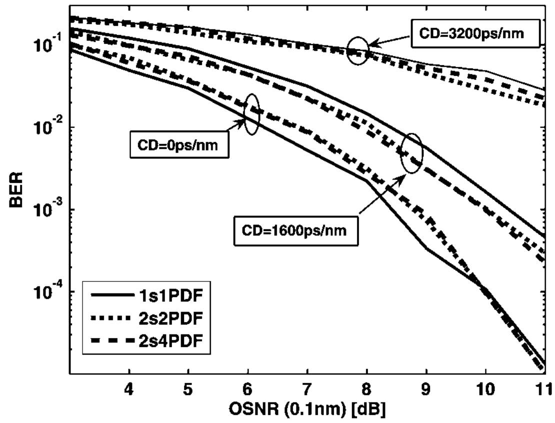

Figure 4: BER performance for the optimum sampling phase of each scheme

The PDFs were histographically estimated without tail extrapolation. Especially for low distortions this can lead to badly conditioned PDFs. Applying 4 PDFs in case of 2s4PDF, this error can accumulate leading to a variation in performance, as it can be seen in Fig.2. Enhanced channel acquisition algorithms and tail extrapolation of the PDFs would avoid such influence.

In case of an optimum choice of the sampling phase the BER performance vs. OSNR (0.1nm) is shown in Fig.4. For a BER of 10^{-2} and below 2s4PDF never performes worse than 2s2PDF and almost always performes equal or better than 3s3PDF (not plotted in the figure).

Further simulations including strong non-linear distortions confirm the robust behaviour of 2s4PDF with respect to sampling phase sensitivity and with respect to BER performance as well.

Conclusion

We propose a new method with overlapping branch metrics, which applies a number of *N* lookup tables out of a *j*-fold over-sampling with *N*>*j*. Especially in case of distoriton by high residual chromatic dispersion, where the phase recovery of the clock signal might be challenging, the method clearly mitigates sampling phase sensitivity. Applying 2-fold over-sampling the scheme 2s4PDF even outperforms 3-fold over-sampling. The method comes only with a slight increase in complexity and would be easy to be implemented in state of the art equalizers like the MLSE.

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