APPLICATION OF BLIND SIGNAL SEPARATION TO WDM OPTICAL TRANSMISSION MONITORING

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ABSTRACT

A cost-effective technique to monitor the performance of wavelength-division-multiplexed (WDM) channels in optical networks is presented. This process uses a blind signal separation (BSS) method based on higher-order-statistics (HOS), and an optical-loop structure. The technique is illustratively demonstrated for four and eight 10-Gb/s channels spaced by 3.2-nm and 1.6-nm respectively. Relative to previously proposed methods for WDM-channel extraction, the HOS-based optical-loop procedure shows a reduced complexity, a better cost-efficiency, and an improved performance.

Keywords: blind signal seperation, higher-order statistics, optical networks, monitoring, wavelength-division multiplexing.

1 INTRODUCTION

For the proper management of WDM transmission systems and particularly optical networks that use optical add-drop multiplexing (OADM) and optical cross-connect (OXC), it is essential to monitor a variety of channel performance parameters such as wavelength, power, SNR, etc., without compromising transparency. Traditional methods for WDM channel monitoring use tunable optical filters [1], phased array demultiplexers [2], or photo-diode arrays with diffraction gratings [3]. The disadvantage of these methods is that complex (expensive) optical components are involved. In a bid to reduce complexity, cost-effective monitoring solutions aim to perform most of the processing electronically. The independence between the transmitted WDM channels has been exploited in recent works [4, 5, 6]. The technique presented in [5] is able to reconstruct the complete channel waveforms, from which performance parameters can be measured. Along the lines of [6], 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. As the WDA has an adjustable non-linear relation between the wavelength and the output power, the independent channels contribute with different strengths to each observation. Thus, 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 [7] was adopted as a separation device. This particular technique, however, presents a number of deficiencies. On the one hand, its complexity is of order 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 [7] — which may hinder the monitoring process in practical cases. More specifically, the method is based on second-order statistics, which causes identifiability problems in the separation of spectrally white sources. In [8, 9], an advanced BSS method based on higher-order-statistics (HOS) was applied. But the disadvantage of [8, 9] is that each channel employs a unique set of WDA and photodetector, which makes this technique less efficient with the increasing of the channel numbers.

In this paper, we aim to overcome these shortcomings by introducing a more cost-effective optical-loop structure to WDM monitoring, but still applying HOS-based BSS.

2 SYSTEM DESCRIPTION

Fig. 1 shows a system setup of the proposed WDM channel monitoring scheme. A small fraction of the N-channel WDM signal is coupled out of the network using an asymmetric power splitter. A predetermined period of this splitted signal is then cut out and sent into an optical loop, which contains a delay fibre and an optical pump, to generate a periodic optical signal sequence by repeating this signal fraction N times. Each period of the signal fraction is spaced to each other by a predetermined length of "all-zeros". An adjustable wavelength-dependent attenuator (WDA) synchronized with the optical-loop is used to attenuate this sequence, the attenuation factor for each period being adjusted to be different from each other. The attenuated optical signal sequence is converted into an electrical signal sequence by a photodetector. Electronic digital signal processing is then used to seperate and reconstruct the WDM channels by analyzing the measured photocur-

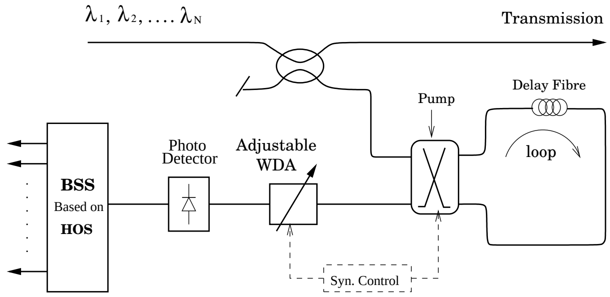

Figure 1: Experimental Setup.

rents.

