DOA Estimation of Desired Signals Using In-Phase Combining of Multiple Cyclic Correlations and Spatial Smoothing Processing

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Abstract – **The cyclic method performs the direction-of-arrival (DOA) estimation of the desired signals by using cyclic correlations of digital-modulation signals. This paper proposes a cyclic method which uses in-phase combining of multiple cyclic correlations (MCC) and the forward and backward spatial smoothing processing (FB-SSP). Also, the way of reducing the computation load in FB-SSP is provided. Computer simulation results show the enhanced performance of the proposed method.**

Index Terms — **Array antenna, DOA estimation, Multiple cyclic correlations, In-phase combining, Spatial smoothing processing.**

1. Introduction

The cyclic method based on MUSIC or ESPRIT performs the direction-of-arrival (DOA) estimation of the desired signals by using cyclic correlations of digital-modulation signals [1], [2]. In this paper, we propose the enhanced cyclic method which uses in-phase combining of multiple cyclic correlations (MCC) and the forward and backward spatial smoothing processing (FB-SSP) [3], [4]. In addition, we consider the method of generating correlation matrices which can reduce the computation load in FB-SSP [4]. Computer simulation demonstrates the proposed method can perform effectively DOA estimation of the desired signals.

2. Cyclostationarity of Signal and DOA Estimation

Most of digital signals used in mobile communications have cyclostationarity [1]. The cyclic auto-correlation function of signal $s(t)$ is defined by

$$R_{ss}(\alpha,\tau) \triangleq \left\langle s(t+\tau/2)\left\{s(t-\tau/2)e^{j2\pi\alpha t}\right\}^{*}\right\rangle_{\infty} \quad (1)$$

where α is frequency shift, τ is time shift, $< \cdot >_{\infty}$ denotes the infinite time average operator, and $*$ denotes complex conjugate. If $R_{ss}(\alpha,\tau)$ is nonzero for discrete values of α, then $s(t)$ has cyclostationarity with the cycle frequency of α. The cycle frequency is normally determined by carrier frequency or symbol rate of signal [2].

Consider that there are multiple desired signals and interferences incident on a uniform linear array. Then, the cyclic correlation matrix of the array input vector $\boldsymbol{x}(t)$ is given by

$$\boldsymbol{R}_{xx}(\alpha,\tau) \triangleq \left\langle \boldsymbol{x}(t+\tau/2)\boldsymbol{x}^{H}(t-\tau/2)e^{-j2\pi\alpha t}\right\rangle_{\infty} \quad (2)$$

When α and τ are equal to the parameters of desired signals which are not equal to those of interferences, the cyclic auto-correlation matrix $\boldsymbol{R}_{xx}(\alpha,\tau)$ is composed of desired signals only. By applying ESPRIT to $\boldsymbol{R}_{xx}(\alpha,\tau)$, we can obtain DOA estimates of the desired signals. This method is referred to as Cyclic ESPRIT [1].

3. The Use of Multiple Cyclic Correlations and FB-SSP

The conventional cyclic method uses single cyclic correlation (SCC). In this paper, we use multiple cyclic correlations (MCC) which are expressed as follows.

$$\boldsymbol{R}_{xx}(\pm\alpha,\pm\tau) = \left\langle \boldsymbol{x}(t\pm\tau/2)\boldsymbol{x}^{H}(t\mp\tau/2)e^{\mp j2\pi\alpha t}\right\rangle_{\infty} \quad (3)$$

In the cyclic method with MCC, the cyclic correlation values are increased by in-phase combining of multiple cyclic correlations of individual desired signals in SAGE algorithm [3].

To improve the average effect and decorrelate the multiple desired signals, we utilize the forward and backward spatial smoothing processing (FB-SSP) of multiple subarrays. It is known that the backward matrix $\boldsymbol{R}^{b}_{xx}$ is normally generated from the forward matrix $\boldsymbol{R}^{f}_{xx}$ as follows.

$$\boldsymbol{R}^{b}_{xx} = \boldsymbol{\Pi}(\boldsymbol{R}^{f}_{xx})^{*}\boldsymbol{\Pi} \quad (4)$$

where $\boldsymbol{\Pi}$ is the exchange matrix with ones on its antidiagonal and zeros elsewhere. We refer to the matrix thus obtained as simple backward (SB) matrix. Note that the backward matrix generated by (4) has different cycle frequency from the forward matrix because of complex conjugate. That is to say, for $\boldsymbol{R}^{f}_{xx}(\alpha,\tau) = \boldsymbol{R}_{xx}(\alpha,\tau)$, we have

$$\boldsymbol{R}^{b}_{xx}(-\alpha,\tau) = \boldsymbol{\Pi}(\boldsymbol{R}^{f}_{xx}(\alpha,\tau))^{*}\boldsymbol{\Pi} \quad (5)$$

That is why FB-SSP with SB matrices is not applicable to the cyclic method with SCC.

On the other hand, we can have the cyclic backward (CB) matrix which is obtained by putting the backward input vector $\boldsymbol{x}^{b}(t) = \boldsymbol{\Pi}\boldsymbol{x}^{*}(t)$ into (2). However, the number of correlation matrices generated by the time average is increased, leading to increased computation load.

