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BEHAVIOUR OF HIGHER ORDER BLIND SOURCE SEPARATION METHODS IN THE PRESENCE OF CYCLOSTATIONARY CORRELATED MULTIPATHS

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ABSTRACT

Over the last decade, higher order (HO) methods have been strongly developed in particular to blindly separate instantaneous mixtures of statistically independent stationary sources. However, in many situations of practical interest, the received sources are (quasi)-cyclostationary (digital radiocommunications) and are not always statistically independent but may be correlated to each other, which occurs in particular for HF links or in mobile radiocommunications contexts where propagation multipaths are omnipresent. In such situations, the behaviour of the classical HO blind source separation methods is not known, which may be a limitation to the use of these methods in operational contexts. The purpose of this paper is precisely to fill the gap previously mentionned by analysing the behaviour, in radiocommunications contexts, of three classical HO blind source separation methods when several potentially correlated paths of each source, assumed (quasi)-cyclostationary, are received by the array.

1. INTRODUCTION

Over the last decade, higher order (HO) methods have been strongly developed in particular to blindly separate instantaneous mixtures of statistically independent and stationary sources [1-5]. In [6-7], the performance of two of these methods, corresponding to the so-called JADE method [2] and to the one which optimizes a constrast function squaring the samples fourth-order autocumulants [3], have been analysed for arbitrary statistically independent and stationary sources scenari. In a same way, the performance of a third method [5], optimizing a constrast function which is not squaring the samples fourth-order autocumulants, have been presented recently in [8] still for statistically independent stationary sources.

However, in many situations of practical interest, the received sources are (quasi)-cyclostationary (digital radiocommunications) and are not always statistically independent but may be correlated to each other, which occurs in particular for HF links or in mobile radiocommunications contexts where propagation multipaths are omnipresent. In such situations, the behaviour of the previous HO blind source separation methods is not known, which may be a limitation to the use of these methods in operational contexts.

The purpose of this paper is precisely to fill the gap previously mentionned by analysing the behaviour, in radiocommunications contexts, of the three HO blind source separation methods introduced in [2], [3] and [5] respectively, when several potentially correlated paths of each source, assumed (quasi)-cyclostationary, are received by the array.

2. HYPOTHESIS AND PROBLEM FORMULATION

Consider an array of N Narrow-Band (NB) sensors and let us call $x(t)$ the vector of the complex amplitudes of the signals at the output of these sensors. Each sensor is assumed to receive a noisy mixture of P statistically independent NB (quasi)-cyclostationary sources, with their associated propagation multipaths. Under these assumptions, the observation vector $x(t)$ can be written as follows

$$x(t) = \sum_{i=1}^{P} \sum_{k=1}^{M_i} \alpha_{ik}\, m_i(t-\tau_{ik})\, e^{-j\omega_0\tau_{ik}}\, a_{ik} + b(t)$$
$$\triangleq \sum_{i=1}^{P} A_i\, m_i(t) + b(t) \triangleq A\, m(t) + b(t) \quad (2.1)$$

where $b(t)$ is the noise vector, assumed zero-mean, stationary, spatially white and Gaussian, ω_0 is the carrier pulsation, M_i is the number of paths associated to the source i, $m_i(t)$ is the complex envelope of the source i, α_{ik}, τ_{ik} and a_{ik} are the complex attenuation, the delay and the steering vector of the path k of the source i, $m_i(t)$ is the $(M_i \times 1)$ vector which components are the complex

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signals $m_{ik}(t) \triangleq \alpha_{ik}\, m_i(t-\tau_{ik})\, e^{-j\omega_0 \tau_{ik}}$ $(1 \le k \le M_i)$, A_i is the $(N \times M_i)$ matrix of the sources steering vectors $\boldsymbol{a}_{ik}$ $(1 \le k \le M_i)$, $\boldsymbol{m}(t)$ is the $(M \times 1)$ vector obtained by concatenation of the vectors $\boldsymbol{m}_i(t)$ and A is the $(N \times M)$ matrix of all the vectors $\boldsymbol{a}_{ik}$, where M is the sum of the M_i, $(1 \le i \le P)$.

