FastICA-Based Blind Separation of Digital Modulation signals for Radio Surveillance

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Abstract

In this paper, we propose a blind signal separation procedure for digital modulation signal using FastICA algorithm. FastICA is one of ICA (Independent Component Analysis) algorithms and it enables very fast optimal weight calculation for signal separation without any the prior information of reference signal. ICA is based on the independence of signal to each other. ICA simultaneously separates all the observation signals by array sensors (antennas, microphones, etc) if the number of incident signals is less than the number of elements. In this paper, we first analyze the undesired phase rotation of the separated signal by FastICA, that happens for complex input signal, and study the compensation technique for the rotation. Moreover, we evaluate the separation accuracy and the computational cost of the proposed algorithm in comparison with some conventional algorithms through computer simulation.

1. INTRODUCTION

In high-speed mobile communication, multiple signal propagation and multipath fading become problems because of the reflecting, diffraction, and scattering by buildings. In order to accurately estimate that multiple propagation environment, many researches of adaptive array antenna on the separation and the estimation of multiple arrival signals have already done like MMSE (Minimum Mean Square Error) adaptive array [1] or CMA (Constant Modulus Algorithm) adaptive array [2]. CMA adaptive array extracts the desired signal while suppressing undesired multiple or interference signals without any prior information of the reference signal. However, CMA extracts only one signal whose electric power is the maximum among the arrival signals. It means, the desired signal cannot be correctly extracted when the electric power of the interference signal becomes more than that of the desired signal or when two or more desired signals comes to the array antenna.

On the other hand, ICA (Independent Component Analysis) is attracted as a representative BSS (Blind Signal Separation) method which has many advantages and applications in the field of audio and speech signal processing [3]–[5]. ICA pays attention to the independency of signals, and can separate all the arrival signals. The problem of the miss capture in CMA has already been studied and applied to communication problems, some for radio surveillance [6]–[8]. However, the signal separation by ICA still takes long calculation time because of their naive searching method of optimal weights. Moreover, there does not exist any previous work on the blind separation of digital modulation signals by ICA.

In this paper, we aim to develop a fast procedure of blind separation of digital modulation signals for radio surveillance, and FastICA [9] is adopted as a method of shortening the computation time instead of ICA. This technique enables very fast optimal weight calculation by limiting the searching range of weights. First we clarify the problem by using FastICA, and then try to how to compensate the problem. The proposed FastICA-based algorithm is evaluated through the accuracy of communication in the sense of BER characteristics under the situation of 2 or more uncorrelated arrival signals.

2. BLIND SIGNAL SEPARATION

A. Problem Formulation

Suppose that L incident signals $s_i(t)(i = 1, \dots, L)$ are observed by M-element array antennas. The observed signal at j-th element $x_j(t)(j = 1, \dots, M)$ can be written as

$$x_j(t) = \sum_{i=1}^{L} (a_{ji} * s_i)(t) + n_j(t) \tag{1}$$

where a_{ji} represents the impulse response from i-th incident signal at j-th element. Then, the incident signals are reconstructed by

$$y_k(t) = \sum_{j=1}^{M} (w_{kj} * x_j)(t) \tag{2}$$

where w_{kj} is the impulse response of the separation filter. In the environment without noise, the observed signals are represented by $\boldsymbol{X} = \boldsymbol{AS}$, where $\boldsymbol{S} = [s_{im}] = [s_i(mT)](m = 1, \dots, N)$, $\boldsymbol{X} = [x_{jm}] = [x_j(mT)]$, and $\boldsymbol{A} = [a_{ji}]$, respectively. Here, T is a sampling period and N is the number of snapshots. Therefore, the separated signal matrix is represented by $\boldsymbol{Y} = \boldsymbol{WX}$, where $\boldsymbol{Y} = [y_{jm}] = [y_j(mT)]$ and $\boldsymbol{W} = [w_{kj}]$, respectively. The necessary and sufficient condition for being $\boldsymbol{Y} = \boldsymbol{S}$ is $\boldsymbol{WA} = \boldsymbol{E}$, where $\boldsymbol{E}$ is an identity matrix.

Next, we consider how to deal with noise. The observed signal can be written as $\boldsymbol{X} = \boldsymbol{AS} + \boldsymbol{N}$ with including the noise, where $\boldsymbol{N} = [n_{jm}] = [n_j(mT)]$ is the noise matrix. Moreover, it can be rewritten as $\boldsymbol{X} = \boldsymbol{A}(\boldsymbol{S} + \tilde{\boldsymbol{N}})$ where

$\boldsymbol{N} = \boldsymbol{A}\tilde{\boldsymbol{N}}$. If $(\boldsymbol{S} + \tilde{\boldsymbol{N}})$ is considered as a incident signal here, $\boldsymbol{X} = \boldsymbol{A}\boldsymbol{S}$ again holds.

