WDM MONITORING USING BLIND SIGNAL SEPARATION BASED ON HIGHER-ORDER STATISTICS

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Abstract: WDM transmission performance in optical networks can be monitored efficiently by first separating the electronic baseband channel mixtures that result after direct photodetection. We carry out this process through a blind signal separation (BSS) method based on higher-order statistics (HOS). Relative to a previously proposed method for WDM-channel extraction, the HOS-based procedure shows a reduced complexity with the number of channels, no stability problems, and an improved performance, as demonstrated by computer experiments.

1. INTRODUCTION

High data-rate WDM optical transmission network management requires monitoring a variety of channel performance parameters such as wavelength, power, SNR, etc., without compromising transparency. In a bid to reduce the number of expensive optical components, cost-effective monitoring solutions aim to perform most of the processing electronically. The (spatial) independence between the transmitted WDM channels has been exploited in recent works [1, 2, 3]. Information about transmission rate and power is shown to be contained within the correlation peak between the outputs of a dispersive delay line and a tunable RF delay [1]. In [2], parameterization of the probability density function (pdf) of the transmitted signals allows the estimation of the optical signal and noise powers. However, the number of channels that can be handled by this method is rather limited.

The technique presented in [3] improves on the above two methods in that the complete channel waveforms are reconstructed, from which performance parameters can be measured. Along the lines of [2], wavelength dependent attenuators (WDAs) are employed to obtain additional observations of the WDM signal, each observation being considered as a mixture of the constituent channels. Because the independent channels contribute with different strengths to each observation, sufficient spatial diversity is available for a suitable blind signal separation (BSS) method to recover the original transmitted waveforms. The symmetric adaptive decorrelation (SAD) technique of [4] was adopted as a separation device. This particular technique, however, presents a number of deficiencies. On the one hand, its complexity is of order $\mathrm{O}(N!)$ for an N-channel WDM transmission. On the other hand, the method has inherent stability and convergence difficulties — including spurious non-separating solutions [4] — which may hinder the monitoring process in practical cases. More specifically, the method is based on second-order statistics, which poses identifiability problems in the separation of spectrally white sources.

The present contribution aims to overcome these shortcomings by applying BSS based on higher-order statistics (HOS) to WDM monitoring.

2. WDM SIGNAL EXTRACTION USING HOS

Let $y_i(k)$, $1 \leqslant i \leqslant M$, denote the M observed photocurrents of the N-channel WDM signal ($M \geqslant N$), where k represents a discrete time index. Accordingly, let $s_i(k)$, $1 \leqslant i \leqslant N$, represent the channel (or source) baseband data, multiplexed within the WDM signal and thus not directly observable. Direct photodetection of the WDM transmission loses all wavelength information. As a result, neglecting additive noise terms, the detected signal appears as a weighted linear combination of the baseband data:

$$y_i(k) = \sum_{j=1}^{N} h_{ij} s_j(k), \qquad 1 \leqslant i \leqslant M. \tag{1}$$

Coefficients h_{ij} represent the WDA effects over channel j in observed photocurrent i. Hence, the observation vector $\mathbf{y}(k) = [y_1(k), \ldots, y_M(k)]^{\mathrm{T}}$ (symbol $^{\mathrm{T}}$ denoting the transpose operator) and the channel vector $\mathbf{s}(k) = [s_1(k), \ldots, s_N(k)]^{\mathrm{T}}$ fulfil at any time instant the linear model:

$$\mathbf{y} = \mathbf{H}\mathbf{s}, \tag{2}$$

where the elements of the $(M \times N)$ mixing matrix $\mathbf{H}$ are given by $(\mathbf{H})_{ij} = h_{ij}$. Eqn. (2) corresponds to the BSS model of instantaneous linear mixtures [5]. Separation is generally achievable under two main assumptions: (A1) the source signals are mutually statistically independent and (A2) the mixing matrix is full column rank; both entities are otherwise unknown in model (2). Note that assumption A2 guarantees considerable freedom in the selection of the WDA attenuation patterns.

As in [3], we aim to perform the monitoring by first extracting the channel waveforms from the photocurrent observations, but here we resort to the BSS method of [6], which is based on HOS. The method operates in two steps

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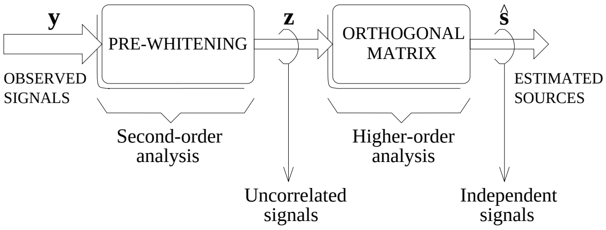

Fig. 1. Two-step approach to BSS.

