# Joint Electronic Dispersion Compensation for DQPSK

**Torsten Freckmann, Carlos Valerio González and José M. Ruiz-Cabello Crespo**
*Institute of Telecommunications, University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany*
*Email: torsten.freckmann@inue.uni-stuttgart.de*

**Abstract:** We investigate electronic dispersion compensation for DQPSK based on linear and nonlinear feed-forward and decision feedback equalizers as well as maximum likelihood sequence estimation. We propose joint processing of the two tributaries to exploit any cross-coupling.

**OCIS codes:** (060.4510) Optical communications (060.5060) Phase modulation

## 1. Introduction

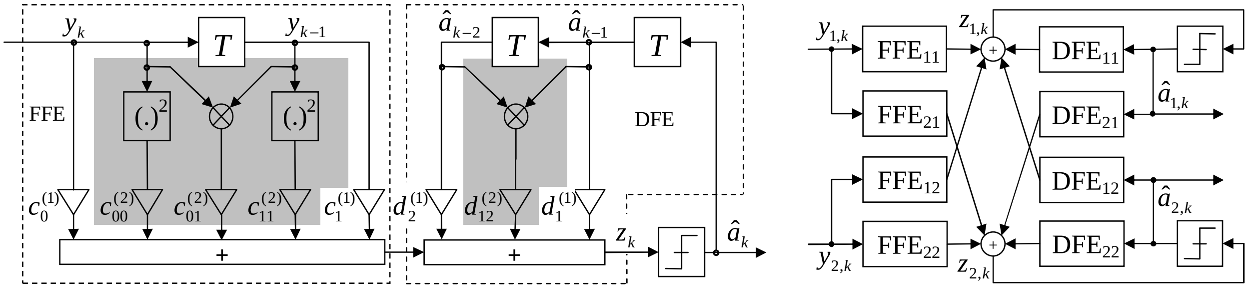
In recent years, differential quadrature phase-shift keying (DQPSK) has attracted quite some attention due to its higher spectral efficiency and reduced symbol rate compared to binary modulation [1]. Moreover, recent progress in high-speed electronics has revived interest in different analog and digital electronic signal processing schemes. The most important of which are electronic equalization by means of feed-forward and decision feedback equalizers (FFE-DFE) and maximum likelihood sequence estimation (MLSE), which have already been successfully demonstrated experimentally for different binary modulation formats [2,3]. Numerical investigations have also been performed for Volterra-based nonlinear FFE-DFE (NL-FFE-DFE) for binary [4] and multilevel [5] modulation.

In this paper we investigate the application of different electronic dispersion compensation (EDC) schemes to increase the tolerance of DQPSK against chromatic (CD) and first order polarization mode dispersion (PMD). The investigation includes linear and nonlinear FFE-DFE as well as MLSE. In particular, we propose joint processing of the two DQPSK tributaries (often also referred to as I- and Q-branch) to exploit any cross-coupling between them.

## 2. Electronic dispersion compensation schemes for DQPSK

### 2.A. Linear and nonlinear feed-forward and decision feedback equalization

The first EDC schemes considered are linear and nonlinear FFE-DFE. Fig. 1(a) shows an example of an NL-FFE-DFE of order $N = 2$ ($M = 2$) and nonlinear order $n = 2$ ($m = 2$) of the FFE (DFE) part of the equalizer. The difference compared to a linear equalizer is the nonlinear combination of the delayed samples $y_l$ and estimated bits $\hat{a}_l$, respectively. Thereby, it is possible to combat nonlinear distortions up to a certain degree depending on the filter orders *N* and *M* and the orders of nonlinearity *n* and *m*. The nonlinear parts of the equalizer in Fig. 1(a) are gray shaded. We introduce the term NL[*n*,*m*]-FFE[*N*]-DFE[*M*] as a short-hand notation for the NL-FFE-DFE. Please note that the considered NL-FFE-DFE is a generalization of the linear FFE-DFE, which is determined by $n = m = 1$. The application of a nonlinear equalizer is motivated by the fact that dispersion leads to nonlinear distortions in the electrical domain after square law detection, which can not be completely equalized by a linear equalizer.