B. ICA Algorithm

The ICA algorithm employs the natural gradient method to minimize the average mutual information [3]. If the separated signal $\boldsymbol{y}_k (k = 1, \ldots, L)$ is independent to each other, the addition of entropy $\sum_{k=1}^{L}(H(\boldsymbol{y}_k))$ and the entropy $H(\boldsymbol{Y})$ of the entire $\boldsymbol{Y}$ are correlated. Therefore, the average mutual information $\overline{I}$ of $\boldsymbol{Y}$ is defined as follows.

$$\overline{I}(\boldsymbol{Y}) = \sum_{k=1}^{L}(H(\boldsymbol{y}_k)) - H(\boldsymbol{Y}) \tag{3}$$

To minimize this average mutual information, we only have to find the solution which satisfies $d\overline{I}(\boldsymbol{Y})/d\boldsymbol{W}$=0, where the separation weight $\boldsymbol{W} = [\boldsymbol{w}_1, \ldots, \boldsymbol{w}_L]$ is the matrix that is obtained by the study rule as follows.

$$\boldsymbol{W}(t+1) = \boldsymbol{W}(t) + \eta\left[\boldsymbol{E} - \phi(\boldsymbol{Y}(t))\boldsymbol{Y}(t)^H\right]\boldsymbol{W}(t) \tag{4}$$

where η is a step size parameter, and $\phi(\cdot)$ is the nonlinear function defined as follows.

$$\phi(\boldsymbol{Y}) = [\phi(\boldsymbol{y}_1), \ldots, \phi(\boldsymbol{y}_L)]^T \tag{5}$$

$$\phi(\boldsymbol{y}_i) = -\frac{\partial}{\partial \boldsymbol{y}_i}\mathrm{log}p(\boldsymbol{y}_i) \tag{6}$$

where $p(\cdot)$ is a probability density function. In [6], the following equation is defined as a nonlinear function that corresponds to the modulation signals like PSK or QAM.

$$\phi(\boldsymbol{y}_i) = \tanh\left(20(\boldsymbol{y}_i + \mathbf{1})\right) + \tanh\left(20(\boldsymbol{y}_i - \mathbf{1})\right) \tag{7}$$

where $\mathbf{1}$ represents the vector of which all the elements are one. However, it takes long computation time for searching the optimal separation weight by this nonlinear function because the optimal weight is found through searching all the matrices.

3. Blind Separation of Digital Modulation Signals by FastICA

A. FastICA Algorithm

FastICA [9] is an algorithm that realizes the same accuracy with ICA that enables very fast optimal weight calculation. First, the observation signal $\boldsymbol{X}$ is whitened as

$$\tilde{\boldsymbol{X}} = \boldsymbol{P}^H \boldsymbol{\Lambda}^{-\frac{1}{2}} \boldsymbol{P}\boldsymbol{X} \tag{8}$$

where $\boldsymbol{P}$ represents the matrix whose row vectors are the eigenvectors of the covariance matrix $E[\boldsymbol{X}\boldsymbol{X}^H]$ of $\boldsymbol{X}$, and $\boldsymbol{\Lambda}$ represents the diagonal matrix whose diagonal elements are the eigenvalues of $E[\boldsymbol{X}\boldsymbol{X}^H]$. When we implement ICA for whitening the signal $\tilde{\boldsymbol{X}}$, it only looks for the separated weight in the orthogonal matrix. Therefore, the search range becomes very limited.

Next, the average mutual information $\overline{I}(\boldsymbol{Y})$ in (3) is calculated under the condition that the whitening has already been done. At this moment, the separation weight $\boldsymbol{W}$ can be limited to the unitary matrix because of the whitening. The determinant of $\boldsymbol{W}$ becomes one when it is an unitary matrix, and the average mutual information can be written as follows.

$$\overline{I}(\boldsymbol{Y}) = \sum_{k=1}^{L}(H(\boldsymbol{y}_k)) + C \tag{9}$$

where C is a constant that does not depend on the separation weight $\boldsymbol{W}$. Therefore, to minimize the average mutual information $\overline{I}(\boldsymbol{Y})$, it is equivalent to minimize the sum of the entropy of each separation signal. Then, $\boldsymbol{w}_1$ minimizes the entropy $E[p_1(\boldsymbol{y}_1)]$ of $\boldsymbol{y}_1 = \boldsymbol{w}_1^T\boldsymbol{X}$ is solved under the condition of $|\boldsymbol{w}_1| = 1$. By Lagrange's method of undetermined multipliers, the evaluation function is given as follows.

