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Wideband Cyclic MUSIC Algorithms: A Frequency-Domain Approach

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Abstract: In this paper, we propose two spectral cyclic MUSIC DOA estimation algorithms for wideband cyclostationary signals: the wideband spectral cyclic conjugate MUSIC (WSCCM) algorithm and the extended wideband spectral cyclic MUSIC (EWSCM) algorithm. The proposed algorithms can be applied to estimate the spectral cyclic conjugate correlation matrix and the extended spectral cyclic correlation matrix of wideband cyclostationary signals. The presented algorithms do not require any knowledge of the optimal time lag parameter, which appears in the similar algorithms in time domain. In the proposed algorithms, the DOAs are estimated at each spectral component of the selected frequency band for a cyclic frequency of interest. This can be used to form the azimuth cyclic frequency diagram, similar to the azimuth frequency diagram in wideband direction-finding systems. Some simulation results are provided to confirm the theoretical findings.

Keywords: Cyclostationarity, direction of arrival (DOA), MUSIC, spectral cyclic (conjugate) correlation matrix.

1 Introduction

MANY signal selective algorithms for DOA estimation have been developed to overcome some limitations of the standard approaches, such as the possibility to automatically classify signals as desired or undesired. The first signal selective algorithm based on cyclostationarity properties is proposed by Gardner [1], and named Cyclic MUSIC. Since then, many algorithms for DOA estimation have been developed to improve performance of Cyclic MUSIC [2, 3, 4]. An Extended

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Cyclic MUSIC algorithm [2] has been proposed to improve the performance of the Cyclic MUSIC algorithm by exploiting both cyclic correlation and cyclic conjugate correlation. However, Cyclic MUSIC and Extended Cyclic MUSIC algorithms were developed only for DOA estimation of narrowband signals. The most serious limitation of the algorithms presented in [1, 2] is reflected in the fact that both algorithms used estimation of the cyclic correlation matrix and the extended cyclic correlation matrix in time domain using one time lag parameter τ. To overcome this limitation, [3] proposes the averaged (conjugate) cyclic MUSIC (ACM) algorithm by averaging the cyclic or cyclic conjugate correlation matrix over different time lags (time delay). The proposed algorithms are designed for wideband cyclostationary signals. The Extended Wideband Cyclic MUSIC (EWCM) algorithm, which exploits both the averaged cyclic and averaged cyclic conjugate correlation matrix, is also presented in [3].

Another possible approach to solve the problem of optimal time lag knowledge is proposed in [4] based on the Fourier transformation of the cyclic correlation matrix. Using this idea, in [5], an algorithm for DOA estimation based on cyclostationarity properties of narrowband signals in frequency domain is proposed. Instead of the cyclic correlation matrix, the spectral cyclic correlation matrix (SCCM) is evaluated in the proposed algorithm. However, the algorithms proposed in [4] and [5] exploit only the cyclic property for DOA estimation, and they do not have the potential performance merit as that of the Averaged Conjugate Cyclic MUSIC and Extended Cyclic MUSIC.

In this paper, we propose the wideband spectral cyclic conjugate MUSIC (WSCCM) algorithm and the extended wideband spectral cyclic MUSIC (EWSCM) algorithm. The algorithm presented in [5] exploits only cyclic properties of signals for DOA estimation, but not cyclic conjugate properties. It is important to note that complete analysis of wideband cyclostationary signals requires estimation of both the spectral cyclic and spectral cyclic conjugate correlation matrix, because some signals have both nonzero spectral cyclic correlation and nonzero spectral cyclic conjugate correlation, e.g., binary phase shift keying (BPSK) or minimum shift keying (MSK). Because of that, we propose WSCCM and EWSCM algorithms modifying the algorithm in [5] with the idea of [2, 4]. These algorithms perform signal selective DOA estimation of wideband and narrowband signals exploiting the spectral cyclic conjugate correlation matrix and extended spectral cyclic correlation matrix. The spectral cyclic properties of cyclostationary signals correspond to the spectral correlation at some frequency associated with the multiple of the baud rate. The spectral cyclic conjugate properties of cyclostationary signals correspond to the spectral correlation at some frequency associated with the carrier frequency. The proposed algorithms can be used in wideband direction finding systems in order to form the azimuth cyclic frequency diagram in the process of spectrum segmentation. Both of our methods work well when signals exploit cyclic properties at the same cyclic frequency.

