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Optical Communication (ECOC 2013), 39th European Conference and Exhibition on

Citation for the published paper:
Eliasson, H. ; Johannisson, P. ; Sunnerud, H. (2013) "Transmitter mask testing for 28 GBaud PM-QPSK". Optical Communication (ECOC 2013), 39th European Conference and Exhibition on

http://dx.doi.org/10.1049/cp.2013.1367

Transmitter Mask Testing for 28 GBaud PM-QPSK

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Abstract *We suggest a method for pass/fail testing of PM-QPSK transmitters. The test is based on mask testing with time-resolved EVM and accepts transmitters where individual impairments cause less than 0.5 dB OSNR penalty. The design of the test is performed by computer simulations followed by experimental verification of some key results.*

Introduction

The new generation of 100G coherent optical communication systems utilizes transmitters with I-Q modulators, modulation formats such as polarization multiplexed quadrature phase-shift keying (PM-QPSK) at 28 GBaud, and coherent receivers with digital signal processing (DSP). As of today, there is no real consensus on how to characterize and test transmitters in such systems. It would thus be of great value to develop efficient pass/fail tests that connect the transmitter characteristics to the actual system performance. One suggested way of characterizing transmitters is in terms of the root mean square (RMS) error vector magnitude (EVM)[1,2]. However as we will show in this paper, the $\mathrm{EVM_{RMS}}$ does not always correlate well with system performance.

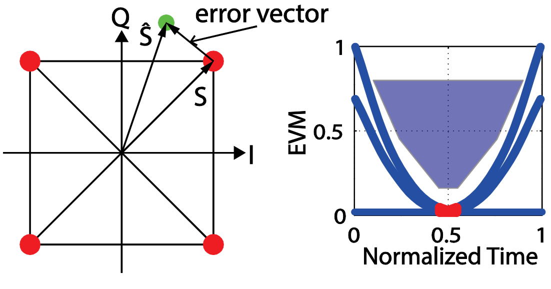
We propose an approach based on mask testing[3] and time-resolved error vector magnitude ($\mathrm{EVM_{TR}}$)[4], which is an extension of the conventional EVM. Different distortions tend to affect the $\mathrm{EVM_{TR}}$ plot in different ways and eventually cause mask violations. In order to determine the mask design we first have to correlate different transmitter distortions to the overall system performance in terms of OSNR penalty. As a limit for the pass/fail test we set the acceptable OSNR penalty to 0.5 dB for each individual distortion in a PM-QPSK system. This method is also scalable to PM-16QAM. The results are based on numerical simulations supported by experimental confirmation of some key results.

Error Vector Magnitude

The error vector magnitude (EVM) is a measure of signal quality. For a measured sample, $\hat{s}$, in the I-Q plane it is calculated as

$$\mathrm{EVM} = \frac{|\hat{s} - s|}{|s|} = \frac{\sqrt{(I\ \mathrm{error})^2 + (Q\ \mathrm{error})^2}}{|s|},$$

where s is the corresponding symbol, see Fig. 1a. The metric used is often the $\mathrm{EVM_{RMS}}$ which is the RMS of the symbol slot center EVM values. By instead including all samples and plotting them with t modulo T_S on the x-axis, where T_S is the symbol duration, and EVM on the y-axis, we generate a $\mathrm{EVM_{TR}}$ plot. This is a plot with time within the symbol slot on the x-axis and the distance in the I-Q plane from the corresponding ideal constellation point on the y-axis, not taking the phase of the error into account. An ideal $\mathrm{EVM_{TR}}$ plot with an example mask is shown in Fig. 1b. For an ideal constellation, EVM is a measure of noise but with a non-ideal constellation it also measures how far the constellation points are from their ideal positions.

