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Optical Performance Monitoring in Amplitude Sampling Receivers

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Abstract *We present a state based OPM estimation, which enables electrical receivers to simultaneously monitor chromatic dispersion and SPM induced non-linearity. The robust estimation is proved on measured NRZ-OOK data showing accurate results.*

Introduction

As optical dense wavelength division multiplex (DWDM) networks become more flexible, optical performance monitoring (OPM) experiences increased importance. Key issues are residual chromatic dispersion (CD), high-power induced non-linearities like self-phase modulation (SPM) and the optical signal-to-noise ratio (OSNR).
Various methods to monitor the signal are known. However, in general they require cost-intensive external devices evaluating the optical spectrum. They also monitor the optical signal, neglecting filters and electric distortions that are crucial for the signal quality at the decision point. In addition, they tap the optical signal reducing the effective receive power. [1][2]
In [3] we have shown a method to estimate the noise power based on the digital receive sequence. This method evaluates electrical amplitude distributions allocated to certain symbol interference patterns, similar to the metrics built in state based equalizers like the MLSE. In the following, we apply the same method to estimate optical signal distortions like CD and non-linearities induced by high launch power (P_{char}).
Within this work we present a method to simultaneously estimate the parameters of CD and P_{char} of a single channel. By the allocation of states to certain bit patterns we can separate intra-channel distortions like CD and SPM from noisy statistical disturbances. The noise power estimation described in [3] is prerequisite to this method. We verify our results by simulations and measurements.

Elimination of Noise Component

During transmission over the optical fiber, the signal is exposed to deterministic linear distortions like CD and non-linear distortions like SPM. Therefore, every bit pattern will lead to a distinct interference pattern at the receiver, which is superimposed by statistic noisy distortions like amplified spontaneous emission (ASE), induced by optical amplifiers. We assume the optical noise components to be statistically independent and Gaussian. Their individual variances add up to the total variance, which defines the total noise power $4\sigma^2$.
After A/D-conversion we sort the received samples r_i by 2^{L+1} states z with the aid of the digital decisions d_i, where every state refers to its according bit pattern. The number of states depends on the number of distinct interference patterns or the channel memory length L respectively. For given statistics and taking into account filtering effects, we know

$$E(r_z) = S^2_{z,\,filt} + 4\,\sigma^2_{filt}$$

By estimating the total signal power $4\sigma^2_{filt}$ (see [3]), we can compute the noiseless representation of the received probe signal $S^2_{z,filt}$.

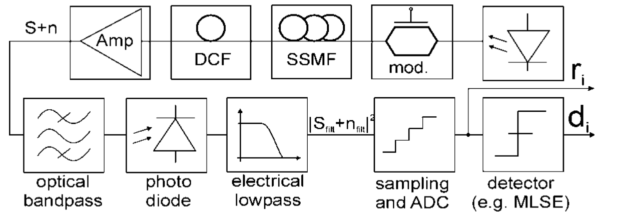

Figure 1: Schematic transmission system

Comparison with Reference

We now compare the probe $S^2_{z,filt}$ with a set of references $S^2_{z,ref}$ at known parameters, obtained from simulations. Reference simulations were all single channel and single span for all combinations of residual chromatic dispersion CD=[0,200,400,…,3600]ps/nm and launch power P_{char}=[0,2,…,16]dBm.
Installed fiber transmission lines usually consist of multiple spans. We define the characteristic power P_{char}, which substitutes accumulated non-linearities due to re-amplification in each span for one equivalent launch power P_{char} (without further re-amplification) leading to the same degree of non-linear distortions. This makes it easy to simulate according references even for probe signals from multi-span transmission lines.
The reference simulations include the receiver with all filters and an ADC. The more accurate the reference model, the more precise is our parameter estimation. According to the state model applied to the received data, we sort the reference sequence by its bit patterns. As the reference should only describe deterministic distortions, we run the simulations without noise. Thus, a noise component elimination is obsolete.
Finally, we compare the pool of reference simulations with the noiseless representation obtained from the received probe signal. The best matching reference $R_{ref,min}$ indicated by the lowest error power between reference and received signal, leads us to the according parameters for CD and P_{char}.

$$R_{ref,\,min} = \min_{ref} \left\{ \sum_{z=1}^{N} \left(S^2_{z,\,ref} - S^2_{z,\,filt} \right)^2 \right\}, \quad N = 2^{L+1}$$

Results from Simulation and Experiment

We evaluate the performance of our method by Monte Carlo simulations and measured data. Measurements were carried out for 10Gbit/s NRZ-OOK (PRBS 2^{15}-1) with variations in launch power, chromatic dispersion (adjusted by according transmission line) and OSNR. The parameter P_{lp} of the probes refers to the actual launch power. After a 50GHz optical band-pass filtering and a photo diode, a sampling oscilloscope (2 samples/bit, 8 bit ADC, 8GHz bandwidth) saved $2\cdot10^6$ samples of the probe signal. Clock recovery was realized by a re-sampling routine. Monte Carlo simulations were carried out under similar conditions.