In these conditions, the correlation matrix of the observation vector, $R_x(t) \triangleq E[\boldsymbol{x}(t)\boldsymbol{x}(t)^\dagger]$, can be written as

$$R_x(t) = A\, R_m(t)\, A^\dagger + \eta_2 I \qquad (2.2)$$

where † means transposition and conjugation, η_2 is the mean power of the noise per sensor, I is the Identity matrix and $R_m(t) \triangleq E[\boldsymbol{m}(t)\, \boldsymbol{m}(t)^\dagger]$ is the correlation matrix of the vector $\boldsymbol{m}(t)$.

In a same way, the quadricovariance $Q_x(t)$ of the observation vector $\boldsymbol{x}(t)$, which components, defined by $Q_x(i, j, k, l)(t) \triangleq \mathrm{Cum}(x_i(t), x_j(t)^*, x_k(t)^*, x_l(t))$, are the fourth order cumulants of $\boldsymbol{x}(t)$, can be written as

$$Q_x(t) = (A \otimes A^*) Q_m(t) (A \otimes A^*)^\dagger \qquad (2.3)$$

where $Q_m(t)$ is the quadricovariance of the vector $\boldsymbol{m}(t)$, * means complex conjugation and ⊗ corresponds to the Kronecker product.

In fact, the expression (2.1) describes N particular convolutive mixtures of P statistically independent sources at the output of the sensors. These mixtures could be processed by every blind separators of convolutive mixtures developed these last years [9]. However, in practical situations, for some reasons such as, for example, that of the numerical complexity, it may be chosen to process the vectorial mixture (2.1) as an instantaneous one, considering a propagation path as a particular source. This is the philosophy we adopt in this paper. In these conditions, although in (quasi)-cyclostationary contexts it may be advantageous to implement a Poly-Periodic (PP) and Widely Linear structure of array filtering [10], the problem of sources separation we address in this paper is to find the Linear and Time Invariant (TI) $(N \times M)$ NB separator W, outputing the vector $y(t) \triangleq W^\dagger \boldsymbol{x}(t)$ and giving, to within a diagonal and a permutation matrix, the best estimate of the vector $\boldsymbol{m}(t)$. In the following sections, we study the behaviour of the tree HO blind source separators W introduced in [2], [3] and [5] respectively, for different scenari of sources and paths, for several digital modulations and relative time delays between the paths.

3. HO BLIND SOURCE SEPARATION OF (QUASI)-CYCLOSTATIONARY SOURCES

3.1 Possible HO blind source separators

In (quasi)-cyclostationary contexts, the matrices (2.2) and (2.3) become Time-Dependent and more precisely PP. As a consequence, the matrices $R_x(t)$ and $Q_x(t)$ have Fourier serial expansions which show off in particular the cyclic frequencies of the observations. It may be very useful to exploit the information contained in all the cyclic frequencies of the observations to improve the performance of the HO blind source separators, as it has been shown recently in [11]. However, for particular reasons such as the numerical complexity, we may prefer to still use, in (quasi)-cyclostationary contexts, the classical methods of HO blind source separation introduced in [2], [3] or [5], which, in this case, exploit only the information contained in the cyclic frequency zero of $R_x(t)$ and $Q_x(t)$, i.e. in the temporal mean $R_x \triangleq \langle R_x(t)\rangle$ and $Q_x \triangleq \langle Q_x(t)\rangle$ of $R_x(t)$ and $Q_x(t)$ respectively, which is the choice we adopt in this paper.

Note that for stationary sources, the temporal mean R_x and Q_x of the 2nd and 4th order statistics correspond to the statistics themselves, which is not the case for (quasi)-cyclostationary sources. In this latter case, R_x and Q_x can still be written as (2.2) and (2.3) but where $R_m(t)$ and $Q_m(t)$ are replaced by their temporal mean noted R_m and Q_m respectively. Thus, the temporal mean operation obviously preserves the algebraic structure of $R_x(t)$ and $Q_x(t)$ and also the potential second and fourth order statistical independence of the paths (R_m is still diagonal and the non zero elements of Q_m are still the 4-th order autocumulants of the paths when the latter are independent).