2 Background

2.1 Wideband data model in frequency domain

Consider an antenna array composed of L omnidirectional elements, which receives K uncorrelated wideband signals $s_k(t)$, $k = 1,\ldots,K$ in a selected frequency sub-band f_BW at central frequency f_C. The wavefronts of K signals impinge on the antenna array from directions $\Theta_1,\Theta_2,\ldots,\Theta_k$ where Θ_k represents azimuth θ_k and elevation φ of the kth signal. Let K_a from K signals exhibit cyclic or cyclic conjugate property at a selected cycle frequency a and let the other $K-K_a$ signals exhibit cyclic or cyclic conjugate features at different cycle frequencies. If we consider that K_a signals are contained in the vector $\boldsymbol{s}(t)$, then $K-K_a$ signals, which exhibit cyclic or cyclic conjugate features at cycle frequencies different from α and any noise are lumped into the vector $\boldsymbol{n}(t)$. If the wideband assumption holds, in the temporal frequency domain, the sensor outputs can be represented in a matrix-vector form as frequency dependent narrowband signals [4, 5].

$$\boldsymbol{X}(f) = \boldsymbol{A}(\theta, f)\cdot\boldsymbol{S}(f) + \boldsymbol{N}(f) \tag{1}$$

where the frequency-dependent steering matrix is $\boldsymbol{A}(\Theta, f) = [\boldsymbol{a}(\Theta_1, f)\ \boldsymbol{a}(\Theta_2, f)\ldots\boldsymbol{a}(\Theta_{K_\alpha}, f)]$ whose columns are steering vectors corresponding to the signals of interest (SOIs). $\boldsymbol{X}(f) = [X_1(f)\ X_2(f)\ldots X_L(f)]^T$ where $[\cdot]^T$ denotes the transpose, is the finite time Fourier transform of the wideband signals received in the observed interval T. $\boldsymbol{S}(f) = [S_1(f)\ S_2(f)\ldots S_{K_\alpha}(f)]^T$ is the finite time Fourier transform of K_a signals down converted to base band by frequency f_C in the same observed interval, $\boldsymbol{N}(f) = [N_1(f)\ N_2(f)\ldots N_L(f)]^T$is the finite time Fourier transform of the interfering signals and the white Gaussian noise.

If the frequency in (1) is fixed, it is possible to use narrowband signal subspace methods such as MUSIC. By the discrete Fourier transformation (DFT) we can perform a narrowband decomposition to obtain sensor outputs with a fixed temporal frequency. The decomposed signal can be represented as:

$$\boldsymbol{X}(f_h) = \boldsymbol{A}(\Theta, f_h)\cdot\boldsymbol{S}(f_h) + \boldsymbol{N}(f_h) \tag{2}$$

where the f_h frequency component is denoted by f_h, $h \in [1,H]$, where H is the total number of spectral components for the selected frequency sub-band f_{BW}.

2.2 Wideband spectral cyclic MUSIC algorithm

Under the condition that the contribution to the SCCM from $K-K_a$ signals and from any noise converges to zero as the integration time tends to infinity, the SCCM of the received signal is given by [4, 5]:

$$\begin{aligned} \boldsymbol{R}_{xx}^{\alpha}(f_h) &= E\Big[\boldsymbol{X}\big(f_h+\frac{\alpha}{2}\big)X^H\big(f_h-\frac{\alpha}{2}\big)\Big] \\ &= \boldsymbol{A}\big(\Theta, f_h+\frac{\alpha}{2}\big)R_{SS}^{\alpha}(f_h)A\big(\Theta, f_h-\frac{\alpha}{2}\big)^H \end{aligned} \tag{3}$$

where $(\cdot)^H$ denotes the conjugate transpose, and where $\boldsymbol{R}_{SS}^{\alpha}(f_h)$ is the spectral cyclic correlation matrix of the signal in the base-band at the hth spectral component. The selected cyclic frequency α denotes the distance between the two spectral components $f_1 = f_h+\alpha/2$ and $f_2 = f_h-\alpha/2$.

One of the advantages of the Wideband Spectral Cyclic MUISC algorithm in frequency domain is the ability to increase the number of detectable signals by estimating SCCM on each spectral component from the selected frequency sub-band at the selected cyclic frequency of interest. The number of detectable signals, which exhibit cyclic features at the selected cycle frequency, is $L-1$ at each spectral component. Using this algorithm, it is possible to estimate DOAs for more signals that use the same frequency sub-band simultaneously and exhibit cyclic features at the same or different cycle frequencies.