Here, it should be noticed that SB matrix which is given by (5) can be used effectively for MCC as shown in (3). Therefore, we can reduce the computation load by using SB matrices in the cyclic method with MCC.

4. Computer Simulation

Computer simulation is carried out under the conditions described in Tables I to III. We have four methods compared. The method using the forward-only SSP (F-SSP) with the four correlation matrices of (3) is called 4MCC. The method using FB-SSP with the four correlation matrices and corresponding

CB matrices is called 4MCC-CB. The method using FB-SSP with the four correlation matrices and SB matrices is called 4MCC-SB. Finally, the method that reduces the number of correlation matrices from four to two in 4MCC-CB is called 2MCC-CB. Fig. 1 illustrates the correlation matrices used in the four methods. As a result, Fig. 2 shows the RMSE of the DOA estimates as a function of input SNR, and Fig. 3 shows the RMSE of the DOA estimates as a function of the number of snapshots. Table IV represents computation times of the four methods. It is found from Fig. 2 and Fig. 3 that 4MCC-CB, 4MCC-SB, and 2MCC-CB can provide high accuracy in DOA estimation. Also, Table IV shows that 2MCC-CB provides the shortest computation time, and you can see that 2MCC-CB has 41.1% reduction in computation time compared to 4MCC-CB. From the above results, it can be said that 2MCC-CB may be the best method in both estimation accuracy and computation.

5. Conclusion

We considered DOA estimation of desired signals which uses in-phase combining of multiple cyclic correlations (MCC) and FB-SSP. Computer simulation results have shown that the method using two cyclic correlation matrices with corresponding cyclic backward matrices (2MCC-CB) is most effective in both estimation accuracy and computation.

References

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TABLE I
Simulation Conditions

Carrier frequency	2.0GHz
Array configuration	Uniform linear array
Number of elements	6
Number of subarray elements	4
Element spacing	0.5λ
Number of desired signals	3
Number of interferences	3
Modulation scheme	QPSK
Input SNR	$-10 \sim 30$ [dB]
Number of snapshots	600
Number of trials	300

TABLE II
Wave Parameters

	Desired signals	Interferences
DOA[deg.]	[−40, 20, 50]	[−60, −30, 10]
Amplitude[dB]	[0, 0, 0]	[0, 0, 0]
Delay time[symbols]	[0, 0, 0]	[0, 0, 0]
Symbol rate[Msps]	2.0	1.5

TABLE III
Computer Specifications

CPU	Intel Core i7-920
RAM	2.0 GB
OS	Windows 7 Professional
Software	MATLAB 2015

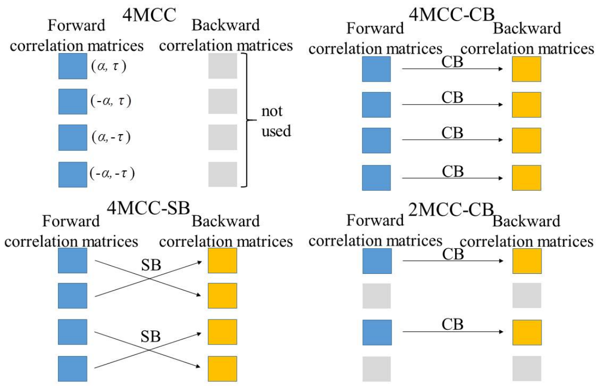

Fig. 1. Methods of generating correlation matrices

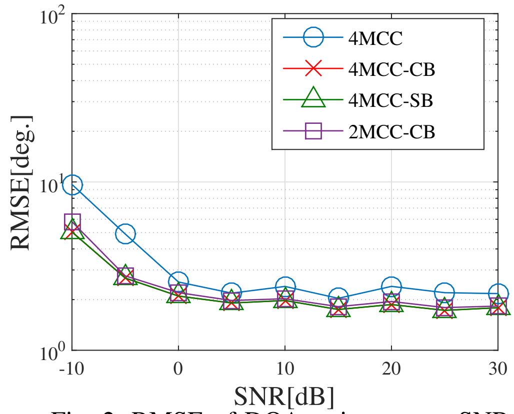

Fig. 2. RMSE of DOA estimates vs. SNR

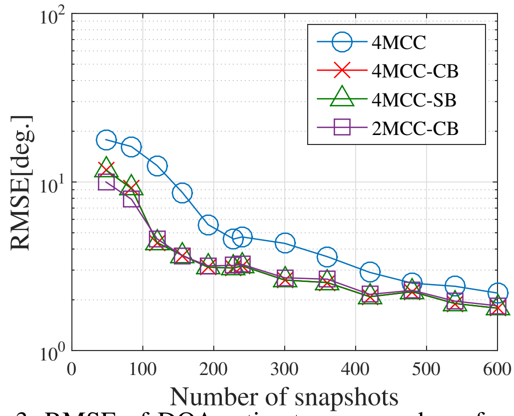

Fig. 3. RMSE of DOA estimates vs. number of snapshots

TABLE IV
Computation Times of Four Methods

4MCC	0.314 sec
4MCC-CB	0.542 sec
4MCC-SB	0.342 sec
2MCC-CB	0.319 sec