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Estimating the Number of Wideband Radio Sources

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ABSTRACT

In this paper, a new approach for estimating the number of wideband sources is proposed which is based on RSS or ISM algorithms. Numerical results show that the MDL-based and EIT-based proposed algorithm have a much better detection performance than that in EGM and AIC cases for small differences between the incident angles of sources. In addition, for similar conditions, RSS algorithm offers higher detection probability compared to ISM one, meanwhile it needs a heavy computational complexity than ISM. Furthermore, the effect of bandwidth on the performance of the proposed algorithm is studied. Simulation results show different detection probabilities for the proposed RSS and ISM algorithms meanwhile decreasing the bandwidth is the reason for increasing the performance of both RSS-EIT and ISM-EIT algorithms.

1. Introduction

Array signal processing has found different applications in radar, sonar, communications, and geophysical exploration. Despite direction of arrival (DOA) estimation and detecting the number of incident sources are two major ones in this field [1-3], the second one is more important because the process of determining the number of radio sources is a necessary pre-processing for DOA estimation.

For determining the number of narrowband signal sources, several algorithms have been proposed [4-6]. One of the most widely-used approaches is that of information theoretic criteria, introduced by Wax and Kailath. They proposed an approach to this problem based on the Akaike's information criterion (AIC) and minimum description length (MDL). In accordance to MDL and AIC algorithms, the number of signal sources will be determined by minimizing AIC or MDL criterion [7].

Ref. [8] proves the effective performance of the eigenvalue gradient method (EGM) for small differences between the DOAs of non-coherent sources, MDL and AIC have a much better detection performance than EGM. The performance of these algorithms will be sharply declined even signals are coherent and/or correlated. So, by using spatial smoothing as a pre-processing step, the coherency/correlation will be removed and MDL, AIC and EGM algorithms can estimate the number of signals [9].

Above mentioned narrowband methods cannot detect the wideband sources, accurately. In this way, there exist a number of different methods to detect the number and also to estimate the DOA of wideband sources [10, 11]. One of the most common way sto analyze wideband signals is to decompose it into narrowband signals through a filterbankor adiscreteFourier transform (DFT). Then, an appropriate DOA method such as multiple signal classification (MUSIC) can be applied on each frequency bin. Final DOA estimate can be obtained by averaging these results at each bin. This algorithm is called incoherent signal-subspace method (ISM) [12].

In 1985, H. Wang proposed coherent signal-subspace method (CSM) [13]. The main problem with this method is to change the signal space from one frequency to another one. The main idea for solving this problem is using linear transfer functions to transfer correlation matricesat each frequency into the center frequency, and obtain the universal correlation matrix. Afterwards, a high-resolution algorithm is applied to estimate the DOAs. This process is called focusing method.

In order to reduce the focusing loss, other methods such as rotational signal-subspace method (RSS) and two sided correlation transformation (TCT) were proposed. New focusing matrices try to eliminate the focusing loss. In TCT method, a two-sided unitary transformation is applied to the correlation matrix. S. Valaee and P. Kabal have shown that TCT has a smaller subspace fitting error than CSM, but its computational load is also the heaviest [14]. H. Hung and M. Kaveh have shown that the RSS class is the most general in its applicability and also it is the most effective in the view of resolution and accuracy [15].

Previous research works show that narrowband methods based on AIC, MDL, EGM and eigen increment threshold (EIT) criteria have no acceptable performance for determining the number of wideband sources. Also, research works about DOA estimation of wideband sources show that an averaging the results in bin frequencies such as ISM or focusing such as RSS is needed. Therefore, in this research, RSS and ISM methods are selected due to their effectiveness and lower computational complexities with respect to TCT and CSM ones. In order to achieve the main goal of this research, detection the number of wideband sources, a novel approach is proposed which combines RSS or ISM with AIC, MDL [7], EGM [16] and EIT [17] methods.

This paper is organized as follows. After the statement and formulation of the problem in Section 2, details of basic blocks of the proposed algorithms, RSS and ISM criteria as well as AIC, MDL, EGM and EIT ones, are described in Section 3. The proposed algorithms for estimating the number of wideband sources are described in Section 4. Numerical analysis is demonstrated in Section 5. Finally, Section 6 concludes this research.