3 Wideband Spectral Cyclic Conjugate Music (WSCCM) Algorithm

Instead of the calculation of SCCM like in [4] and [5], we propose to calculate SCCCM and estimate DOAs based on conjugate cyclic properties of signals. Our goal is to obtain a matrix which has a form similar to (3).

Under the condition that the contribution to the SCCCM from K-K signals and from any noise converges to zero as the integration time tends to infinity, the estimation of the spectral cyclic conjugate correlation matrix of the real-valued signals can be expressed as:

$$\begin{aligned} \boldsymbol{R}_{xx^*}^{\alpha}(f_h) &= E\Big[\boldsymbol{X}\big(f_h+\frac{\alpha}{2}\big)\boldsymbol{X}^T\big(f_h-\frac{\alpha}{2}\big)\Big] \\ &= \boldsymbol{A}\big(\Theta, f_h+\frac{\alpha}{2}\big)\boldsymbol{R}_{SS^*}^{\alpha}(f_h)\boldsymbol{A}\big(\Theta, f_h-\frac{\alpha}{2}\big)^T \end{aligned} \tag{4}$$

where

$$\boldsymbol{R}_{SS^*}^{\alpha}(f_h) = E\Big[\boldsymbol{S}\big(f_h+\frac{\alpha}{2}\big)\boldsymbol{S}^T\big(f_h-\frac{\alpha}{2}\big)\Big]$$

is the spectral cyclic conjugate correlation matrix of real-valued signals at the hth spectral component for the cyclic frequency of interest α.

If we observe a bi-frequency plane (f,α), all signals in a selected frequency band exhibit conjugate cyclostationarity properties around the intermediate frequency of the selected frequency sub-band, or around the zero-intermediate frequency after down-conversion. However, in the case of complex-valued signals, the spectral cyclic conjugate correlation matrix can not be estimated using (4), because there is no symmetry in the Fourier transform of the received signal around the zero-intermediate frequency. In the case of the complex-valued signals, the estimation of the spectral cyclic conjugate correlation matrix for cyclic frequency α can be expressed as:

$$\begin{aligned}\boldsymbol{R}_{xx^*}^{\alpha}(f_i) &= E\left[\boldsymbol{X}\left(\frac{\alpha}{2}\right)\boldsymbol{X}^T\left(\frac{\alpha}{2}\right)\right]\\ &= \boldsymbol{A}\left(\Theta,\frac{\alpha}{2}\right)\boldsymbol{R}_{SS^*}^{\alpha}(f_i)\boldsymbol{A}\left(\Theta,\frac{\alpha}{2}\right)^T\end{aligned} \tag{5}$$

where f_i denotes the ith frequency component that corresponds to the zero-intermediate frequency, $\alpha = 2f_h$, and

$$\boldsymbol{R}_{xx^*}^{\alpha}(f_i) = E\left[\boldsymbol{S}\left(\frac{\alpha}{2}\right)\boldsymbol{S}^T\left(\frac{\alpha}{2}\right)\right]$$

is the spectral cyclic conjugate correlation matrix of signals in the base-band at the ith spectral component for the cyclic frequency of interest α.

Digital Frequency Smoothed Method DFSM [6] can be used in order to frequency smooth the spectral cyclic conjugate correlation matrix in a frequency range around the zero-intermediate frequency. In this case, the frequency-smoothed spectral cyclic conjugate correlation matrix in the range $|m| \leq M/2$ can be expressed as:

$$\boldsymbol{R}_{xx^*}^{\alpha}(f_i) = E\left[\boldsymbol{X}\left(\frac{\alpha}{2}+m\right)\boldsymbol{X}^T\left(\frac{\alpha}{2}-m\right)\right] \tag{6}$$

where m corresponds to the mf_{BW}/H frequency component.

The proposed algorithm for DOA estimation of wideband cyclostationary signals based on estimation of SCCCM can be described in few steps.

Step 1. The received continuous-time signals $x_l(t)$, $l = 1,\ldots,L$ are down converted to the base-band by IQ mixing at each antenna and then converted to discrete-time by sampling with the sampling frequency $f_s = f_{BW}$.

Step 2. The received discrete-time signals $x_l(t)$ are divided into Q vectors, $x_l^q(t)$, $l = 1,\ldots,L$, $q = 1,\ldots,Q$ (the total number of vectors is LQ).