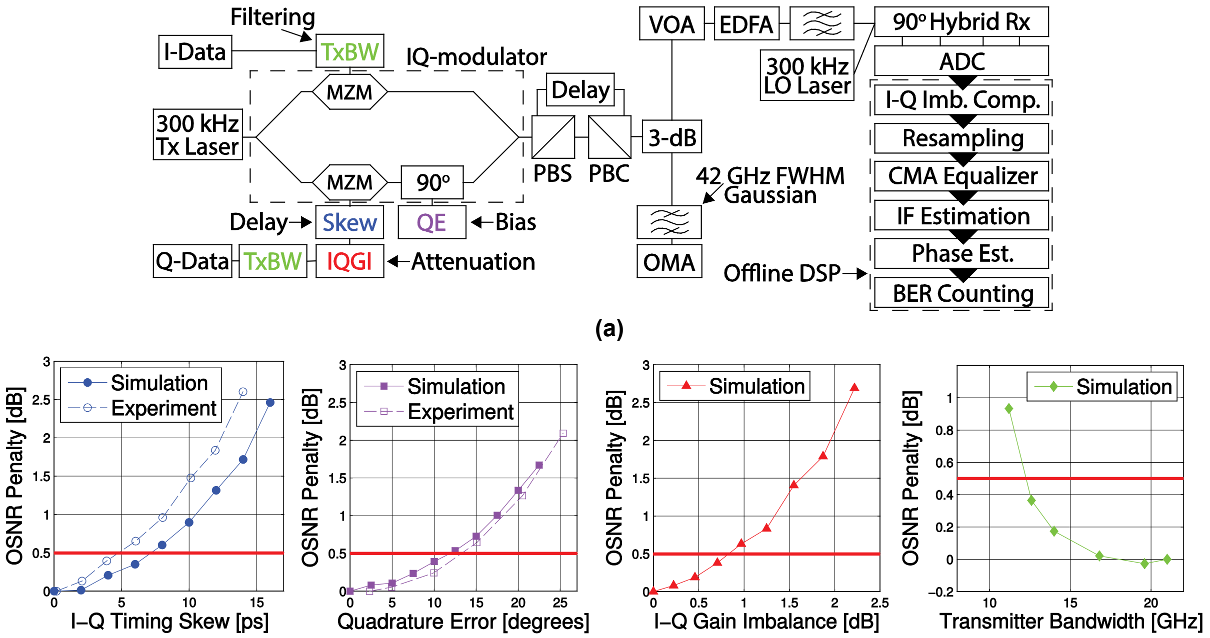


(a) (b)

Fig. 1: **(a)** Definition of the error vector, ŝ is the measured sample and s is the corresponding symbol. **(b)** An $\mathrm{EVM_{TR}}$ plot with an example mask, the red samples are used to calculate $\mathrm{EVM_{RMS}}$.

Simulations and Experiments

We utilize an optical modulation analyzer (OMA) directly at the transmitter, which measures the signal and characterizes it in terms of $\mathrm{EVM_{RMS}}$ and $\mathrm{EVM_{TR}}$. The OMA consists of a coherent receiver together with electrical or optical sampling[4,5], real-time or equivalent-time sampling with a specified (and advantageously standardized) analyzer filtering characteristic[6] (that can be defined by the receiver bandwidth in combination with DSP settings). It is important that the OMA measurements show the real transmitted signal, i.e. not equalized by DSP. In this study we want to correlate the OMA measurements with back-to-back BER measurements with a receiver with conventional



(a)

(b) (c) (d) (e)

Fig. 2: (a) System setup used in simulations and back-to-back experiments. The origin of the studied transmitter impairments is shown in colored text. Also the subsystems of the offline DSP is shown. **(b-e)** OSNR penalties @ BER=10^{-3} for varying amounts of the different impairments **(b)** I-Q timing skew **(c)** quadrature error **(d)** I-Q gain imbalance **(e)** transmitter electrical bandwidth (6th order Bessel characteristic). The horizontal red lines mark the limit of 0.5 dB OSNR penalty.