(a) (b)

Fig. 1. (a) Example of a nonlinear feed-forward and decision feedback equalizer NL[2,2]-FFE[2]-DFE[2], (b) joint symbol FFE-DFE

Similarly to [5] we can define state vectors $\mathbf{y}_k$ and $\hat{\mathbf{a}}_k$ and coefficient vectors $\mathbf{c}$ and $\mathbf{d}$ for the FFE and DFE parts of the equalizer, respectively. This allows the output signal $z_k$ of the equalizer to be written as scalar product $z_k = (\mathbf{c}^T, \mathbf{d}^T) \cdot (\mathbf{y}_k^T, \hat{\mathbf{a}}_k^T)^T = \breve{\mathbf{c}}^T \cdot \breve{\mathbf{y}}_k$. From this fact we can conclude that the output of the equalizer is linearly depending on its coefficients. Consequently, the optimal coefficients according to the minimum mean squared error (MMSE) criterion are given by the well known Wiener solution in the same way as for a linear FFE-DFE.

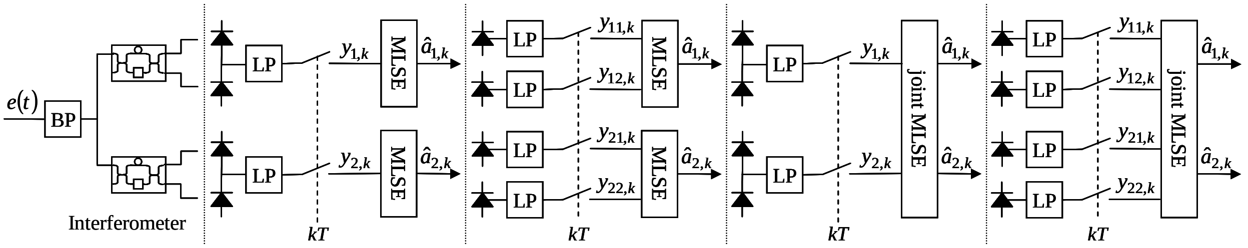
### 2.B. Joint feed-forward and decision feedback equalization

So far I- and Q-branch were processed independently by two separate equalizers. However, it is obvious that these tributaries are not independent of each other since optical impairments lead to interference on symbol level (ISI) rather than on bit level. Therefore, we suggest the application of a joint FFE-DFE – realized in the well known butterfly structure – to jointly process the two tributaries. A block diagram of the resulting equalizer structure is given in Fig. 1(b), where the blocks denoted by "FFE" and "DFE" may each contain the corresponding part of the structure described in Fig. 1(a). We restrict ourselves in the scope of this paper to the case that all FFE and DFE parts in Fig. 1(b) are linear (i.e. $n = m = 1$) and have the same filter orders *N* and *M*, respectively.

Similar to section 2.A. we can define state vectors and coefficient vectors for the eight partial equalizers in Fig. 1(b) and write the outputs $z_{1,k}$ and $z_{2,k}$ of the equalizer in a vector notation. Consequently, the optimal coefficients of the joint FFE-DFE according to the MMSE criterion are again given by the Wiener solution.

### 2.C. Maximum likelihood sequence estimation

The last EDC scheme considered is MLSE implemented by the Viterbi algorithm and therefore also referred to as Viterbi equalizer (VE). Instead of deciding all symbols separately as in the case of a simple threshold receiver, the MLSE searches through a whole sequence of symbols and selects the "most likely" one. Different architectures and simulation results for the VE for DQPSK have been previously reported in [6] at 10 Gb/s. In this paper we investigate four different VE for DQPSK, which are depicted in Fig. 2. They differ in complexity in terms of the necessary number of analog-to-digital converters (ADC) and trellis size. In case of two separate VE for I- and Q-branch in Fig. 2(a,b) each trellis has $2^{N-1}$ states and $2^{N}$ branches since these VE are operating on bit level. Opposed to that the complexity of the joint VE in Fig. 2(c,d), which is operating on symbol level, is considerably higher with $4^{N-1}$ states and $4^{N}$ branches. For the VE that follow balanced detectors (BD) in Fig. 2(a,c) one ADC per receiver (rx) branch is sufficient, whereas two ADC per rx branch are required for the VE in Fig. 2(b,d), which follows two photodiodes which separately detect the constructive and the destructive port of the delay interferometer.