Step 3. The H-point DFT for each of the LQ vectors is calculated $X_l^q(f) = \mathrm{DFT}[x_l^q(n)]$, $l = 1,\ldots,L$, $q = 1,\ldots,Q$. The number of points for the DFT depends on the cyclic resolution $\alpha_{rez} = f_{BW}/H$.

Step 4. The spectral cyclic conjugate correlation matrix is evaluated for a selected cyclic frequency $\alpha = 2f_h$.

$$\boldsymbol{R}_{xx^*}^{\alpha}(f_i) = \frac{1}{Q}\sum_{q=1}^{Q}\sum_{m}\boldsymbol{X}^q\Big(\frac{\alpha}{2}+m\Big)\boldsymbol{X}^q\Big(\frac{\alpha}{2}-m\Big)^T \tag{7}$$

A simplified spectral cyclic conjugate correlation matrix computational flow graph of the proposed algorithm at a selected cycle frequency is shown in Fig. 1.

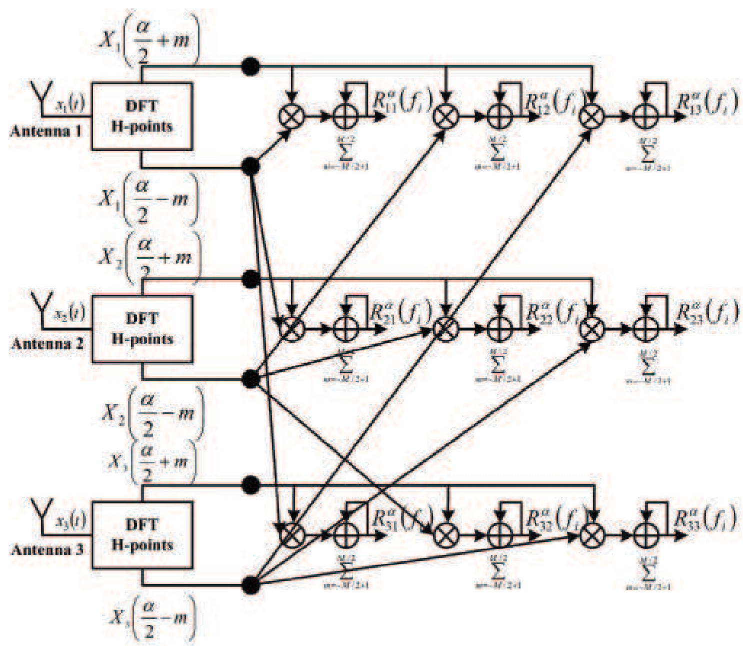

Fig. 1. Simplified SCCCM computational flow graph for the proposed algorithm.

Step 5. The number of signals K_α, which exploit the cyclic conjugate properties at the selected cyclic frequency, is determined by using Canonical Correlation Significance Test (CCST).

Step 6. DOA is estimated using MUSIC algorithm, at the selected cyclic frequency.

$$P_{MUSIC}\Big(\Theta,\frac{\alpha}{2}\Big) = \frac{\boldsymbol{a}\big(\Theta,\frac{\alpha}{2}\big)\boldsymbol{a}\big(\Theta,\frac{\alpha}{2}\big)^*}{\Big\|\boldsymbol{a}\big(\Theta,\frac{\alpha}{2}\big)\boldsymbol{E}_{n,\alpha}\Big\|^2} \tag{8}$$

where $\boldsymbol{a}(\Theta,\alpha/2)$ is the steering vector evaluated at the frequency component that corresponds to $\alpha/2$, and $\boldsymbol{E}_{n,a}$ is the noise subspace matrix of $\boldsymbol{R}_{xx^*}^{\alpha}(f_i)$.

Step 7. In order to estimate DOA at all cyclic frequencies repeat steps from step 4. to step 6 for each of the H frequency components, $f_h = \alpha/2$.