(Fig. 1). The first step is called (spatial) pre-whitening, and seeks to normalize and decorrelate the observations by means of conventional second-order statistical analysis (principal component analysis). This operation results in a signal vector $\mathbf{z}$ which is linked to the channel components through an unknown $(N \times N)$ orthogonal transformation $\mathbf{Q}$:

$$\mathbf{z} = \mathbf{Q}\mathbf{s}. \tag{3}$$

The second step finds an estimate $\hat{\mathbf{Q}}$ of $\mathbf{Q}$, from which the channel signals can be reconstructed as $\hat{\mathbf{s}} = \hat{\mathbf{Q}}^{\mathrm{T}}\mathbf{z}$. In the two-signal case ($N = 2$), matrix $\mathbf{Q}$ becomes a Givens rotation defined by a single real-valued parameter θ:

$$\mathbf{Q} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}. \tag{4}$$

The estimation of θ can be accomplished in closed form. Several analytic expressions exist, but the estimator of [6] presents the advantage that it approximates the maximum-likelihood solution when the source signals have the same statistics. This is the case in the WDM monitoring problem, where all transmitted channels are composed of bit streams, possibly contaminated by noise and interference. This estimator expression reads:

$$\hat{\theta} = \frac{1}{4}\angle\big(\xi \cdot \mathrm{sign}(\gamma)\big), \tag{5}$$

with

$$\xi = (\kappa^z_{40} - 6\kappa^z_{22} + \kappa^z_{04}) + j4(\kappa^z_{31} - \kappa^z_{13}) \tag{6}$$
$$\gamma = \kappa^z_{40} + 2\kappa^z_{22} + \kappa^z_{04} \tag{7}$$

where $\kappa^z_{mn} = \mathrm{Cum}_{mn}[z_1,\, z_2]$ represents the $(m+n)$th-order cumulant of the whitened components, and $j^2 = -1$ is the imaginary unit. Notation "$\angle a$" denotes the principal value of the argument of complex-valued quantity a.

To achieve the source estimation for $N > 2$ channels, the closed-form expression is applied over each pair of whitened signals until convergence is reached. Since there exist $N(N-1)/2$ signal pairs and usually around $(1 + \sqrt{N})$ sweeps over the signal pairs are necessary for convergence, the method's complexity with respect to the number of channels is of order $\mathrm{O}(N^{5/2})$. This value is lower than the $\mathrm{O}(N!)$ of [3], specially for a large number of channels.

In addition, this HOS-based method ignores any temporal structure in the processed signals, so that spectrally white photocurrents could also be separated. If the data symbols transmitted by a single user are uncorrelated, such spectrally white photocurrents could arise when sampling the photodectector output at rates as low as the symbol rate. Low sampling frequencies enable to reduce the speed requirements, and hence the cost, of the DSP used for the WDM channel extraction and monitoring without sacrificing performance.

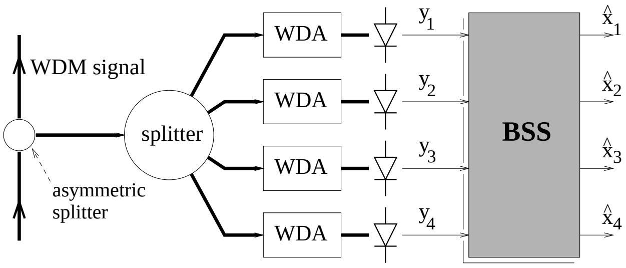

Fig. 2. Experimental set-up. Optical and electrical paths are represented, respectively, by thick and thin lines.

3. SIMULATION RESULTS

Illustrative experiments are carried out with the aid of the VPI™ simulation software, with the blind separation part implemented in MATLAB™ code. The set-up is analogous to that described in [3], and is outlined in Fig. 2. Four data channels at wavelengths 1551.2, 1552.8, 1554.4 and 1556.0 nm (i.e., 1.6-nm separation), respectively, compose the WDM signal. The laser sources are modulated via Mach-Zehnder modulators by NRZ data from a pseudorandom binary sequence at 10-Gb/s bit rate. A small fraction of the transmitted WDM signal is diverted from the optical link into the monitoring system through an asymmetric splitter. This WDM signal fraction is further split in four branches. Each branch is equipped with a WDA and a photodetector, which generate the corresponding observed photocurrents shown in Fig. 3. These electronic signals are then processed by the HOS-based BSS method described in the previous section. A block of 256 bits (32768 samples) was processed, of which only a short portion is displayed in the figures for the sake of clarity. The normalized (i.e., zero-mean, unit-power) estimated channel data are shown in the solid lines of Fig. 4. Observe the accuracy with which the estimated sequences approximate the actual transmitted data (dotted lines).

The proposed method is also capable of monitoring a higher number of channels. Fig. 5 shows the separation results for an 8-channel WDM transmission, under the above general conditions.[1]

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[1] The eight photocurrents observed in this experiment are not shown here, but are analogous to those in Fig. 3.