3.2 Statistics estimation

It is well known that for zero-mean, stationary and ergodic sources, the classical estimators of the 2nd and 4th order cumulants provide asymptotically unbiaised estimates of the 2nd and 4th order cumulant of the data, which variance tends to zero when the number of independent samples increases. However, in the presence of (quasi)-cyclostationary and cyclo-ergodic sources, we must wonder whether these classical estimators still generate asymptotically unbiaised estimates of the data statistics temporal mean. The answer to this question has been given in [12] and is negative in the general case for the 4th order cumulant. More precisely, noting $R_x^\alpha(i, j)$, $C_x^\beta(i, j)$ and $M_x^\gamma(i, j, k, l)$ the coefficients associated to the cyclic frequencies α, β and γ in the Fourier serial expansion of $R_x(i, j)(t) \triangleq E[x_i(t)x_j(t)^*]$, $C_x(i, j)(t) \triangleq E[x_i(t)x_j(t)]$ and $M_x(i, j, k, l)(t) \triangleq E[x_i(t)x_j(t)^* x_k(t)^* x_l(t)]$ respectively, it has been shown in [12] that

$$Q_x(i, j, k, l) = M_x^0(i, j, k, l) - \sum_\alpha R_x^\alpha(i, j)\, R_x^{-\alpha}(l, k) - \sum_\alpha R_x^\alpha(i, k)\, R_x^{-\alpha}(l, j) - \sum_\beta C_x^\beta(i, l)\, C_x^\beta(j, k)^* \qquad (3.1)$$

while the classical 4th order cumulant estimator generates asymptotically an apparent 4th order cumulant given by

$$Q_{xa}(i,j,k,l) \triangleq M_x^0(i,j,k,l) - R_x^0(i,j)\,R_x^0(l,k) - R_x^0(i,k)\,R_x^0(l,j) - C_x^0(i,l)\,C_x^0(j,k)^* \quad (3.2)$$

Comparing (3.1) and (3.2), we deduce that for (quasi)-cyclostationary sources, the classical estimators of the 4th-order cumulant do not generate, in the general case, the true value of the latter, which must be taken into account in the behaviour analysis of the classical HO blind separators in (quasi)-cyclostationary contexts and which may even prevent (in very particular situations) the separation of statistically independent non Gaussian sources [13].

3.3 Classical HO blind separators description

The indirect HO methods presented in [2], [3] and [5] aim at blindly identifying the sources steering vectors before the effective sources separation, the latter being done by implementing a spatial filtering operation from the steering vectors estimates [6]. The blind identification of the latter requires a prewhitening of the data, by the pseudo-inverse, $R_s^{-1/2}$, of a square root of $R_s \triangleq A\, R_m\, A^\dagger$, which aims at orthonormalizing (for statistically independent paths) these steering vectors so as to search for the latter through a unitary matrix simpler to handle. For each of the methods presented in [2], [3] and [5], this unitary matrix must maximize a particular blind criterion which is theoretically a function of the Q_z elements, where Q_z is the temporal mean of the quadricovariance of the whitened data $z(t) \triangleq R_s^{-1/2} x(t)$. However practically, the blind criterion optimized by the classical HO blind separators is a function of the Q_{za} elements, where Q_{za} is the apparent quadricovariance of the whitened data.

Using (2.1), the vector $z(t)$ can be written as

$$z(t) = \sum_{i=1}^{P} \sum_{k=1}^{M_i} m'_{ik}(t)\, a'_{ik} + b'(t) \triangleq A'm'(t) + b'(t) \quad (3.3)$$

where $m'_{ik}(t)$ is the normalized complex envelope of the path ik, A' is the $(M \times M)$ matrix of the whitened paths steering vectors a'_{ik} and $b'(t)$ is the whitened noise vector. Consequently, the Q_z and Q_{za} matrices can be written as

$$Q_{z(a)} = (A' \otimes A'^*)\, Q_{m'(a)}\, (A' \otimes A'^*)^\dagger \quad (3.4)$$

where $Q_{m'}$ and $Q_{m'a}$ are the true and the apparent temporal mean of the quadricovariance of $m'(t)$ respectively.