Step 8. The final estimates of DOAs can be performed averaging those spectral components which are joined in the same signals

4 Extended Wideband Spectral Cyclic MUSIC (EWSCM) Algorithm

To develop our EWSCM algorithm, an extended spectral wideband cyclic correlation matrix will be constructed. In order to exploit both the spectral cyclic correlation matrix and spectral cyclic conjugate correlation matrix for DOA estimation in frequency domain, the following extended data vector is formed:

$$\boldsymbol{X}_E^{\alpha}(f_h) = \begin{bmatrix} \boldsymbol{X}(f_h + \frac{\alpha}{2}) \\ \boldsymbol{X}^*(f_h - \frac{\alpha}{2}) \end{bmatrix} \tag{9}$$

where $\boldsymbol{X}_E^{\alpha}(f_h)$ is an extended data vector of the signal received at the selected frequency component f_h and the cycle frequency of interest α. $\boldsymbol{X}_E^{\alpha}(f_h)$ is a $2L \times 1$ matrix. The extended spectral cyclic correlation matrix for the extended data vector can be calculated as:

$$\begin{aligned} R_E^{\alpha}(f_h) &= E[\boldsymbol{X}_E^{\alpha}(f_h)\boldsymbol{X}_e^{-\alpha^H}(f_h)] \\ &= \begin{bmatrix} E[\boldsymbol{X}(f_h + \frac{\alpha}{2})\boldsymbol{X}^H(f_h - \frac{\alpha}{2})] & E[\boldsymbol{X}(f_h + \frac{\alpha}{2})\boldsymbol{X}^T(f_h + \frac{\alpha}{2})] \\ E[\boldsymbol{X}^*(f_h - \frac{\alpha}{2})\boldsymbol{X}^H(f_h - \frac{\alpha}{2})] & E[\boldsymbol{X}^*(f_h - \frac{\alpha}{2})\boldsymbol{X}^T(f_h + \frac{\alpha}{2})] \end{bmatrix} \end{aligned} \tag{10}$$

where $\boldsymbol{R}_E^{\alpha}(f_h)$ is the extended spectral cyclic correlation matrix with dimensions $2L \times 2L$.

Based on the definition of the SCCM (2) and SCCCM (5), we can replace the lower two sub-matrices with:

$$\left(\boldsymbol{R}_{xx}^{-\alpha}(f_h)\right)^* = E\left[\boldsymbol{X}(f_h - \frac{\alpha}{2})^*\boldsymbol{X}^T(f_h + \frac{\alpha}{2})\right] \tag{11}$$

and

$$\left(\boldsymbol{R}_{xx^*}^{\alpha_1}(f_i)\right)^* = E\left[\boldsymbol{X}^*(f_h - \frac{\alpha}{2})\boldsymbol{X}^H(f_h - \frac{\alpha}{2})\right] \tag{12}$$

where $\alpha_1 = 2f_h - \alpha$.

In order to exploit cyclic and cyclic conjugate properties of the wideband signal for DOA estimation, the SCCM and SCCCM have to be estimated at the same cyclic frequency of interest α. Based on (10) and (11), it can be concluded that

SCCM and SCCCM matrices are not estimated at the same cyclic frequency. To estimate SCCM and SCCCM matrices at the same cyclic frequency α it is necessary that the carrier frequency of the selected signal corresponds to the central frequency of the selected frequency sub-band. In that case, after the down conversion in the base-band, the signal exhibits cycle conjugate properties at the same cyclic frequency as the cycle properties for some cyclostationary signal like the BPSK signal. Signals in the base-band exhibit cyclic and cyclic conjugate properties at spectral components f_i which correspond to the zero-intermediate frequency.

Based on (10) and (11), and by replacing f_h with f_i it is possible to construct the ESCCM matrix similarly to [3]:

$$\boldsymbol{R}_E^{\alpha}(f_i) = \begin{bmatrix} \boldsymbol{R}_{xx}^{\alpha}(f_i) & \boldsymbol{R}_{xx^*}^{\alpha}(f_i) \\ \left(\boldsymbol{R}_{xx^*}^{-\alpha}(f_i)\right)^* & \left(\boldsymbol{R}_{xx}^{-\alpha}(f_i)\right)^* \end{bmatrix} \tag{13}$$

This ESCCM matrix can be written in the following form:

$$\begin{aligned} \boldsymbol{R}_E^{\alpha}(f_i) = &\begin{bmatrix} \boldsymbol{A}(\Theta, \frac{\alpha}{2}) & \mathbf{0} \\ \mathbf{0} & \boldsymbol{A}^*(\Theta, -\frac{\alpha}{2}) \end{bmatrix} \begin{bmatrix} \boldsymbol{R}_{xx}^{\alpha}(f_i) & \boldsymbol{R}_{xx^*}^{\alpha}(f_i) \\ \left(\boldsymbol{R}_{xx^*}^{-\alpha}(f_i)\right)^* & \left(\boldsymbol{R}_{xx}^{-\alpha}(f_i)\right)^* \end{bmatrix} \\ &\begin{bmatrix} \boldsymbol{A}(\Theta, \frac{\alpha}{2}) & \mathbf{0} \\ \mathbf{0} & \boldsymbol{A}^*(\Theta, -\frac{\alpha}{2}) \end{bmatrix}^H \end{aligned} \tag{14}$$

The matrix $\boldsymbol{A}(\Theta, \alpha/2)$ is evaluated at the frequency $f_C + \alpha/2$ because it is supposed that the carrier frequency of the selected signal is the same as the central frequency of the selected frequency sub-band.