DSP. The transmitter consisted of an I-Q modulator followed by split-delay-recombine polarization multiplexing, the system setup with the origin of the transmitter impairments is shown in Fig. 2a. Also shown are the constituents of the DSP in the offline processing. The steps of the receiver DSP are I-Q imbalance compensation by Gram-Schmidt orthogonalization followed by resampling to 2 samples/symbol and 17 tap CMA equalization. The phase estimation was done with the Viterbi-Viterbi algorithm. Monte Carlo simulations were performed to find the bit error rate (BER) as a function of the OSNR for different amounts of impairments. The effects are quantified by the OSNR penalty caused by impairments. In this study, four different impairments were investigated: I-Q timing skew (Skew), quadrature error (QE), I-Q gain imbalance (IQGI), and limited transmitter electrical bandwidth (TxBW). Two of these impairments were also investigated experimentally back-to-back: QE and Skew. All of the simulations and experiments were performed with 28 GBaud PM-QPSK. From these simulations, the induced OSNR penalty from different impairments could be extracted. The 42 GHz FWHM Gaussian optical filter before the OMA controls the bandwidth characteristic of the measurements for connecting transmitter impairments to system performance, i.e. $\mathrm{EVM_{RMS}}$ and $\mathrm{EVM_{TR}}$. The OMA used in the experiments was an EXFO PSO-200.

Results

The results from the investigations of OSNR penalties with different transmitter impairments are shown in Fig. 2b-e. From these plots we can identify what level of impairment that causes a 0.5 dB OSNR penalty. The simplest measure of the transmitted signal quality is $\mathrm{EVM_{RMS}}$. To quantify the relation between $\mathrm{EVM_{RMS}}$ and system performance, the OSNR penalty is plotted as a function of induced $\mathrm{EVM_{RMS}}$ for the different impairments in Fig. 3. Note that the $\mathrm{EVM_{RMS}}$ is measured directly after the transmitter, whereas the power penalty requires BER simulations of the whole system including transmitter, channel model, and receiver with DSP. A few aspects should be noted in this figure. First we see that the experimental and simulated curves diverge from different $\mathrm{EVM_{RMS}}$ values. This is due to the measurement SNR of the OMA being different in experiments and simulations and $\mathrm{EVM_{RMS}} \approx 1/\sqrt{\mathrm{SNR}}$ for an ideal constellation[3]. By decreasing the SNR of the OMA measurements, the curves will shift to the right. The second difference between experiments and simulations is that the slopes of the curves are different, which is due to the transmitter bandwidth. In the simulations, the data signals had a Bessel characteristic with a bandwidth of 21 GHz in all cases except when studying the effects of limited transmitter bandwidth. The transmitter bandwidth in the experiments was higher, a pattern generator capable of 32 GBaud was used. By choosing

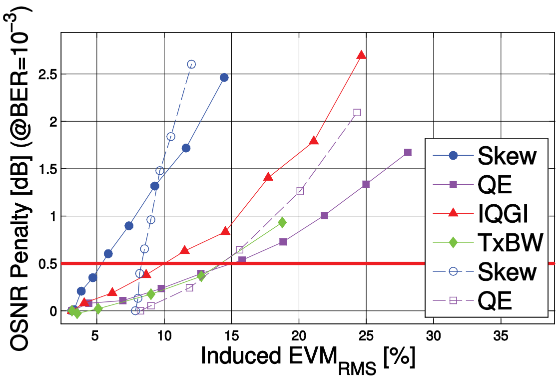
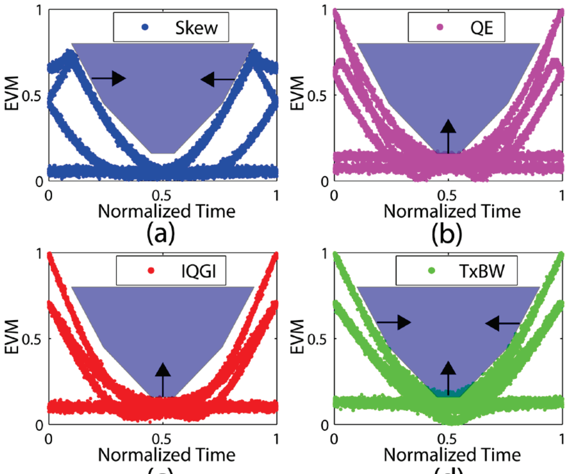


Fig. 3: The OSNR penalty as a function of EVM$_{\mathrm{RMS}}$ induced by different transmitter impairments. Solid lines are simulation results and dashed lines are results from experiments. The 0.5 dB allowed OSNR penalty is shown as a horizontal red line.