The wavelength-dependent attenuating procedure above is a form of nonlinear optical signal processing which can compensate for the loss of the wavelength information caused by the conversion from optical domain to electrical domain [6]. By applying appropriate electrical signal processing methods, upto some extent, we do not need to know the details of this nonlinear optical signal processing (i.e., the WDA). In the next section, we show that blind signal seperation methods based on higher-order statistics (HOS) can be applied to extract the WDM signals.

3 WDM SIGNAL EXTRACTION USING HOS-BASED BSS

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 [10]. 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).

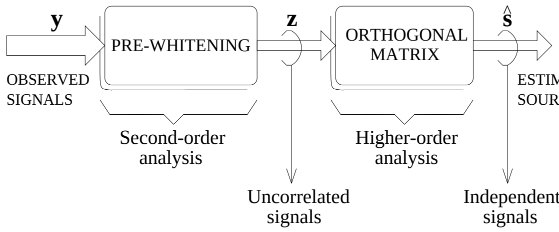

Figure 2: Two-step approach to BSS.

Note that assumption A2 guarantees considerable freedom in the selection of the WDA attenuation patterns.

As in [6], 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 [11], which is based on HOS. The method operates in two steps (Fig. 2). The first step is called (spatial) prewhitening, 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 [11, 12, 13], but here the estimator of [11] is used. This estimator expression reads:

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

with

$$\xi = (\kappa_{40}^z - 6\kappa_{22}^z + \kappa_{04}^z) + j4(\kappa_{31}^z - \kappa_{13}^z) \tag{6}$$

$$\gamma = \kappa_{40}^z + 2\kappa_{22}^z + \kappa_{04}^z \tag{7}$$

where $\kappa_{mn}^z = \mathrm{Cum}_{mn}[z_1, z_2]$ 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

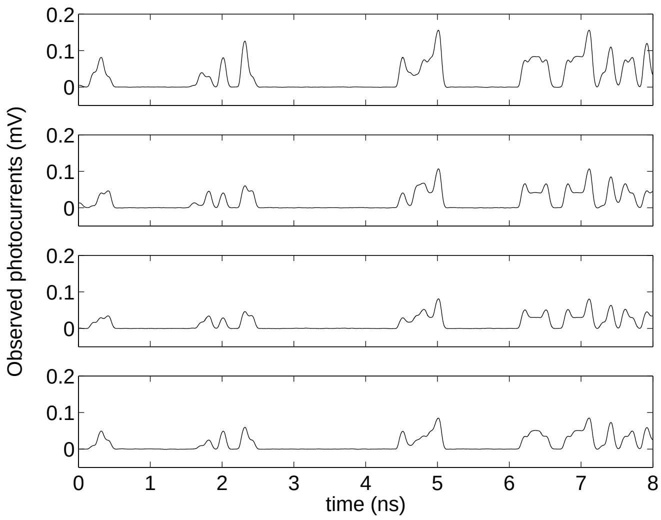

Figure 3: Observed photocurrents in the 4-channel experiment.

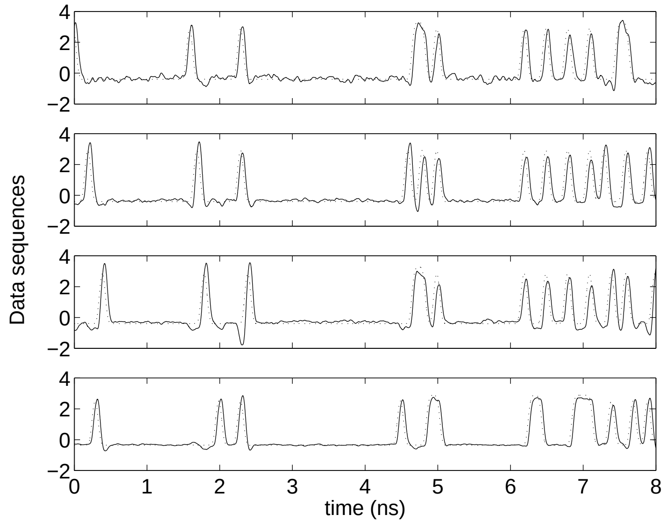

Figure 4: Normalized data sequences in the 4-channel experiment. Dotted lines: transmitted data. Solid lines: channel data estimated by the HOS-based BSS method from the photocurrents shown in Fig. 3.

convergence, the method's complexity with respect to the number of channels is of order $O(N^{5/2})$. This value is lower than the $O(N!)$ of [6], 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. Our lower-complexity method reduces the cost of the DSP needed for the WDM channel extraction and monitoring without sacrificing performance.