For the state model, we sorted the probe signal and the reference by 2^5 states (L=4). In a first step, the noise power and the OSNR (0.1nm) were estimated. In the experiment the OSNR was measured by the aid of an OSA. Table 1 compares measured and estimated OSNR. The estimated OSNR shows accurate results independently from deterministic signal distortions, which is in excellent agreement with simulations carried out in [3].

Condition	Measured	Estimated
P_{lp}=0dBm, CD=1250ps/nm	10.0 dB	10.3 dB
P_{lp}=0dBm, CD=1250ps/nm	13.0 dB	13.1 dB
P_{lp}=0dBm, CD=3050ps/nm	14.3 dB	14.0 dB
P_{lp}=15dBm, CD=3050ps/nm	15.0 dB	14.8 dB

Table 1: Comparison of measured and estimated OSNR

After the noise power correction, the probe signal $S^2_{z,filt}$ sorted by states was compared with all references. Fig. 2 and Fig. 3 show the normalized error power R_{ref} for two exemplary probes with [P_{lp}=0dBm, CD=1250ps/nm] and [P_{lp}=15dBm, CD=3050ps/nm]. Both figures indicate that the minimum of R_{ref} from measured data (white arrow on black grid) determines the given parameters of the probe signal. Simulations under same conditions show equally accurate results (black circle on gray faced grid). Taking into account that the probe with CD=3050ps/nm was

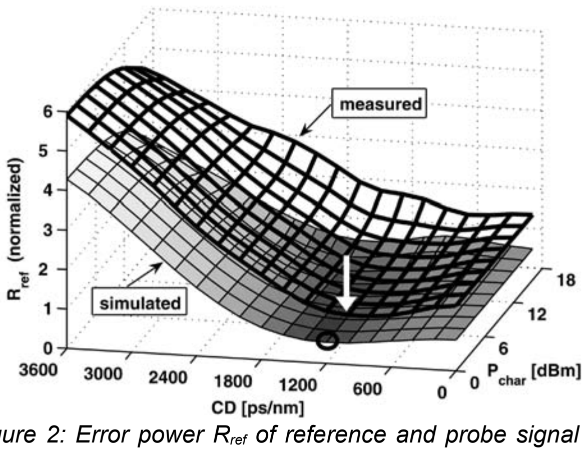

Figure 2: Error power R_{ref} of reference and probe signal for condition [P_{lp}=0dBm, CD=1250ps/nm]

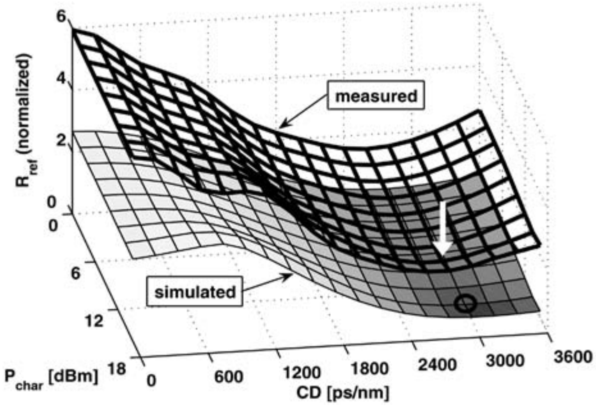

Figure 3: Error power R_{ref} of reference and probe signal for condition [P_{lp}=15dBm, CD=3050ps/nm]

multi-span, the estimated P_{char}=16dB considers re-amplification during transmission and actually tends towards a slight underestimation.

Conclusions

We have shown a method for a simultaneous estimation of deterministic non-linear signal distortions caused by the launch power and deterministic linear distortions like residual chromatic dispersion in amplitude sampling receivers with ADC. The state based estimation employs the sampled receive sequence and the according digital decisions from a decision unit. Furthermore, a reference signal at known parameters is utilized.

In case of an appropriate state model with sufficient memory length, the comparison of the reference and the probe leads to an accurate estimation of the mentioned parameters. The estimation is independent from statistic signal distortions and delivers an OSNR estimation as a by-product.

Prerequisite to the estimation is a parametric statistic description of the receive signal dependent on the noise process. An evaluation with measured data proves the use of an appropriate model and predicts equally good results for all OOK modulation formats.

The results show a satisfactory indication for CD with a clear minimum. Supplementary methods to support the indication of P_{char} with its lower gradient are currently under investigation.

No additional measuring device needs to be applied to the receiver, which makes this method a cost effective and easy to implement alternative to customary OPM.

Acknowledgement

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References

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