(a) (b)

(c) (d)

Fig. 4: Simulated time-resolved EVM plots with 0.5 dB OSNR penalty induced by **(a)** I-Q timing skew **(b)** quadrature error **(c)** I-Q gain imbalance **(d)** I-Q transmitter electrical bandwidth.

simulations parameters carefully it is possible to get good accordance with experiments in Fig. 3.

Another approach to transmitter testing is to utilize time-resolved EVM together with mask testing. To evaluate the feasibility of this approach, EVM$_{\mathrm{TR}}$ plots were generated for the 0.5 dB penalty cases for the different impairments. The amount of impairments needed to cause a 0.5 dB penalty was found by interpolation in Fig. 2b-e. For this approach to be usable, we need to find a mask which catches all impairments at approximately the same OSNR penalty. The EVM$_{\mathrm{TR}}$ plots for the four cases together with example masks are shown in Fig. 4. The arrows in the figure indicate how the samples protrude into the mask for a further increased impairment.

Discussion

The first and simplest of the proposed metrics is EVM$_{\mathrm{RMS}}$. When using this metric in the simulations to set a limit of 0.5 dB allowed power penalty, it is seen in Fig. 3 that the

Tab. 1: The OSNR penalty [dB] limits that will be set by the different tests for the different impairments according to simulations.

	Skew	**QE**	**IQGI**	**TxBW**
EVM$_{\mathrm{RMS}}$	0.5	0.09	0.15	0.03
EVM$_{\mathrm{TR}}$ + mask	0.5	0.5	0.5	0.17

maximum allowable EVM$_{\mathrm{RMS}}$ is 5.4 %. Using this metric will limit the OSNR penalty induced by transmitter bandwidth limitations to 0.03 dB, far from the originally intended 0.5 dB. The case is similar for quadrature error and I-Q gain imbalance. A transmitter test based solely on EVM$_{\mathrm{RMS}}$ would then put much stricter requirements on some impairments compared to others, which is clearly undesirable. The experimental results also confirm this as seen from the dashed curves in Fig. 3. It should be pointed out that the accuracy of the EVM$_{\mathrm{RMS}}$ test could potentially be improved by optimizing the filter characteristic of the OMA.

To achieve stronger correlation to OSNR penalty we instead use EVM$_{\mathrm{TR}}$ together with mask testing. By doing this we can relax the restrictions on EVM$_{\mathrm{RMS}}$ and instead catch the 0.5 dB case induced by I-Q Timing Skew by limiting the protrusion of the EVM$_{\mathrm{TR}}$ plot into the sides of the mask, see Fig. 4a. In this way it is possible to design a transmitter test that would catch all impairments closer to 0.5 dB penalty, see Tab. 1. Impairments caused by bandwidth limitations will start causing mask hits at a lower penalty of 0.17 dB. The reason for this is the capability of the adaptive equalizer to reduce the impact of ISI.

The shape of the proposed example mask is dependent on the choice of parameters in the computer simulations. Two parameters which will strongly influence the design of the mask are transmitter bandwidth and SNR of the measurement at the transmitter side. To design a test, a reference transmitter characteristic and a minimum required SNR of the measurement instrument should be clearly defined.

Conclusions

We have proposed and demonstrated the accuracy of a transmitter mask test based on EVM$_{\mathrm{TR}}$. The precision of the test is higher than a test based on EVM$_{\mathrm{RMS}}$, and the test could prove efficient for testing transmitters in manufacturing.

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