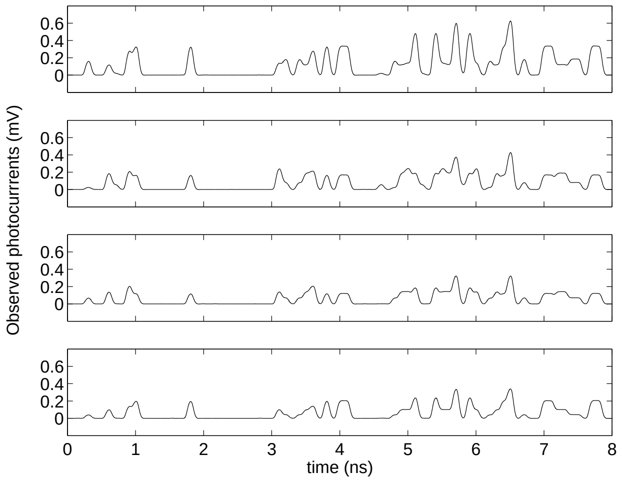

Fig. 3. Observed photocurrents in the 4-channel experiment.

4. CONCLUSIONS

WDM monitoring in optical networks can be carried out after the separation in the electronic domain of the individual baseband channels, from which suitable performance parameters can then be measured. We have applied a blind signal separation method based on higher-order statistics. The method provides an approximate optimal solution (in the maximum-likelihood sense) for the case of two channels, and entails a computational cost of $O(N^{5/2}L)$ when processing L-sample blocks of an N-channel WDM signal. For the signal distributions typically occurring in WDM monitoring, the method presents no undesired solutions. In addition, the case of spectrally white channels can also be handled, thus allowing beneficial reductions in the rates at which the photocurrents are sampled. Although the suggested procedure operates on signal blocks (batch processing), fast adaptive implementations can easily be designed as well [7].

Remark that the blind separation approach is not only useful in monitoring, but is effectively demultiplexing the WDM signal. This feature envisages an enormous potential for BSS in optical transmission systems. The use of a WDA and a photodetector per observed branch in the proposed architecture achieves in a simple fashion the necessary signal synchronism at the separator's input, but it would obviously be an expensive configuration in practice, with WDM signals typically composed of a large number of channels. This configuration was used here for illustration purposes only. Promising cost-effective synchronization solutions are currently under investigation, and will be presented in further works. Also, the impact of noise on the BSS-based monitoring system is being addressed.

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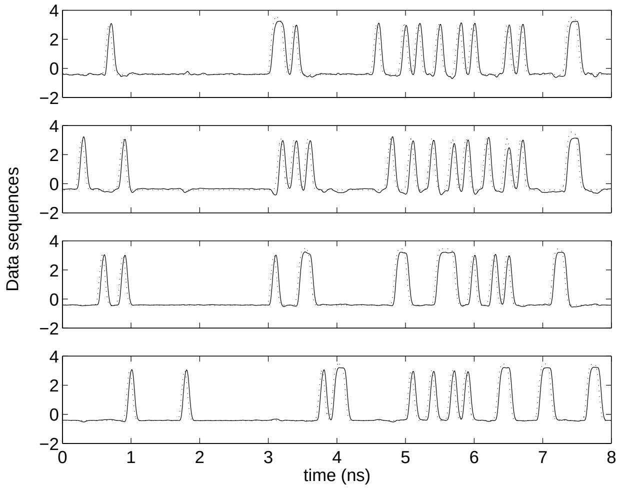

Fig. 4. Normalized data sequences in the 4-channel experiment. Dotted lines: transmitted data. Solid lines: channel data estimated by the HOS-based BSS method from the photocurrents shown in Fig. 3.

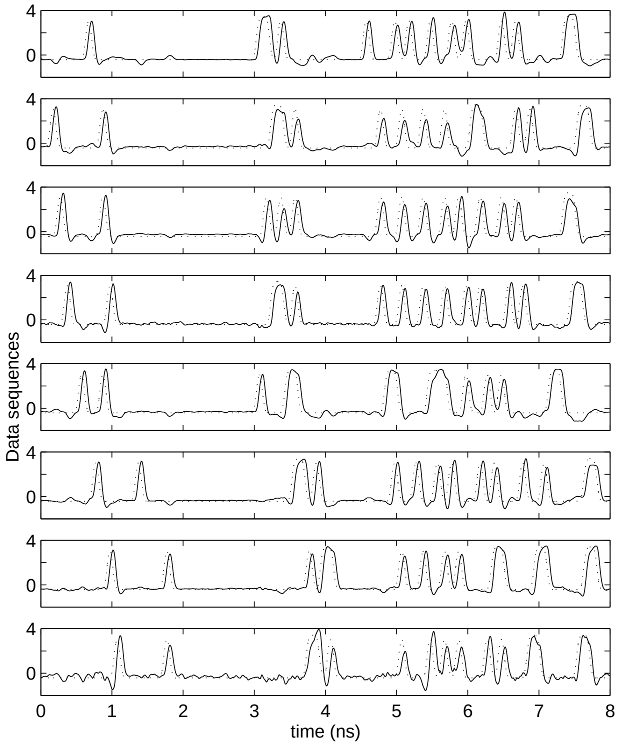

Fig. 5. Normalized data sequences in the 8-channel experiment. Dotted lines: transmitted data. Solid lines: channel data estimated by the HOS-based BSS method from the observed photocurrents.

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