2. WIDEBAND SIGNAL MODEL

Assume an array of p sensors exposed to $q < p$ far-field wideband sources in white noise space. The signals of the sources can be partially or fully correlated. The output of the sensors is shown as [11]:

$$x_i(t) = \sum_{l=1}^{q} s_l(t - \tau_i(\theta_l)) + n_i(t)), \quad 1 \le i \le p \tag{1}$$

where s_l, is the lth source signal, θ_l is angle of arrival for the lth source. $\tau_i(\theta_l)$is propagation delay for the lth source at the sensor i with respect to the reference point of the array. For a uniform linear array (ULA), $\tau_i(\theta_l) = (i-1)\frac{d}{c}\sin\theta_l$ where $d$is the sensor spacing, and c is the propagation velocity.

The array output in the frequency domain is represented by:

$$X(\omega) = A(\omega, \theta)S(\omega) + N(\omega) \tag{2}$$

where$s\ (\omega)$ and $N(\omega)$ are the Fourier transforms of the signal and the noise vectors, respectively. Matrix $A(\omega, \theta) = [a(\omega, \theta_1), \dots, a(\omega, \theta_q)]$ is called the location matrix, and is assumed to be full rank. If the noise field is spatially uncorrelated at each frequency, the covariance matrix of the observation vector at frequency $\omega$is as (3) [15]:

$$R(\omega) = A(\omega, \theta)R_s(\omega)A^H(\omega, \theta) + \sigma^2 I \tag{3}$$

where $R_s(\omega) = E[S(\omega)S^H(\omega)]$.

For a sufficiently long duration of sensor output observation, the sampled data are divided into N snapshots, each containing Jsamples. Consequently, a discrete Fourier transform is applied to each snapshot. So, N sets of transformed data are available which each set contains J frequency samples of the spectrum of the observation vector. Here, we represent these samples by x_j, $j = 1, \dots, J$. It should be noted that, each $x_j$depends on the snapshot in which it has been produced. For simplicity, we show the frequency variable representing $R(\omega_j)$ by R_j, $R_s(\omega_j)$ by $R_{s_j}$and $A(\omega_j, \theta)$ by A_j.

3. BASIC BLOCKS OF THE PROPOSED ALGORITHMS

A. The RSS and ISM Criteria

ISM is incoherent method but RSS is coherent one. In ISM the results of frequency bins will be averaged but in RSS, first a focusing from frequency bins to center frequency will be applied and then can be averaged. It means, the main difference between these methods is related to correlation matrices which in RSS can be changed due to focusing.

In RSS method the focusing matrices are found by minimizing [14]:

$$min_{T(f_j)}\|T(f_j)A(f_j) - A(f_0)\|_F$$
$$T^H(f_j)T(f_j) = I,\ j = 1, \dots, K \tag{4}$$

The solution of Equation (4) is obtained as:

$$T_j = V_j U_j^H \tag{5}$$

where V_j and U_j are the singular left and right vectors of $A_0 A_j^H$, respectively. The matrix T transfers the observation vector at different frequency bins as:

$$y_j = T_j x_j \tag{6}$$

The observation vectors y_j , $j = 1,2,..,J$ are in the focusing subspace. The sample correlation matrices of these transformed observation vectors are given by:

$$R_j^{(y)} = \frac{1}{N}\sum_{l=1}^{N} y_j^{(l)} {y_j^{(l)}}^H \quad (7)$$

An average of these correlation matrices makes a general focused sample correlation matrix that can be used for detection and estimation [14, 15].

$$R = \frac{1}{J}\sum_{j=1}^{J} R_j^{(y)} = A_0 R_S A_0^H + \sigma^2 R_n \quad (8)$$

where

$$R_S = \frac{1}{J}\sum_{j=1}^{J} S_j \quad (9)$$

$$R_n = \frac{1}{J}\sum_{j=1}^{J} T_j T_j^H \quad (10)$$

B. AIC, MDL, EGM and EIT Criteria

There are different methods to detect the number of narrowband sources. AIC and MDL are the two most popular methods for detecting the number of signals based on information theoretic criteria [6]. The MDL and AIC criteria are given by Equations (11) and (12) as:

$$AIC(k) = -2\log\left[\frac{\prod_{i=k+1}^{p} l_i^{1/(p-k)}}{\frac{1}{p-k}\sum_{i=k+1}^{p} l_i}\right]^{(p-k)N} + 2k(2p-k) \quad (11)$$

$$MDL(k) = -\log\left[\frac{\prod_{i=k+1}^{p} l_i^{1/(p-k)}}{\frac{1}{p-k}\sum_{i=k+1}^{p} l_i}\right]^{(p-k)N} + \frac{1}{2}k(2p-k)\log N \quad (12)$$

where l_i , $i = 1,2,\dots,k$ are the eigenvalue of sample correlation matrix $\widehat{R}$ which is given by:

$$\widehat{R} = \frac{1}{N}\sum_{t=1}^{N} x(t)x^H(t) \quad (13)$$

N is the number of snapshots. The number of signals $\hat{d}$ is determined as the value of $k \in \{0,1,\dots,p-1\}$, for which either the AIC or the MDL is minimized [6].

