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Dispersion tolerant 21.4-Gb/s DQPSK using simplified Gaussian Joint-Symbol MLSE

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Abstract: We experimentally apply different MLSE schemes to 21.4-Gb/s NRZ-DQPSK. Joint-Symbol MLSE (JS-MLSE) of the in-phase and quadrature components after balanced detection gives best performance, even with a simplified Gaussian model for the MLSE channel estimation.

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1. Introduction

Differential quadrature phase modulation (DQPSK), has gained considerable interest in recent years due to some favorable transmission characteristics compared to binary modulation formats such as differential phase shift keying (DPSK) or on-off keying (OOK). Multi-level modulation formats such as DQPSK benefit of a high spectral efficiency combined with a better tolerance against chromatic dispersion (CD) and polarization-mode dispersion, when compared to binary modulation formats at the same bit rate [1]. Combined with balanced detection, DQPSK furthermore has a lower OSNR requirement compared with OOK or Duobinary [1, 2].

Besides multi-level modulation formats, electronic equalization is another possibility to improve the CD tolerance. Maximum likelihood sequence estimation (MLSE) is one of the most promising electronic equalization techniques that has shown to provide excellent performance when combined with OOK [3]. However, when the same MLSE model is applied to DPSK or DQPSK modulation, the improvement in CD tolerance is negligible [4, 5].

As a solution, joint-decision maximum likelihood sequence estimation is proposed [5]. In [6], we experimentally demonstrated the use of joint decision MLSE (JD-MLSE) for DPSK modulation. In this paper, we further extend our investigations to the comparison of different MLSE schemes for DQPSK modulation. We demonstrate that the joint symbol MLSE (JS-MLSE) scheme is the optimal detection method and that it can be implemented with low complexity using a Gaussian channel model.

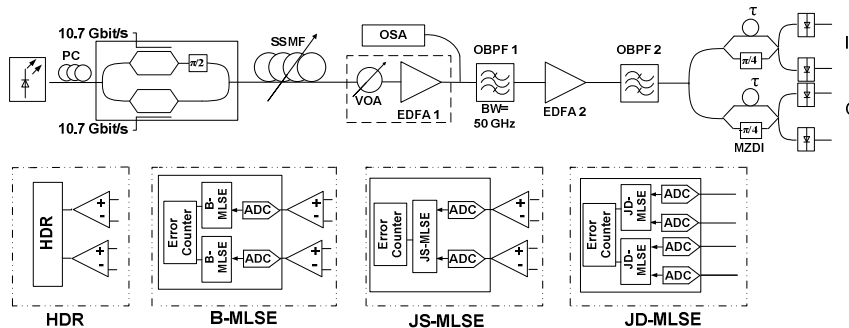


Fig. 1 Experimental setup; OSA: optical spectrum analyzer, ADC: analog to digital converter

2. Experimental setup

Fig. 1 shows the experimental setup of the DQPSK transmitter, as well as the different MLSE schemes used in the receiver. The output of a distributed feed-back (DFB) laser is modulated using an integrated ‘super Mach-Zehnder’ structure for DQPSK modulation. Both inputs are driven with a 10.7-Gb/s PRBS having a length of $2^{15}-1$ bits and a relative delay of 8 bits. Different lengths of standard single mode fiber (SSMF) are used to add increasing amounts of CD in the range of 0 to 3500 ps/nm. The input optical power is set to 0 dBm to avoid nonlinear impairments.

At the receiver, a variable optical attenuator (VOA) along with an Erbium doped fiber amplifier (EDFA) is used to vary the OSNR (measured with 0.1 nm res. bw.) of the received signal. After an optical band pass filter (OBPF) with a 3-dB bandwidth of 50 GHz, the received signal is input to a second EDFA and OBPF to maintain a constant power to the receiver. The output signal is split into two parts by means of a 3-dB splitter, and afterwards input into two Mach-Zehnder delay interferometers (MZDI). The MZDIs are set to a phase difference of $+45^\circ$ and -45°

between the two arms to demodulate the in-phase (I) and quadrature(Q) tributary, respectively. Fig. 1 displays the four applied receiver schemes. First of all, a standard HDR is used as a reference measurement. For the other three schemes, a digital storage oscilloscope (DSO) TDS 6804B with a sampling rate of 20 Gsample/s is used to store the I and Q tributaries, simultaneously. The bandwidth of the DSO is 8 GHz, which is close to the optimum electrical filtering bandwidth. To obtain exactly 2 samples/bit, the signal is re-sampled to 21.4 Gsample/s using a software-based clock recovery based on the digital filter and square timing recovery algorithm [7]. To determine the MLSE performance, data sequences of 10^6 bits have been processed by the MLSE algorithms, in order to achieve an accuracy of 99.99% for a BER of 10^{-3} [8].