$$J = E\left[p_1(\boldsymbol{y}_1)\right] - \frac{\lambda}{2}\left(\boldsymbol{w}_1^H\boldsymbol{w}_1 - 1\right) \tag{10}$$

where λ is an undetermined multiplier value, partially differentiated by $\boldsymbol{w}_1$, we have the following recursive formula.

$$\begin{aligned}\boldsymbol{W}(t+1) &= \boldsymbol{W}(t) + \boldsymbol{D}\big(\boldsymbol{\Lambda}_2 \\ &\quad -E\left[p'(\boldsymbol{Y}(t)\boldsymbol{Y}(t)^H\right]\big)\boldsymbol{W}(t)\end{aligned} \tag{11}$$

Here, $\boldsymbol{D}$ represents the diagonal matrix whose diagonal element is $(E[p_i''(\boldsymbol{y}_i)] - \lambda_i)^{-1}, i = 1, \ldots, L$, and $p'(\boldsymbol{Y}) = (p_1'(\boldsymbol{y}_1), \ldots, p_L'(\boldsymbol{y}_L))^T$. The separation weight is updated by orthogonalizing this separation weight to be a unitary matrix. ICA procedure shown by (11) is called FastICA, and it is often used as an ICA technique to calculate the weight very fast. In the next section, the problem of the phase rotation by using FastICA is investigated, and we propose the solution for that problem.

B. The problem of phase rotation and the solution

Figure 1(a) shows an example constellation pattern when separating QPSK modulation signals by FastICA with 4-element ULA, where SNR is 7[dB]. From Fig. 1(a), we see that the signals are separated but rotated. This is because: the independence doesn't collapse even if the separated signal $\boldsymbol{y}_k(t)$ is resumed to be $\boldsymbol{y}_k(t) = \boldsymbol{s}_i(t)\exp(j\theta_i)$. Therefore, the phase θ_i is not determined by the estimated incident signal $\boldsymbol{s}_i$. We recall that the following relation holds.

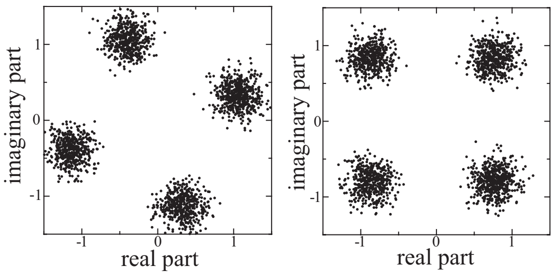
$$\boldsymbol{a}_i\boldsymbol{s}_i = (\boldsymbol{a}_i\exp(-j\theta_i))\,(\boldsymbol{s}_i\exp(j\theta_i)) \tag{12}$$

If $\boldsymbol{s}_i$ is the distribution of the spherical symmetry, that is, the distribution of $\boldsymbol{s}_i$ depends only on the absolute value of $\boldsymbol{s}_i$, it doesn't change even if the constant $\exp(j\theta_i)$ is multiplied. Hence, the distribution of $\boldsymbol{X}$ also doesn't change. Therefore, the argument of $\boldsymbol{s}_i$ cannot be preserved, and we have to estimate the rotation angle θ_i.

Hence, θ_i is estimated by the following procedure.

1) The Direction of Arrival (DOA) is estimated by searching the angle that is for the main beam of the directivity response pattern.
2) The array mode vector at the estimated DOA is assumed to be $\boldsymbol{A}$.
3) The phase of the diagonal element of $\boldsymbol{W}\boldsymbol{A}$ is calculated from originally $\boldsymbol{W}\boldsymbol{A} = \boldsymbol{E}$, and this phase is estimated as the rotation angle θ_i.

Figure 1(b) shows the example when the rotation angle θ_i is estimated by this operation, the term $\exp(-j\theta_i)$ is multiplied to the separation weight, and extract the separation signal. Thus, an accurate separation and the extraction of the incident signals become possible.



(a) separated signal by FastICA (b) After phase compensation

Fig. 1: Constellation patterns of separated signals

C. BSS by FastICA

The proposed technique in this paper that separates digital modulation signals is summarized as follows.