(a) (b) (c) (d)

Fig. 2. DQPSK-interferometer followed by (a) two balanced detectors and two separate MLSE, (b) four single photodiodes and two separate MLSE, (c) two balanced detectors and one joint MLSE and (d) four single photodiodes and one joint MLSE

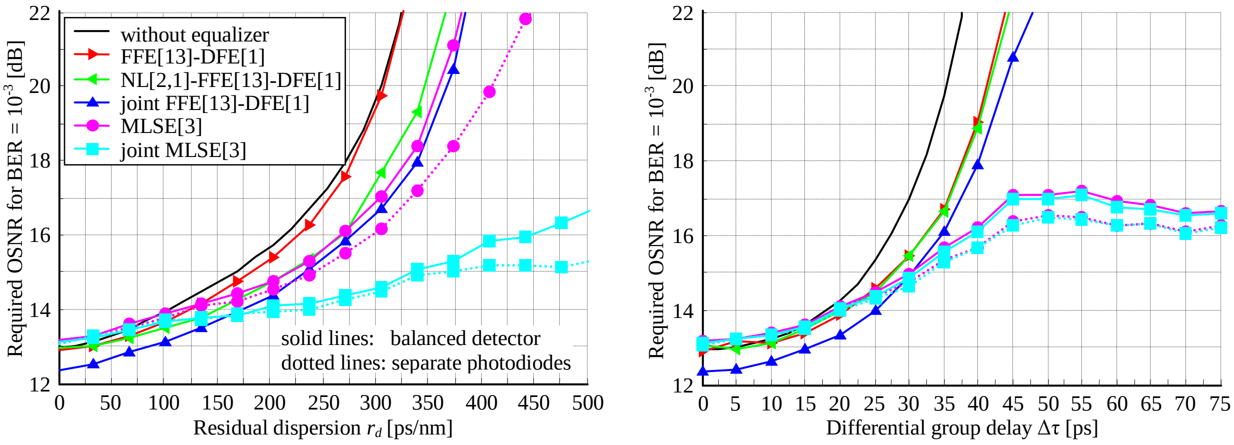
### 3. Simulation results

The investigated DQPSK system uses a transmitter with two parallel Mach-Zehnder modulators and time-domain raised-cosine impulse shapers with a roll-off factor of 0.35 and a rx comprising two Mach-Zehnder interferometers and two BD as in [1]. The optical rx filter is a second order Gaussian band-pass (BP) with a 3-dB bandwidth of $5.0 \cdot R_S$ and the electrical rx filter is a third order Bessel low-pass (LP) with a 3-dB cut-off frequency of $0.5 \cdot R_S$. $R_S = 1/T_S = R_b/2$ is the symbol rate and $R_b$ is the considered bit rate of 42.7 Gb/s, including 6.8% FEC-overhead. We restrict to a linear channel model with CD and first order PMD only. All EDC schemes are assumed to operate at $2R_S = R_b$, which means a tap-spacing of $T = T_S/2$ for all FFE and 2 samples/bit for all MLSE.

Fig. 3(a) shows the required optical signal-to-noise ratio (OSNR) to achieve a bit error ratio (BER) of $10^{-3}$ versus residual dispersion $r_d$. It can be observed, that the linear FFE-DFE is not specifically effective in compensating distortions caused by CD and increases the CD-tolerance by only about 6% at 3-dB OSNR penalty. The reason is that CD leads to nonlinear distortions in the electrical domain after square law detection, which may not be fully compensated by a linear equalizer. Opposed to that the NL-FFE-DFE with nonlinearities of the second order in the FFE part performs much better than the linear FFE-DFE and improves the 3-dB-CD-tolerance by about 25%. Further simulations have shown that an increase of the order of nonlinearity of $n > 2$ for the FFE part does not result in a significant performance improvement and does therefore not justify the considerably higher complexity according to [5]. Moreover, neither an increase of *M* nor a nonlinear structure of the DFE part showed to be beneficial.