In this work we considered three different MLSE equalization schemes, where all of them have a 5-bit quantization resolution, 2 symbol channel memory and use 2 samples/bit. Firstly, we consider the standard balanced-MLSE (B-MLSE), which used two MLSE equalizers applied separately to the balanced outputs of the I and Q tributary. Secondly, we consider a joint symbol MLSE (JS-MLSE) scheme. JS-MLSE uses samples from the I and Q balanced outputs simultaneously to compute the branch's metrics in the Viterbi decoder. For the joint symbol MLSE estimation two separate approaches have been tested: (I) using histograms, based on the formula stated in [5] and (II) by assuming a Gaussian channel model and minimizes the Euclidean distance defined as

$$\min_S \sum_k \sum_{ts} |x_{k,ts} - \text{mean}(x_{ts} | S)|^2, \quad (1)$$

where the complex variable x is defined by $x = x_I + j \cdot x_Q$, with x_I and x_Q are the samples from the I and Q tributary, respectively. And $\text{mean}(x | S)$ is the mean value of x that belongs to state S . The Euclidean distance is minimized for k successive symbols at sampling instants $t_s = [T/4, 3T/4]$. The Gaussian model is just an approximation of the DQPSK channel statistics, but it has been shown in [9] that it is a fair assumption when balanced detection is used. Note that with a 2 symbol channel memory, the B-MLSE has a $2^2=4$ -state Viterbi decoder, whereas the JS-MLSE has a $4^2=16$ -state Viterbi decoder. As a third approach, two joint decision-MLSE (JD-MLSE) equalizers have been applied to the I and Q tributaries separately. JD-MLSE uses samples from the constructive port and destructive ports simultaneously to compute the branch's metrics in the Viterbi decoder.

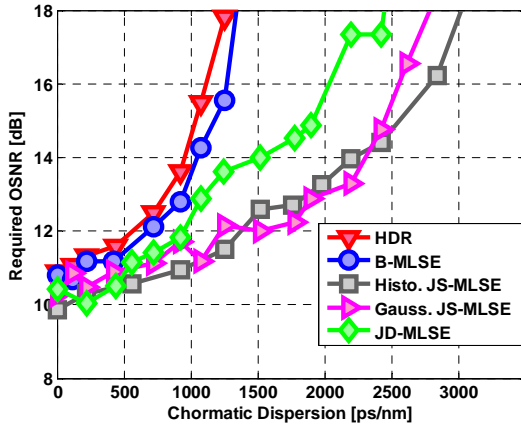


Fig. 2: Required OSNR for BER= 10^{-3} , different receiver types

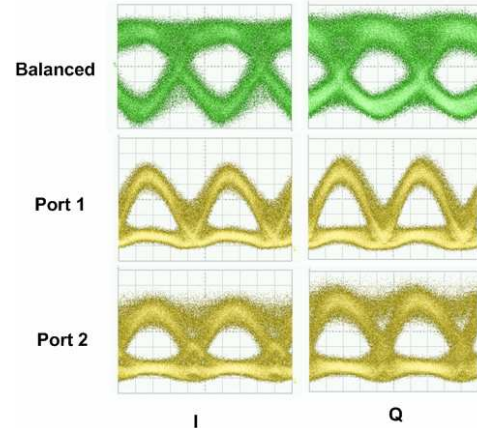


Fig. 3: eye diagrams of the I and Q tributary with DQPSK modulation

3. Experimental results

Fig. 2 reports the measured OSNR penalty curves as function of CD for the different considered MLSE schemes. It is evident that B-MLSE provides almost no advantage when compared to HDR. For DPSK modulation the absence of improvement in CD tolerance with MLSE is explained in [6] by noting the difference in CD tolerance of the constructive and destructive outputs of the MZDI. In the case of DQPSK modulation, the I or Q tributary result from a $\pm 45^\circ$ phase difference between the MZDI arms, so all four outputs of the two MZDIs result from *partial* interference between the signal and its delayed copy. However, the two outputs of the MZDI used for I or Q demodulation are still Duobinary or alternative mark inversion-like, but with some crosstalk from the other tributary due to the *partial* interference. This crosstalk, as shown in Fig. 3, is responsible for the lower OSNR tolerance of DQPSK in comparison to DPSK at the same bit rate [1]. Therefore we conjecture that B-MLSE fails to improve the CD tolerance in DQPSK for the same reason as in DPSK [6].

