Estimation Accuracy of Polarization State from Coherent Receivers for Sensing Applications

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***Abstract*—We experimentally investigate on the intrinsic accuracy in fiber State of Polarization estimation from the DSP of commercial coherent tranceivers, in terms of angular uncertainty on the Poincaré's sphere vs. received OSNRs, for sensing applications. We then demonstrate how using a moving average enhances accuracy.**

***Index Terms*—State of Polarization, Optical Fiber Sensing**

I. Introduction

The evolution of the State of Polarization (SOP) at the output of a fiber link is often proposed as a parameter for sensing mechanical stresses induced on optical fibers. Several applications, including submarine [1] and metropolitan [2] fiber links, or even fiber-based mountain engineering [3] alarm systems, are indeed exploiting SOP monitoring to detect events occurring in the surrounding environment, usually in order to generate alarms after some anomalies are sensed. The working principle is based on fiber birefringence, which changes when external mechanical stresses are induced on the fiber, consequently changing the received SOP, that can thus be exploited to identify anomalous vibrational events. A large part of today's fiber networks use high-bitrate coherent transceivers which, at the receiver side (RX), need to internally estimate the received signal SOP to decode it [4]. Therefore, the SOP information is in principle already available, potentially allowing for early warning of unsafe conditions which could compromise the network health status (fiber cuts, for example).

In this work, we focus on estimating the accuracy that can be obtained from a commercial coherent card on the extracted SOP, for different Optical Signal to Noise Ratio (OSNR) values. A set of numerical simulations is also presented in order to check the consistency of results. The paper is organized as follows: in Section II, the simulation and experimental setups are described, while in Section III the obtained results are presented and discussed.

II. Simulation and Experimental Setup

We started by studying through numerical simulation the intrinsic accuracy that we can obtain on SOP extraction from optical transceiver digital signal processing (DSP). Our final target here is to evaluate the standard deviation of the estimated SOP, assuming that fiber birefringence is constant and the system is working at a given OSNR level. We simulated a DP-QPSK transmission at 34.7 GBaud (shaped with a square-root raised-cosine filter with roll-off $\rho = 0.2$) in a back-to-back configuration affected only by ASE noise. Different OSNR values at the RX side were considered, i.e., from $6\,\mathrm{dB}$ up to $12\,\mathrm{dB}$, considering a noise bandwidth equal to the symbol rate. To perform SOP extraction, a simulated standard coherent RX DSP chain operating at a 2 samples/symbol was employed. Specifically, the SOP was estimated by leveraging the tap coefficients obtained from an LMS-based 2×2 adaptive equalizer, with $N_{tap} = 16$ taps. The relation between the input signal $\boldsymbol{x}[n]$ and the output signal $\boldsymbol{y}[n]$ at this stage is $\boldsymbol{y}[n] = \boldsymbol{w}^{(n)}\boldsymbol{x}[n]$, where the equalization matrix at discrete-time index n is defined as

$$\boldsymbol{w}^{(n)} = \begin{bmatrix} \boldsymbol{w}_{11}^{(n)} & \boldsymbol{w}_{12}^{(n)} \\ \boldsymbol{w}_{21}^{(n)} & \boldsymbol{w}_{22}^{(n)} \end{bmatrix} \tag{1}$$

and each element is a $N_{tap} \times 1$ vector. The DC components of each column of $\boldsymbol{w}^{(n)}$ are Jones vectors from which the SOP can be estimated as a vector $\vec{S}_n$ evolving over the discrete time. In our simulations, we extracted the equalizer tap coefficients every $200\,\mathrm{ns}$ while processing a sequence of 20 million samples, leading to a SOP sampling frequency of $f_s = 5$ Msamples/s. We then repeated the estimation at different received OSNRs.

The same transmission scenario was also studied experimentally using a commercial coherent transceiver in a back-to-back configuration with constant birefringence. ASE noise loading was used to generate different OSNRs and, consequently, different BER values in the range from 10^{-2} to error free condition, corresponding to the OSNR values from $6\,\mathrm{dB}$ up to $18\,\mathrm{dB}$ and measured over the same noise bandwidth as in the numerical simulation. The transceiver extracts SOP samples at around 20 samples/s.

III. Results and Discussion

The DSP-estimated SOP values $\vec{S}_n$ have been processed in the same manner in both simulation and experimental scenarios, as described in the previous section. The algorithm used to determine the amount of noise in each case consists