Interestingly, the joint FFE-DFE, even though it is composed of linear FFE-DFE, performs slightly better than the NL-FFE-DFE. It gains about 30% increase in the 3-dB-CD-tolerance and about 0.5 dB higher rx sensitivity. This shows that exploiting the cross-coupling between the two DQPSK tributaries is at least as effective as introducing two separate NL-FFE-DFE. It should be mentioned in this context that the complexity in terms of the number of taps is about four times lower for the joint FFE-DFE, which has $4\times13=52$ FFE taps and $4\times1=4$ DFE taps, compared to $2\times104=208$ FFE taps and $2\times1=2$ DFE taps for the NL-FFE-DFE [5]. Both, the NL-FFE-DFE as well as the joint FFE-DFE show a similar performance as two separate 4-state VE with BD according to Fig. 2(a), which increase the 3-dB-CD-tolerance by about 25%. Some additional 10% increase in CD-tolerance at 3-dB OSNR penalty can be achieved by two separate VE with two inputs according to Fig. 2(b). Finally we can observe that the joint MLSE according to Fig. 2(c,d) achieves the highest performance of the considered EDC schemes and increases the 3-dB-CD-tolerance by more than a factor of two. The great difference between two separate MLSE and joint MLSE is again attributed to the fact that the joint MLSE exploits any cross-coupling between the two DQPSK tributaries.

Fig. 3(b) shows the required OSNR for $\mathrm{BER}=10^{-3}$ versus differential group delay $\Delta\tau$ quantifying first order PMD. We can observe that there is almost no difference between linear and nonlinear FFE-DFE. This is plausible, since first order PMD results in linear distortions in the electrical domain. Both EDC schemes achieve about 18% increase in the 3-dB-PMD-tolerance. Moreover, also the joint FFE-DFE does only yield an 8% higher 3-dB-PMD-tolerance compared to two separate FFE-DFE. This shows that there is no significant cross-coupling between I- and Q-branch in case of first order PMD and therefore joint processing is not beneficial. The same fact can be observed when comparing joint MLSE with two separate MLSE. Again the performance of these two EDC schemes is almost identical. The MLSE with BD according to Fig. 2(a,c) achieves an increase in PMD-tolerance of about 40% at 3-dB OSNR penalty, whereas the MLSE with separate photodiodes according to Fig. 2(b,d) gains another 15%. It is interesting to note that for all MLSE schemes the OSNR penalty saturates at around 3.5–4 dB.



(a) (b)

Fig. 3. (a) CD- and (b) PMD-Toleranz für DQPSK for various EDC schemes

In conclusion we investigated the performance of linear and nonlinear FFE-DFE as well as MLSE for DQPSK with direct detection. It turned out that joint processing of the I- and Q-branch yields a considerably higher CD-tolerance compared to separate processing for both FFE-DFE and MLSE. Opposed to that the PMD-tolerance may not be considerably increased by joint processing for neither FFE-DFE nor MLSE. The earlier proposed NL-FFE-DFE without joint processing [5] yields about the same performance as the joint FFE-DFE or two separate MLSE.

## 4. References

[1] R. A. Griffin *et al.*, “Optical differential quadrature phase-shift key (oDQPSK) for high capacity optical transmission,” in *Proc. Opt. Fiber Comm. Conf.*, pp 367-368, 2002.

[2] B. Franz *et al.*, “Performance improvements of different modulation formats by applying adaptive electronic equalisation in 43 Gbit/s systems,” in *Proc. European Conf. on Opt. Comm.*, paper 3.1.2, 2007.

[3] A. Faerbert, “Application of digital equalization in optical transmission systems,” in *Proc. Opt. Fiber Comm. Conf.*, OTuE5, 2006.

[4] C. Xia *et al.*, “Nonlinear electrical equalization for different modulation formats with optical filtering,” in *Journal of Lightwave Technology*, vol. 25, No. 4, pp. 996-1001, 2007.

[5] T. Freckmann *et al.*, “Linear and nonlinear electronic feed-forward equalizers for DQPSK,” in *Proc. IEEE/LEOS Annual Meeting*, paper MP4 (accepted for oral presentation), 2007.

[6] M. Cavallari *et al.*, “Electronic signal processing for differential phase modulation formats,” in *Proc. Opt. Fiber Comm. Conf.*, TuG2, 2004.