In the case of JD-MLSE, the system can tolerate 400 ps/nm more CD at a 2-dB OSNR penalty in comparison to HDR. However, when combined to DPSK a more significant performance improvement is obtained for JD-MLSE

[6]. This can be attributed to the fact that in DQPSK the performance of both I and Q tributaries is deteriorated due to the partial interference. Finally, JS-MLSE provides the optimum performance with a CD tolerance of about 2000 ps/nm compared to only 800 ps/nm for the HDR (at 2-dB OSNR penalty). Hence, applying the optimal MLSE scheme to DQPSK results in about a factor of two and half times improvement in CD tolerance. The histogram JS-MLSE and Gaussian JS-MLSE show nearly the same performance. However the complexity to store, update and compute the branch metric is strongly reduced in the case of the Gaussian model. This is possible because only the mean value for each state is stored in the lookup tables and only Euclidean distances are computed in the trellis diagram. In addition, no complex tail extrapolation to the histogram needs to be applied as in the histograms method. Referring to the same suboptimal demodulation problem in DQPSK, JS-MLSE is capable of providing the best performance because it has knowledge of both I and Q simultaneously. Note that a ~ 1 dB improvement in back-to-back OSNR requirement can be observed between HDR and JS-MLSE. In this experiment, the two phase shifters for the I and Q tributary are manually controlled with no feed-back loop. DQPSK is more sensible to phase errors in the MZDI compared to DPSK [10], and the phase drift results therefore in a noticeable penalty. We conjecture that when JS-MLSE equalization is applied the receiver has a higher tolerance against phase mismatches in the MZDI.

In order to verify the experimentally obtained results, simulations for the four detection schemes are conducted. Fig. 4(a) shows the results for the three MLSE schemes compared to HDR. The simulation results are similar to the experimental ones. To underline the excellent match between experimental and simulations results, a detailed comparison between both of them for HDR, JD-MLSE and Gaussian JS-MLSE is shown in Fig. 4 (b). The small mismatch in all plots can be attributed to the instability of the phase shifters in the MZDI's, and to the partial failure of the clock recovery method at high accumulated CD.

4. Conclusion

We experimentally demonstrated a 2000-ps/nm chromatic dispersion tolerance for 21.4-Gb/s DQPSK using Joint-sample MLSE (JS-MLSE). It is furthermore shown that a JS-MLSE can efficiently work even if a simple Gaussian model for MLSE equalizer is utilized.

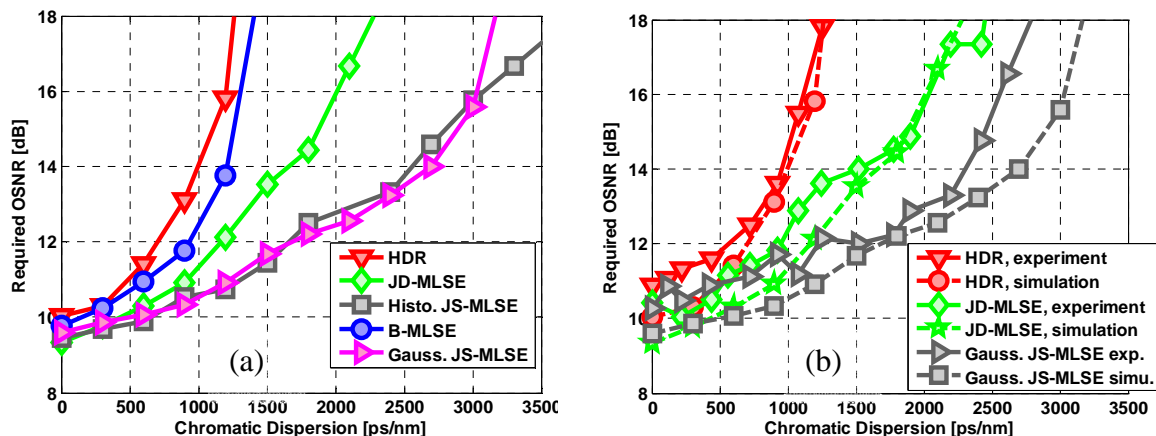


Fig. 4: (a) Simulations results for the different MLSE receivers, (b) comparison between experimental and simulations results

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