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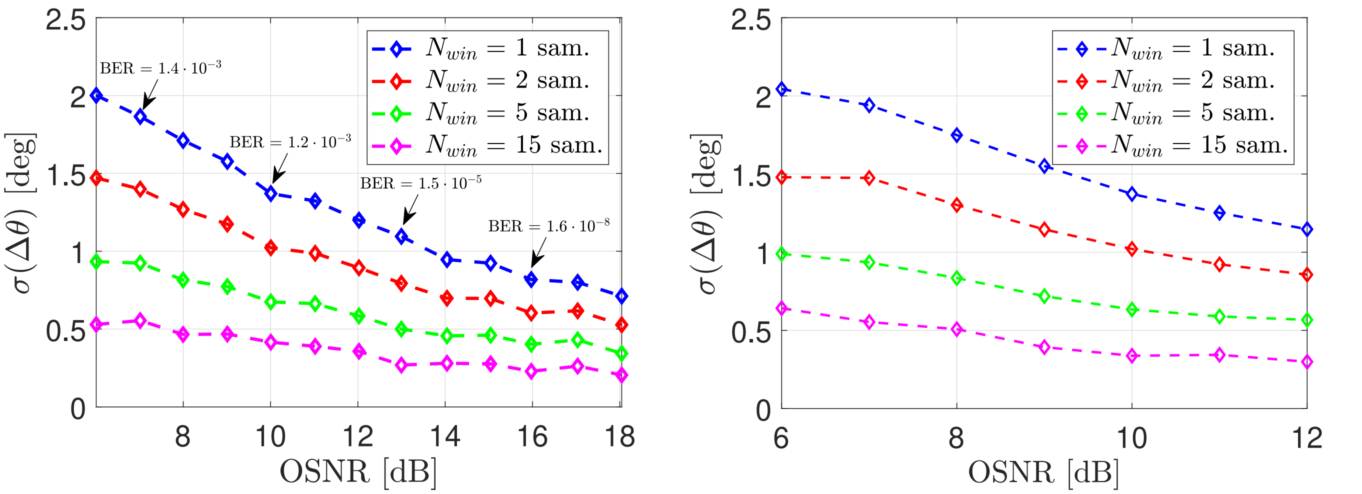

(a) (b)

Fig. 1: Angular distances standard deviations computed at different OSNRs and N_{win} values in (a) experimental and (b) numerical simulation scenarios.

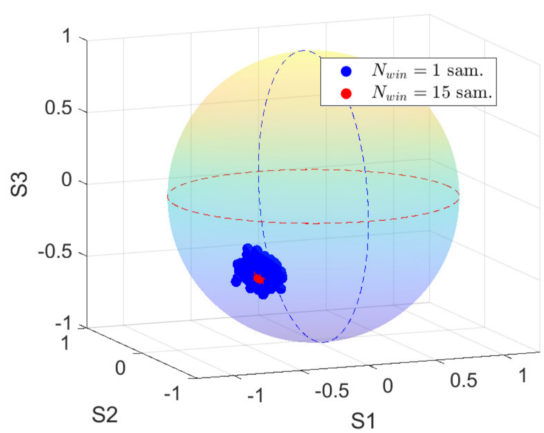

Fig. 2: Experimental SOP on the Poincaré sphere for OSNR $=$ 6 dB and two different values of N_{win}.

in i) computing the moving average $\vec{S}_{mov}$ of the Stokes parameters $\vec{S}_n$, using different window lengths N_{win} (we will report in the following also the interesting case N_{win}=1 sample corresponding to the "raw" SOP values obtained from the RX DSP); ii) evaluating the angular distance $\Delta\theta$ between $\vec{S}_{mov}$ and a long-term average $\vec{S}_{avg}$; iii) computing the resulting standard deviation $\sigma(\Delta\theta)$, which we use as the main metric to determine the resulting SOP estimation accuracy at different OSNRs (and BERs) values, as reported in Fig. 1. Intuitively, $\sigma(\Delta\theta)$ indicates how large is the angular aperture of the resulting SOP "cloud" (shown in Fig. 2). In Fig. 1, the $N_{\text{win}} = 1$ case (blue curve), corresponds to the SOP estimate $\vec{S}_n$ coming from the DSP without any further averaging. In this case, we observe that for the typical BER threshold values in modern coherent systems (i.e. for BER$< 10^{-3}$ and OSNR$\simeq 6dB$ for PM-QPSK) the $\sigma(\Delta\theta)$ is around 2 degrees, thus generating a quite "noisy" SOP estimation (as shown in Fig. 2) since, for instance, the resulting $\pm 3\sigma$ cloud of SOP points would cover a range of about 12 degrees peak-to-peak. Consequently, in a fiber sensing scenario, the SOP based approach would be able to detect vibration-induced variations only if they create significantly larger SOP angular variation on the Poincaré's sphere, typically in the ten degrees range (for a comparison, see for instance [1], Fig. 2). In order to reduce this angular noise on $\vec{S}_n$, we thus propose a further processing through a moving average on N_{win} $\vec{S}_n$ samples since, as shown in Fig. 1, the resulting $\sigma(\Delta\theta)$ can be greatly decreased. For instance, for $N_{\text{win}} = 15$ samples we have that $\sigma(\Delta\theta)$ is reduced to 0.5 degrees or less on all the OSNR range that we tested.

Finally, we observe that the results reported in Fig. 1 for the experiments (a) and the simulations (b) are quite consistent, demonstrating that the $\sigma(\Delta\theta)$ values we experimentally obtained using the commercial coherent transceiver available in our laboratory are very close to the somehow more "ideal" conditions used in the simulations. We can thus infer that the results shown in Fig. 1 are the "intrinsic" SOP accuracy that can be obtained for a given OSNR levels at the receiver input, and that they are quite independent on the actual RX DSP implementation.

References

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