The DOAs are estimated by using the spatial spectrum of the Extended Wideband Cyclic MUSIC method proposed in [3]. The spatial spectrum has the form:

$$\boldsymbol{P} = \left[\lambda_{min}[\boldsymbol{B}^H(\Theta, \frac{\alpha}{2})\boldsymbol{U}_N\boldsymbol{U}_N^H\boldsymbol{B}(\Theta, -\frac{\alpha}{2})]\right]^{-1} \tag{15}$$

where $\lambda_{min}[\cdot]$ denotes the minimum eigenvalue of the matrix $\boldsymbol{B}^H(\Theta, \alpha/2)\boldsymbol{U}_N\boldsymbol{U}_N^H\boldsymbol{B}(\Theta, -\alpha/2)$, $\boldsymbol{U}_N$ is the noise subspace of $\boldsymbol{R}_E^{\alpha}(f_i)$, estimated by applying the SVD, and $\boldsymbol{B}(\Theta, \alpha/2)$ is a matrix defined as:

$$\boldsymbol{B}(\Theta, \frac{\alpha}{2}) = \begin{bmatrix} \boldsymbol{a}(\Theta, \frac{\alpha}{2}) & \mathbf{0} \\ \mathbf{0} & \boldsymbol{a}^*(\Theta, -\frac{\alpha}{2}) \end{bmatrix} \tag{16}$$

5 Simulation Results

Three simulations have been carried out in order to illustrate the effectiveness of the proposed algorithms. In all simulated examples it is supposed that the wideband signals are received by a linear, uniformly spaced array with five antennas, spaced by a half wavelength of frequency $f_A = 20\text{MHz}$ ($\lambda_A = c/f_A = 2d$) where d denotes the distance between two adjacent antennas in the observed time interval around $\Delta T = 5\text{ms}$ (96256 samples). Frequency sub-band $f_{BW} = 19.2\text{MHz}$ is selected at the central frequency $f_C = 20\text{MHz}$. In all simulations the length of the FFT was H=1024.

In the first example, the possibility to estimate DOAs exploiting both cyclostationarity and conjugate cyclostationarity is tested. The results obtained by the proposed algorithm are compared with the Wideband Spectral Cyclic MUSIC algorithm and Wideband Spectral Cyclic Conjugate MUSIC algorithm. It is supposed that SOIs arrive at the antenna array from the azimuth of 0°, 30° and 15° and elevation 0°. The carrier frequencies of SOIs are $f_{C_1} = 20\text{MHz}$, $f_{C_2} = 21.6\text{MHz}$, and $f_{C_3} = 20\text{MHz}$ The signal to noise ratio (SNR) is 10 dB for each signal.

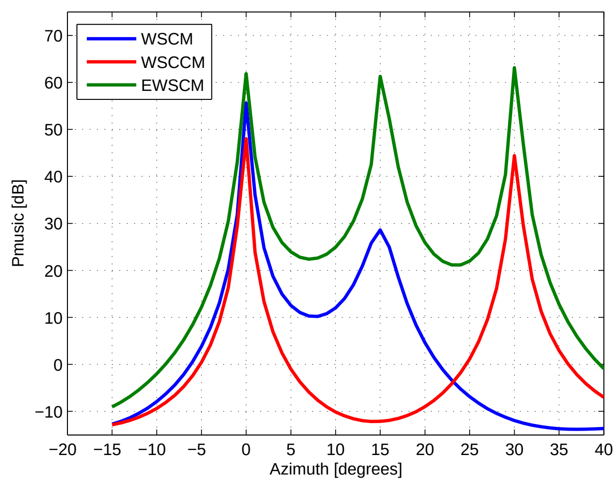

Fig. 2. Spatial spectra for environment containing three wideband SOIs with 0°, 15° and 30° DOA estimated by using WSCM, WSCCM and EWSCM.