For M stationary and statistically independent total paths, the HO blind separators introduced in [2], [3] and [5] have high performance [6-8], which is directly related to the fact that the M vectors $a'_{ik} \otimes a'_{ik}$ are orthonormal eigenvectors of $Q_z = Q_{za}$ associated to the non zero eigenvalues. We must then wonder whether this result still holds for (quasi)-cyclostationary and potentially correlated paths and if not, what is the behaviour of these separators in such situations, which is the purpose of the following.

4. FOURTH ORDER CORRELATION PROPERTIES OF DIGITAL MODULATIONS

The analysis of the eigenstructure of Q_z and Q_{za} in the presence of several potentially correlated (quasi)-cyclostationary paths requires the analysis of $Q_{m'}$ and $Q_{m'a}$ in the same context and in particular the analysis of the 4th-order correlation properties of digital modulations. For this purpose, we consider in this section only one source ($P = 1$) with two paths ($M_1 = 2$), we assume that $\tau_{11} = 0$, $\tau_{12} = \tau$, we note $m_1(t)$ simply $m(t)$ and we analyse the evolution of the 16 $Q_{m'}$ and $Q_{m'a}$ elements as a function of τ. Note that due to the particular symetries of these matrices, the 16 elements of each matrix can be deduced from only 5 elements corresponding to the element (1, 1, 1, 1) (temporal mean of the 4th order true or apparent autocumulant) and to the 4 elements (1, 1, 1, 2), (1, 1, 2, 2), (1, 2, 2, 1) and (1, 2, 2, 2) (temporal mean of the 4th order true or apparent crosscumulants).

Recalling that the 2nd order correlation coefficient between the two considered paths is defined by $\rho_2(\tau) \triangleq \langle E[m'(t)\, m'(t-\tau)^*] \rangle e^{j\omega_0\tau}$, we define, for each of the two matrices $Q_{m'}$ and $Q_{m'a}$, four 4th-order correlation coefficients (associated to the indices $ijkl$ = 1112, 1122, 1221 and 1222) defined by

$$\rho_{4(a)}[ijkl](\tau) \triangleq Q_{m'(a)}[ijkl] \,/\, Q_{m'(a)}[1111] \quad (4.1)$$

The four coefficients $\rho_4[ijkl](\tau)$ and the four others $\rho_{4a}[ijkl](\tau)$ characterize the true and the apparent 4th-order correlation of all the modulations respectively. From these coefficients, it is also possible to define, for each matrix $Q_{m'}$ and $Q_{m'a}$, an average 4th order correlation coefficient which modulus can be defined by the following expression

$$|\rho_{4(a),av}(\tau)| \triangleq (1/14)[4|\rho_{4(a)}[1112](\tau)| + 4|\rho_{4(a)}[1122](\tau)| + 2|\rho_{4(a)}[1221](\tau)| + 4|\rho_{4(a)}[1222](\tau)|] \quad (4.2)$$

In order to quantify the 4th-order correlation of some modulations, let us consider the linear modulations, characterized by a complex envelope $m(t)$ given by

$$m(t) = \sum_n a_n\, v(t - nT) \quad (4.3)$$

where the complex symbols a_n are i.i.d. random variables, T is the symbol duration and $v(t)$ is a real-valued pulse function. Under these assumptions, it is possible to show that :

- $|\rho_2(\tau)|$ and the modulus of the four true 4th-order correlation coefficient only depend on τ and $v(t)$ but do not depend on the symbol statistics.
- the modulus of the four apparent 4th-order correlation coefficient depend on τ, $v(t)$ and also on the 2th and 4th-order symbol statistics, which confirms the fact that the classical 4th-order cumulant estimator changes the 4th-order correlation of the linear modulations.

For example, if we choose the square pulse such that $v(t) = 1$ if $0 \leq t < T$ and $v(t) = 0$ elsewhere, we find that $\rho_2(\tau)$ and the four true 4th-order correlation coefficients have the same modulus equal to $1 - |\tau|/T$. This implicates that $|\rho_{4,av}(\tau)| = |\rho_2(\tau)|$ and shows that generally a 2nd order correlation between paths generates also a 4th order correlation.