4 SIMULATION RESULTS

Illustrative experiments are carried out with the aid of the VPI™ simulation software. The blind separation part is implemented in MATLAB™ code. We first demonstrate the technique in a four-channel WDM setup. Four data channels at wavelengths 1551.0, 1554.2, 1557.4 and 1560.6 nm (i.e., 3.2-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. As explained in Section 2, a small fraction of the transmitted WDM signal is diverted from the optical link into the monitoring system through an asymmetric splitter. A block of this WDM signal fraction is then let into a optical loop. The signal block runs in the loop four circles, at the end of each circle the signal is coupled out of the optical loop, which means that the output of the optical loop are four blocks of repeated optical signal. These four signal blocks are sent to an optical signal processor, i.e., the adjustable

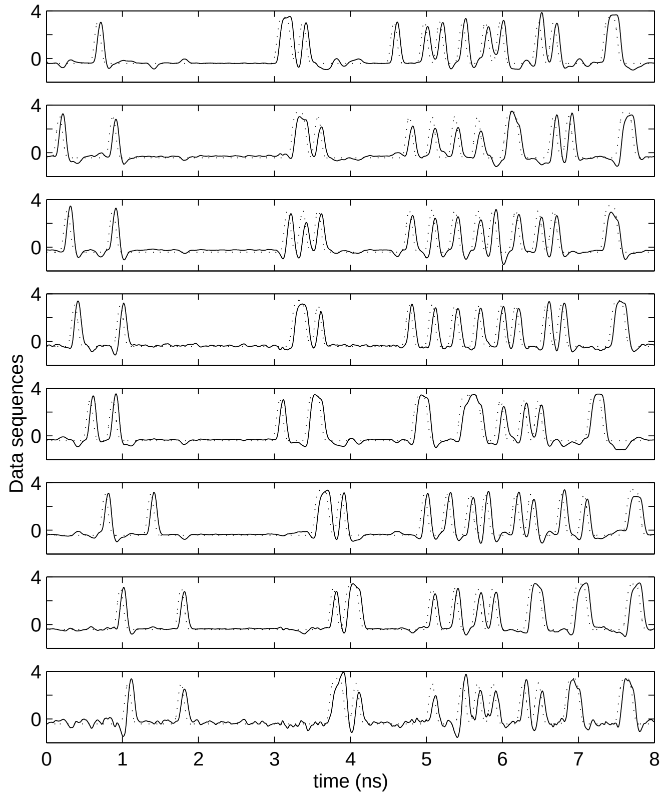

Figure 5: Normalized data sequences in the 8-channel experiment. Dotted lines: transmitted data. Solid lines: channel data estimated by the HOS-based BSS method from the observed photocurrents.

WDA, sequentially. The adjustable WDA is synchronized with the optical loop, and is tuned to have different attenuation on each of the signal blocks. All these attenuated signal blocks are detected by a p-i-n photodetector, which generate the corresponding observed photocurrents shown in Fig. 3. These electronic signals are then collected and processed by the HOS-based BSS method described in Section 3 to obtain the signal separation. 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 with 1.6-nm channel spacing, under the above general conditions. The eight photocurrents observed in this experiment are not shown here due to the lack of space, but are analogous to those in Fig. 3.

5 CONCLUSIONS

We have proposed and demonstrated an optical transmission monitoring technique that utilizes a blind signal separation method based on higher-order statistics, and an optical-loop structure. 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 [14].

Relative to previously proposed methods [6, 8, 9], the optical-loop structure presented in this paper has cost-effective features, especially when WDM signals are composed of a large number of channels.

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.

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