The first SOI is a wideband BPSK signal with the symbol interval of $T_0 = 0.10417\mu\text{s}$ which exhibits the cyclic property at the cyclic frequency $\alpha_1 = 1/T_0 = 9.6\text{MHz}$ and the conjugate cyclic property at cycle frequencies $\alpha_{2,3} = 2(f_{C_1} - f_C) \pm 1/T_0 = \pm 9.6\text{MHz}$. The second SOI is also a wideband BPSK signal with the symbol interval of $T_0 = 0.15625\mu\text{s}$ which exhibits the cyclic property at the cyclic frequency $\alpha_1 = 1/T_0 = 6.4$MHz and the conjugate cyclic properties at cycle frequencies $\alpha_{2,3} = 2(f_{C_1} - f_C) \pm 1/T_0$ $\alpha_2 = 9.6$MHz, $\alpha_3 = 3.2$MHz. The third SOI is an MSK signal with the symbol interval of $T_0 = 0.10417\mu$s which exhibits the cyclic property at cyclic frequency $\alpha_1 = 1/T_0 = 9.6$MHz and the conjugate cyclic properties at cycle frequencies $\alpha_{2,3} = 2(f_{C_1} - f_C) \pm 1/T_0 = \pm 4.8$MHz.

Fig. 2 shows the DOAs estimation using the algorithms based on the estimation of ESCCM, SCCM and SCCCM matrices at the cycle frequency $\alpha = 9.6MHz$. Based on the results shown in Fig. 2, it can be concluded that using the Extended Wideband Spectral Cyclic MUSIC algorithm in frequency domain, it is possible to estimate DOAs that exploit both cyclostationarity and conjugate cyclostationarity of the received signals. Using the Wideband Spectral Cyclic MUSIC and Wideband Spectral Cyclic Conjugate MUSIC algorithms it is not possible to detect all signals which exhibit cyclostationarity and conjugate cyclostationarity at a selected cyclic frequency.

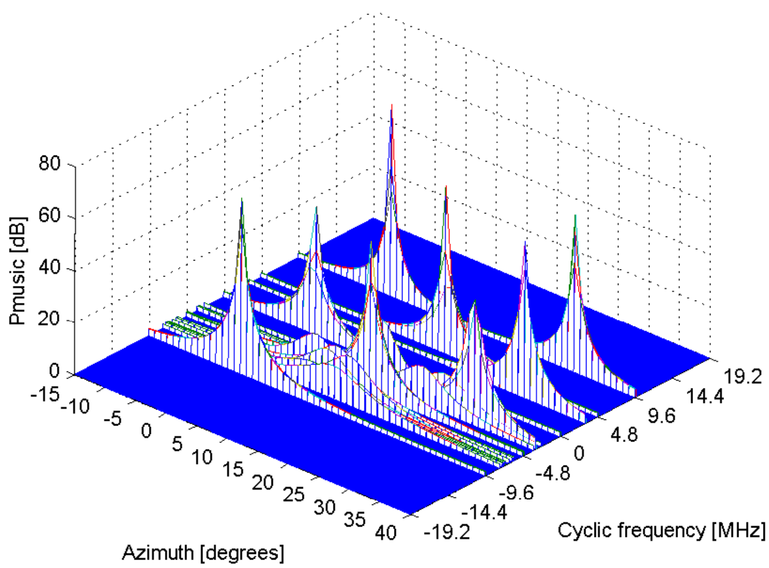

Fig. 3. 3-D spatial spectra for environment containing three wideband SOIs with 0°, 15° and 30° DOA estimated by using WSCCM algorithm.

The DOAs estimation using the proposed WSCCM algorithm, based on the estimation of SCCCM, is shown in Fig. 3. Based on the results shown in Fig. 3, it can be concluded that the proposed algorithms enable detection and estimation DOAs of wideband cyclostationary signals that exhibit cyclic conjugate properties. Using the proposed algorithms three SOIs are detected. Two pairs of three cyclic frequencies with the same estimated DOAs correspond to BPSK signals and two cyclic frequencies with the same DOAs correspond to MSK signals.

In the following example, the dependence of the mean error (RMSE) of the estimated DOA on the signal bandwidth to carrier frequency ratio is studied. The RMSE of the estimated DOA for the algorithm proposed in [5] varies with the chosen frequency for evaluating the steering vector. The wideband spectral cyclic conjugate MUSIC algorithm and extended wideband spectral cyclic MUSIC algorithm should not have this problem. In order to see this effect, in the example, the signal bandwidth to carrier frequency ratio is varied from 3.33% to 66.66%. It is supposed that the SOI is a BPSK signal which arrives at the antenna array from the azimuth of 10°. The DOA is estimated using the proposed algorithms for the case of wideband signals and their forms for narrowband signals. In case of narrowband signals, the steering vector is evaluated at the carrier frequency of the signal. For wideband signals, the steering vector is evaluated at the frequency which depended on the chosen cyclic frequency and carrier frequency.