1) The observed signal $\boldsymbol{X}$ is whitened, and $\tilde{\boldsymbol{X}}$ is obtained.
2) The optimal separation weight $\boldsymbol{W}$ is calculated by the FastICA algorithm.
3) The phase rotation angle θ_i of the obtained separation signal $\boldsymbol{Y}$ is estimated, and $\exp(-j\theta_i)$ is multiplied to the separation signals.

An accurate separation signal is obtained by the above-mentioned procedure. In the next section, the accuracy and the calculation speed of the Ref. [6] are compared with those of the proposed method.

4. Simulation

This section shows the simulation result of using the ICA via BER characteristics. We compare the proposed method with Ref. [6]. Specifications of simulation are shown in Table 1.

TABLE 1: SIMULATION PARAMETER

	Fig. 2	Fig. 3	Fig. 4	Fig. 5
Number of arrival signal	2	4		3
Number of elements	4			3
Array antenna	Half wavelength uniform linear array			
Modulation method	QPSK 16QAM	QPSK	16QAM	QPSK 16QAM
Number of snapshots	100,000 samples			
DOA of 1st signal	0°	−60°		0°
DOA of 2nd signal	40°	−20°		−60°
DOA of 3rd signal	–	20°		40°
DOA of 4th signal	–	60°		–
Power of 1st signal	0[dB]			
Power of 2nd signal	0[dB]	−5[dB]		0[dB]
Power of 3rd signal	–	−10[dB]		0[dB]
Power of 4th signal	–	−20[dB]		–

A. Case of 2 incident signals

Suppose that two QPSK or 16QAM signals arrive at ULA. At this time, the BER characteristics of the received signal that has come is shown in Fig. 2. As a result, we see that the proposed and Ref. [6] method have high and equal accuracy.

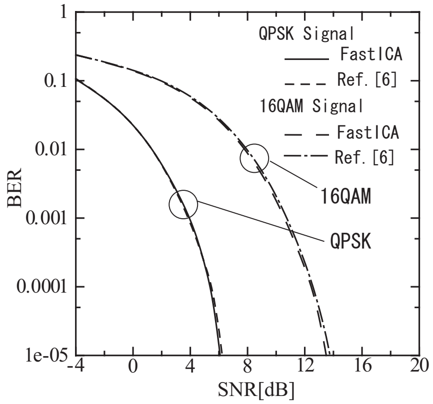


Fig. 2: BER characteristics for two QPSK (or 16QAM) signals

B. Case of 4 incident signals

Next, the characteristics when the number of coming signals is four signals is evaluated. Figures 3 and 4 show the result of the BER characteristics for the QPSK and 16QAM signals, respectively. From these figures, in the low SIR environment, though the signal can be separated, the accuracy is greatly deteriorated. Moreover, we see that there is no accuracy difference between the proposed method and Ref. [6].

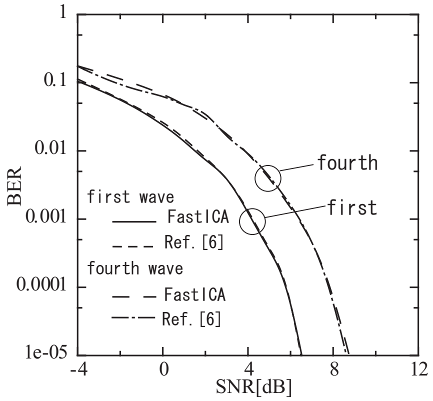


Fig. 3: BER characteristics for four QPSK signals

C. Case of QPSK and 16QAM signals

In the environment where QPSK signal are observed together with 16QAM signal, it is simulated whether either of signals are also extracted. Figure 5 show the BER characteristics of QPSK or 16QAM signals. As a result, even if the QPSK

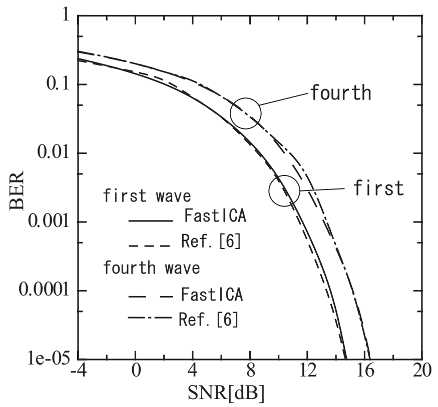


Fig. 4: BER characteristics for four 16QAM signals

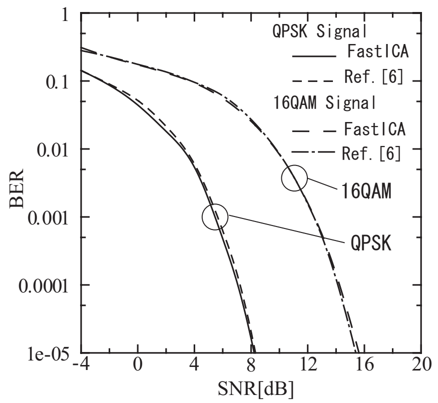


Fig. 5: BER characteristics for QPSK and 16QAM signals

signal exists together with 16QAM signal, we can separate signals with a good accuracy.