The previous results are illustrated at figure 1 which shows the variations of $|\rho_{4,av}(\tau)|$ and $|\rho_{4a,av}(\tau)|$ as a function of $|\rho_2(\tau)|$ for a BPSK and a QPSK modulation and for two pulse functions corresponding to the square and the half-Nyquist function with a roll-off of 0.25.

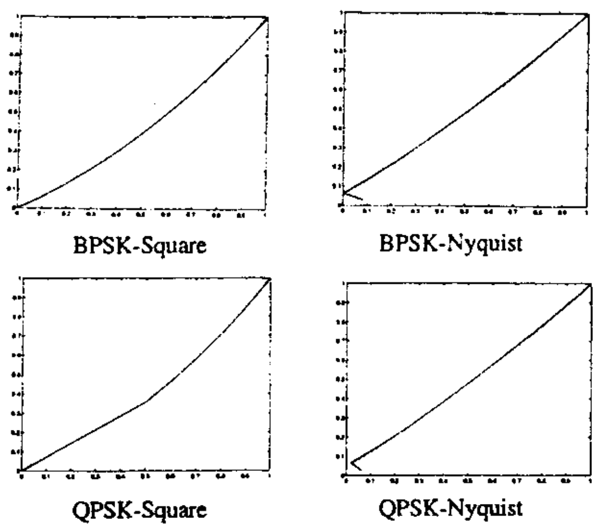

Fig. 1 - *$|\rho_{4,av}(\tau)|$ and $|\rho_{4a,av}(\tau)|$ as a function of $|\rho_2(\tau)|$*
--- : $|\rho_{4a}|$, ···· : $|\rho_4|$

5. EIGENSTRUCTURE OF Q_z AND Q_{za}

We analyse, in this section, the eigenstructure of the matrices Q_z and Q_{za} in the presence of correlated paths of (quasi)-cyclostationary independent sources.

5.1 Prewhitening of the data

The prewhitening stage of the data by the matrix $R_s^{-1/2}$ transforms (2.1) into (3.3). It is then possible to show that in the presence of correlated paths, the whitened steering vectors a'_{ik} are no longer orthonormalized. More precisely, it can be shown that :

- a'_{ik} is orthogonal to a'_{jl} if and only if $m'_{ik}(t)$ and $m'_{jl}(t)$ are not correlated
- a'_{ik} is normalized if and only if $m'_{ik}(t)$ is uncorrelated with all the $m'_{jl}(t)$ $(jl \neq ik)$

For example, in the case where $P = 1$ and $M_1 = 2$, noting ρ_2 the 2nd order correlation coefficient between $m'_{11}(t)$ and $m'_{12}(t)$, we find that

$$a'^{\dagger}_{11} a'_{11} = a'^{\dagger}_{12} a'_{12} = 1 / (1 - |\rho_2|^2) \qquad (5.1)$$

$$a'^{\dagger}_{11} a'_{12} = - \rho_2 / (1 - |\rho_2|^2) \qquad (5.2)$$

5.2 Eigenstructure of Q_z

The statistical independence of the P considered sources implicates that the Q_z matrix, defined by (3.4), can be written as

$$Q_z = \sum_{i=1}^{P} (A'_i \otimes A'^{*}_i)\, Q'_{mi}\, (A'_i \otimes A'^{*}_i)^{\dagger} \triangleq \sum_{i=1}^{P} Q_{zi} \quad (5.3)$$

where A'_i is the $(M \times M_i)$ matrix of the sources steering vectors a'_{ik} $(1 \leq k \leq M_i)$ and Q'_{mi} is the temporal mean of the quadricovariance of the vector $m'_i(t)$ which components are the $m'_{ik}(t)$ $(1 \leq k \leq M_i)$. The orthogonality of the vectors a'_{ik} and a'_{jl} for $i \neq j$ (section 5.1) implicates that for $1 \leq i \leq P$, the eigenvalues and eigenvectors of Q_{zi} are also eigenvalues and eigenvectors of Q_z. Consequently, the eigenvalues and eigenvectors of Q_z correspond to the reunion of the eigenvalues and eigenvectors of the matrices Q_{zi}. In other words, statistical independent sources contribute to the eigenstructure of Q_z without any interaction between themselves. The rank r of Q_z is then equal to the sum of the rank, r_i, of the matrices Q_{zi}.

