WDM monitoring through blind signal separation based on higher-order statistics

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Abstract: WDM transmission performance can be monitored efficiently by blind signal separation methods based on higher-order statistics for WDM-channel extraction. Relative to a recent method, our procedure has reduced complexity, no stability problems, and better performance.

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1 Introduction

High data-rate WDM optical transmission network management requires monitoring a variety of channel performance parameters such as wavelength, power, SNR, etc. Cost-effective monitoring solutions aim to perform most of the processing electronically, in a bid to reduce the number of expensive optical components. The (spatial) independence between the transmitted WDM channels has been exploited in recent works [1, 2, 3]. The technique presented in [3] is able to reconstruct the complete channel waveforms, from which performance parameters can then be measured. 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. Its complexity is of order $O(N!)$ for an N-channel WDM transmission, and it has inherent stability and convergence difficulties — including spurious non-separating solutions [4] — which may hinder the monitoring process in practical cases. Also, the method is based on second-order statistics, which causes identifiability problems in the separation of spectrally white sources.

2 WDM signal extraction using BSS based on higher-order statistics

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:

$$\mathbf{y} = \mathbf{Hs}, \tag{2}$$

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

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full column rank; both entities are otherwise unknown in model (2). 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 subsequently we propose to apply BSS based on higher-order statistics (HOS). One of such HOS-based BSS methods is presented in [6], and operates in two steps. 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 $\mathbf{Q}$, that is, $\mathbf{z} = \mathbf{Qs}$. 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, with the shape $\mathbf{Q} = \left[\begin{smallmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{smallmatrix}\right]$. 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. In principle, this is the case in the WDM monitoring problem, where all transmitted channels are composed of bit streams, possibly contaminated by noise and interference. The estimator expression reads:

$$\hat{\theta} = \frac{1}{4}\angle\big(\xi \cdot \mathrm{sign}(\gamma)\big), \qquad \text{with } \left\{ \begin{array}{l} \xi = (\kappa^z_{40} - 6\kappa^z_{22} + \kappa^z_{04}) + j4(\kappa^z_{31} - \kappa^z_{13}) \\ \gamma = \kappa^z_{40} + 2\kappa^z_{22} + \kappa^z_{04} \end{array} \right. \tag{3}$$

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 of the $N(N-1)/2$ whitened-signal pairs until convergence is reached. Usually, around $(1 + \sqrt{N})$ sweeps over all signal pairs are necessary for convergence, yielding a complexity with respect to the number of channels 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 necessarily sacrificing performance.

3 Simulation results

Illustrative experiments are carried out on the VPI™ simulation software, with the blind separation part implemented in MATLAB™. The set-up is analogous to that described in [3], and is outlined in Fig. 1. 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 of length $2^7 - 1$ 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. 2(a). 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. 2(b). The estimated sequences approximate very accurately the actual transmitted data (dotted lines). The proposed method is also capable of monitoring a higher number of channels.

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

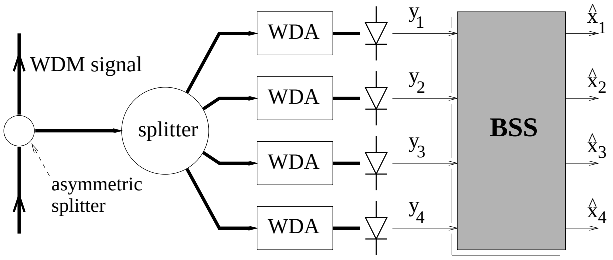
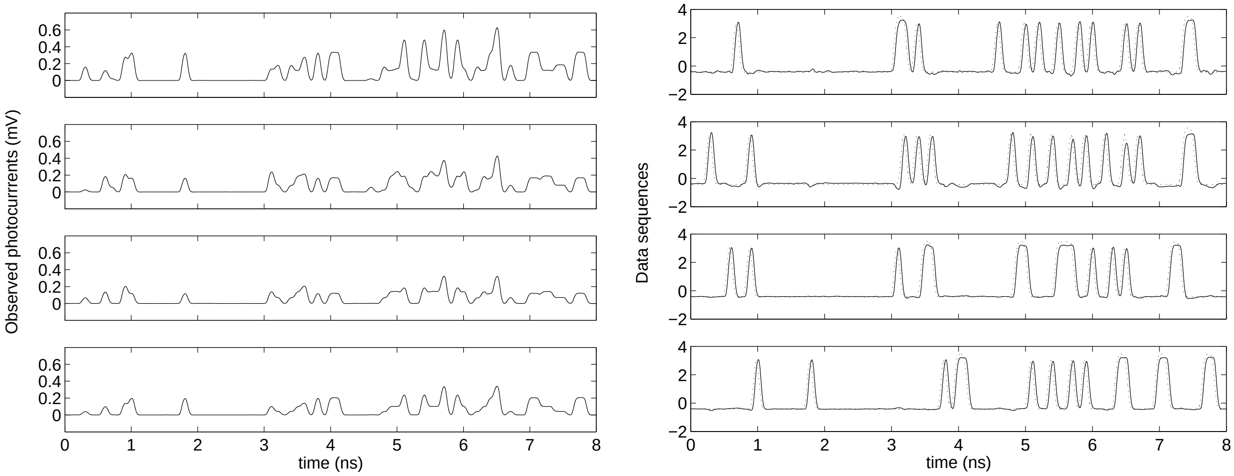


Fig. 1. Simulation set-up. Thick and thin lines represent optical and electrical paths, respectively.



(a) (b)

Fig. 2. Signals from the simulation experiment. (a) Observed photocurrents. (b) Normalized data sequences; dotted lines: transmitted data; solid lines: estimated channel data from the photocurrents shown in (a).

have proposed to apply blind signal separation based on higher-order statistics. The specific BSS method considered provides an approximate optimal solution (in the maximum-likelihood sense) for the case of two channels, and has 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].

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