D. Comparison of calculation time

In this subsection, the computational cost of the proposed method and that of Ref. [6] are evaluated. Assume that the observed signals are separated if the array response value of the direction of the interference signal is low and stays constant. Also assume that the number of signals is two and SNR is 7[dB].

Figure 6 shows the comparison result of the calculation time when the number of arrays is changed. The comparison result at the calculation time of each process when the QPSK signal is received by for arrays is shown in Table 2. The calculation speed of FastICA is very fast, and it is very useful in a real environment as a result in the separation of both the QPSK and 16QAM signals.

5. Conclusion

A fast BSS method for digital modulation signals like QPSK 16QAM was presented. We proposed the compensation method to the phase rotation problem that arises when using FastICA. Moreover, the separation accuracy and the calculation time in Ref. [6] were compared with ICA method. From the above-mentioned result, this technique can separate signals in a very short time and with high accuracy as long as independence is satisfied among signals, and corresponds to all kinds of modulation types.

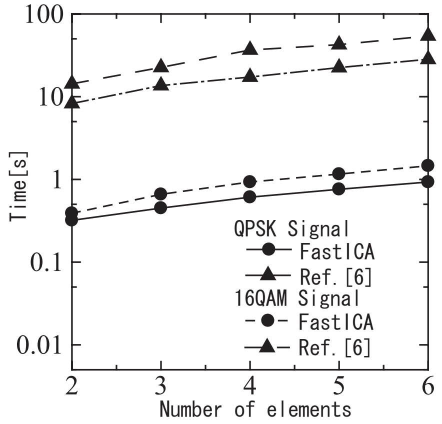


Fig. 6: Comparison of computation time

Table 2: Calculation time

	whitening	optimal weight searching	rotation angle correction	total
ICA of Ref. [6]		17.3[s]		17.3[s]
FastICA	0.0310[s]	0.67[s]	0.016[s]	0.70[s]

References

[1] B.Widrow, P.E.Mantey, L.J.Griffiths, B.B.Goode, ”Adaptive Antenna Systems”, Proc. IEEE, vol.55, No.12, pp.2143-2159, Dec. 1967.

[2] J.R.Treichler, B.G.Agee, ”A New Approach to Multipath Correction of Constant Modulus Signals”, IEEE Trans. Acoustic, Speech and Signal Processing, vol.31, No.2, pp.459-472, Apr. 1983.

[3] S.-I. Amari, A.Cichocki, and H.H.Yang, ”A new learning algorithm for blind source separation”, In Advances in Neural Information Processing Systems, vol.8, pp.757-763, 1996

[4] H.Sawada, R.Mukai, S.Araki, S.Makino, ”A Robust and Precise Method for Solving the Permutation Problem of Frequency-Domain Blind Source Separation”, IEEE Trans. Speech and Audio Processing, vol.12, pp.530-538, Sep. 2004.

[5] F.Asano, S.Ikeda, M.Ogawa, H.Asoh, N.Kitawaki, ”Combined Approach of Array Processing and Independent Component Analysis for Blind Separation of Acoustic Signals”, IEEE Trans. Speech and Audio Processing, vol.11, pp.204-215, May 2003.

[6] H.Imamura, J.Okello, H.Ochi, ”Blind source separation of PSK and amplitude modulated signals,” Proc. Int’l Sympo. on Intelligent Signal Processing and Communication Systems, pp. 343-346, Nov. 2004.

[7] E.Carlos, J.Takada, ”ICA Based Blind Source Separation Applied to Radio Surveillance”, IEICE Trans. Commun. vol.E86-B, no. 12, Dec. 2003.

[8] K.Yokoi, N.Hamada, ”ICA-Based Separation and DOA Estimation of Analog Modulated Signals in Multipath Environment”, IEICE Trans. Commun. Letter, vol.E88-B no. 11, Nov. 2005.

[9] A.Hyvarinen, ”Fast and robust fixed-point algorithms for independent component analysis”, IEEE Trans. Neural Networks, vol.10, pp.626-634, May 1999.