On the other hand, the rank of Q_{zi}, r_i, may vary between M_i (independent paths of the source i) and M_i^2 (all the paths of the source i are correlated to each other). However, it can be shown that for linear modulations, even when all the paths of the source i are correlated to each other, $r_i < M_i^2$. Besides, whatever the kind of modulation, it can be shown that the eigenvalues of Q_{zi} and thus those of Q_z do not depend on the mixture matrix A.

5.3 Eigenstructure of Q_{za}

The modification of the 4th-order correlation of the sources by the classical 4th-order cumulant estimators implicates that it may exists situations for which the apparent 4th-order cross-cumulant temporal mean of two statistically independent sources is not zero [13]. Consequently, Q_{za} may have a structure not similar to that described by (5.3) and the results of section 5.2 may not be applied for Q_{za}. However, in most practical cases the structure (5.3) still holds exactly or approximately for Q_{za}, with Q'_{mi} and Q_{zi} replaced by Q'_{mia} and Q_{zia}, and the results of section 5.2 can still be applied, despite of the fact that the apparent 4th-order autocumulants are no longer equal to the true ones. However note that for linear modulations, the rank of Q_{zia} is often equal to M_i^2 when all the paths of the source i are correlated to each other.

5.4 Illustrations

The figure 2 illustrates the previous results by showing the values of the non zero eigenvalues modulus of Q_z and Q_{za} in the presence of $P = 3$ independent sources (QPSK-Nyquist, QPSK-Square, BPSK-Square) with $M_1 = 2$, $M_2 = 1$ and $M_3 = 1$, for several values of τ/T, where τ is the relative time delay between the two paths of the source 1. The varations of τ does not modify the 2 highest values.

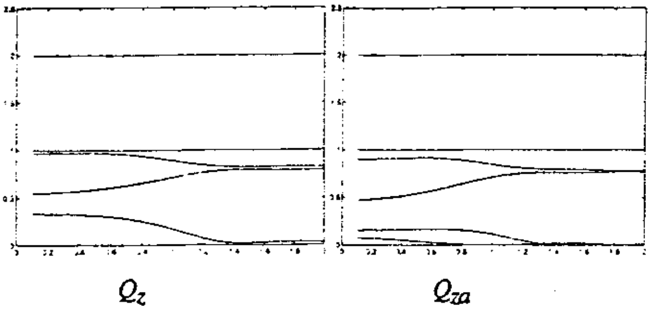

Fig. 2 - *Eigenvalues modulus of Q_Z and Q_{Za}, for $P = 3$ with $M_1 = 2$, $M_2 = 1$ and $M_3 = 1$, as a function of τ/T*

6. BLIND IDENTIFICATION AND SOURCE SEPARATION

In the presence of one source with several correlated paths, the blind identification of the paths steering vectors cannot be done exactly since the whitened steering vectors are not orthogonal to each other (section 5.1). In this case, the blind estimates of the paths steering vectors are linear combination of the true ones with coefficients directly related to the 4th-order correlation between the paths. Consequently, the separation of correlated paths cannot be optimal but still occurs up to a relatively high level of 2nd-order correlation, depending on the Q_Z matrix which is exploited (true or apparent), the modulation and the pulse function for linear modulations.

In the presence of several independent sources with their own paths, although it exists situations for which the separation of the different sources (not paths) fails, even from the exploitation of the true Q_Z, in most practical cases, this separation occurs even from the use of Q_{Za}.