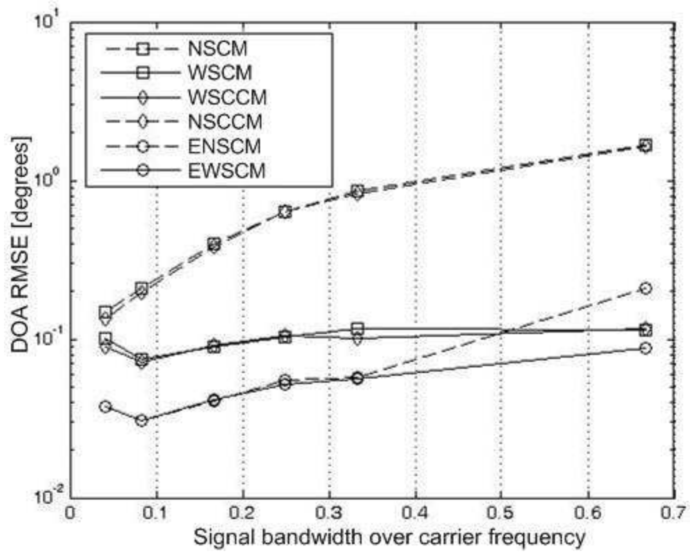

Fig. 4. RMSE of the estimated DOA versus signal bandwidth to carrier frequency ratio

The algorithms are run 100 times and the RMSE of the estimated DOA versus the signal bandwidth to carrier frequency ratio is shown in Fig. 4. Based on the results shown in Fig. 4, we can notice that the RMSE of the estimated DOA for the proposed wideband algorithms is almost the same for different signal bandwidth to carrier frequency ratios. In the case of narrowband algorithms, RMSE of the estimated SOI changes proportionally with the signal bandwidth to carrier frequency ratio. This effect is not present when using the extended narrowband spectral cyclic MUSIC algorithm. Based on the obtained results, we can notice that the wideband and narrowband extended spectral cyclic MUSIC algorithms gave almost the same RMSE of the estimated DOA up to 33.33% of the signal bandwidth to carrier frequency ratio.

6 Conclusion

This paper has presented a frequency domain approach for wideband Cyclic MUSIC algorithms. The proposed algorithms can be applied to estimate the spectral cyclic conjugate correlation matrix and the extended spectral cyclic correlation matrix of wideband cyclostationary signals. In these algorithms DOAs are estimated at each spectral component of the selected frequency band for the cyclic frequency of interest. This can be used to form the azimuth versus cyclic frequency diagram, similar to the azimuth versus frequency diagram in wideband direction-finding systems. The effectiveness of the proposed algorithms has been demonstrated by simulation results.

References

[1] W. A. Gardner, "Simplification of MUSIC and ESPRIT by exploitation of cyclostationarity," *Proc. IEEE*, vol. 76, no. 7, pp. 845–847, July 1988.

[2] P. Charge, Y. Wang, and J. Saillard, "An extended cyclic MUSIC algorithm," *IEEE Trans. On Signal Processing*, vol. 5, no. 7, pp. 1695–1701, July 2003.

[3] H. Yan and H. H. Fan, "Wideband cyclic MUSIC algorithms," *Signal Processing (Elsevier)*, vol. 85, pp. 643–649, Mar. 2005.

[4] K. D. Mauck, "Wideband cyclic MUSIC," in *IEEE Int. Conf. on Acoustic, Speech and Signal Processing*, Apr. 1993, pp. IV–288–291.

[5] I. P. Pokrajac, D. Vučić, and M. Erić, "Direction of arrival estimation via exploitation of cyclostationarity, a frequency domain approach," in *Proc. of EUROCON 2005 Conf.*, Belgrade, Serbia, Nov. 22–24, 2005, pp. 1606–1609.

[6] W. A. Brown and H. H. Loomis, "Digital implementations of spectral correlation analyzers," *IEEE Trans. on Signal Processing*, vol. 41, no. 2, pp. 703–720, Feb. 1993.