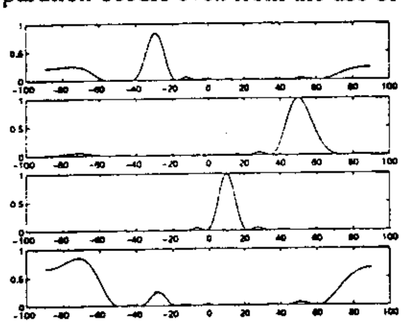

Fig. 3 - *Spatial correlation coefficient as a function of θ*

The Figure 3 illustrates the previous results by showing the spatial correlation coefficient between the 4 blind steering vector estimates and the array manifold of a ULA of 10 sensors as a function of θ for one QPSK-Nyquist source (ro 0.25) with two paths which DOA are −70° and −30° and such that $\tau/T = 0.4$, a QPSK-Square (30°) and a BPSK-Square (50°) with one path each. Note that Q_Z and Q_{Za} give, in that case, the same good estimation of the paths DOA by this DF method called Blind-Maxcor [14].

8. CONCLUSION

The behaviour of the classical indirect HO blind source separation methods has been analysed in the presence of correlated paths of several (quasi)-cyclostationary sources, through the analyses of the 4th-order correlation of digital modulation and the eigenstructure of the whitened quadricovariance. The choice of the 4th-order cumulant temporal mean estimator has been shown to be crutial in some cases. In most practical situations, the classical methods do not mix paths of independent sources and separate correlated paths up to a high 2nd order correlation.

REFERENCES

[1] C. JUTTEN, J. HERAULT, "Blind separation of sources, Part I: An adaptive algorithm based on neuromimetic architecture", *Signal Processing*, Vol 24, pp 1-10, 1991.

[2] J.F. CARDOSO, A. SOULOUMIAC, "Blind Beamforming for Non Gaussian Signals", *IEE Proc-F*, Vol 140, N°6, pp 362-370, Dec 1993.

[3] P. COMON, "Independent Component Analysis", *Signal Processing*, Vol 36, N°3, Special Issue On Higher Order Statistics, pp 287-314, Apr. 1994.

[4] L. DeLATHAUWER, B. DeMOOR, J. VANDEWALLE, "Independent Component Analysis based on Higher Order Statistics only ", *Proc. IEEE SP Workshop on SSAP*, Corfu (Greece), pp 356-359, June 1996.

[5] P. COMON, E. MOREAU, "Improved Contrast dedicated to Blind Separation in Communications", *Proc. ICASSP*, Munich (Germany), pp 3453-3456, Apr. 1997.

[6] P. CHEVALIER, "On the Performance of Higher Order Blind Source Separation Methods", *Proc. IEEE ATHOS Workshop on Higher Order Stat.*, Begur (Spain), pp 30-34, June 1995.

[7] P. CHEVALIER, "Méthodes Aveugles de Filtrage d'Antenne", *Revue d'Electronique et d'Electricité*, SEE, N°3, pp 48-58, Sept. 1995.

[8] P. COMON, P. CHEVALIER, V. CAPDEVIELLE, "Performance of Contrast-Based Blind Source Separation", *Proc. IEEE SP Workshop on SP Advances in Wireless Communications*, SPAWC, Paris (France), pp 345-349, April 1997.

[9] J.K. TUGNAIT, "On Blind Separation of Convolutive Mixture of Independent Linear Systems", *IEEE SP Workshop on SSAP*, Corfu , pp 312-315, June 1996.

[10] P. CHEVALIER, A. MAURICE, "Constrained Beamforming for Cyclostationary Signals", *Proc. ICASSP*, Munich (Germany), pp 3789-3792, Apr. 1997.

[11] A. FERREOL, P. CHEVALIER, "Higher Order Blind Source Separation using the Cyclostationarity Property of the Signals", *Proc. ICASSP*, Munich, pp 4061-4064, Apr. 1997.

[12] P. MARCHAND, D. BOITEAU, "Higher Order Statistics for QAM Signals : A Comparison between cyclic and stationary representations", *Proc. EUSIPCO*, Triestre (Italy), pp 1531-1534, Sept. 1996.

[13] P. CHEVALIER, A. FERREOL, "Limites des Estimateurs Classiques de Cumulant d'Ordre Quatre pour la Séparation Aveugle de Sources Cyclostationnaires", *Proc. GRETSI*, Grenoble (France), Sept. 1997.

[14] P. CHEVALIER, G. BENOIT, A. FERREOL, "DF after Blind Identification : Blind-Maxcor and Blind-MUSIC", *EUSIPCO*, Triestre (Italy), pp 2097-2100, Sept. 1996.