Just like MDL and AIC, EGM and EIT methods also determine the number of non-coherent sources according to the eigenvalues of autocorrelation matrix. According to [16], EGM is cited as follows: 1. After calculating the autocorrelation matrix of the output data $x(t)$ of the sensor array by Equation (13), we arrange the eigenvalues in descending order as

$$\lambda_1 \geq \cdots \geq \lambda_q \geq \lambda_{q+1} \geq \cdots = \lambda_p = \sigma_n^2 \quad (14)$$

2. Then, by defining the gradients of all neighbor eigenvalues by:

$$\Delta\lambda_i = \lambda_i - \lambda_{i+1}, \quad i = 1,\dots,p-1 \quad (15)$$

3. The average grads of all eigenvalues will be calculated by:

$$\text{Threshold} \equiv \Delta\bar{\lambda} = (\lambda_1 - \lambda_p)/(p-1) \quad (16)$$

4. Finally, all i satisfying $\Delta\lambda_i \leq$ threshold to construct the set $\{i_k\} = \{i \mid \Delta\lambda_i \leq \text{threshold}\}$ will be found. The estimated number of signals is $\hat{d} = i_0 - 1$.

In EIT algorithm [17], first steps is the same as EGM but this threshold is given as:

$$\lambda_i - \lambda_{i+1} \leq \text{threshold} \equiv \eta(p,N)\frac{P_s}{\left(1+\sqrt{\frac{P_s}{\lambda_p}}\right)^2}, i = p-1, p-2, \dots, 1 \quad (17)$$

where $P_s = \frac{\lambda_1 - \lambda_p}{p}$ is the power of source, and $\eta(p,N)$ is a coefficient function with following features:

- $\eta(p,N) = 1$ when $N \to \infty$
- $\eta(p,N)$ increases when N reduces
- $\eta(p,N)$ decreases when p increases

4. Proposed Algorithms

A. RSS-based Algorithm

1. Divide the output of sensors into L equal parts $x_l(t)$, $1 \leq l \leq L$

2. Generate $X_l(f_j)$; $f_{low} \leq f_j \leq f_{high}$ $(1 \leq l \leq L)$ by applying FFT to each $x_l(t)$

3. Form the correlation matrix by:

$$\tilde{R}_l = E\left[X_l(f_j)X_l(f_j)^H\right] \quad (18)$$

4. Find T_l by

$$T(f_j) = V(f_j)U(f_j)^H \quad (19)$$

where V_j and U_j are the singular left and right vectors of $A_0 A_j^H$, respectively.

5. Determine the unitary transformation matrices by:

$$\tilde{R} = \frac{1}{L}\sum_{l=1}^{L} T_l \tilde{R}_l T_l^H \quad (20)$$

6. Apply MDL, AIC, EGM or EIT to find the number of wideband sources.

B. ISM-based Algorithm

1. Divide the output of sensors into L equal parts $x_l(t)$, $1 \leq l \leq L$

2. Generate $X_l(f_j)$; $f_{low} \leq f_j \leq f_{high}$ $(1 \leq l \leq L)$ by applying FFT to each $x_l(t)$.

3. Form the correlation matrix by Equation (18).

4. Apply MDL, AIC, EGM or EIT on each frequency bin of $x_l(t)$ to estimate the number of sources.

5. Find the average of these results to obtain the number of wideband sources.

5. Simulation Results

Numerically, the effectiveness of the proposed RSS and ISM algorithms is investigated in different cases, in this section.

A. Performance Evaluation of RSS-based Algorithm

Experiment 1. Consider a linear array of 10 sensors exposed to the two wideband wave fronts arriving from 5° and 20°. The spacing between sensors is half of the wavelength in the center frequency. Centre frequency, bandwidth and sampling frequency are equal to 100 Hz, 40 Hz and 360 Hz (3× highest frequency), respectively. The output of the sensors is decomposed into 100 snapshots, each consisting of 33samples. Signal to noise ratio (SNR) changes from -20 dB to 20 dB with step size 5 dB and all signals assumed to have the same power. In this case, $\eta(p, N) = 2$ is chosen for EIT algorithm. For each SNR, 500 independent trials are run. As shown in Fig. 1, in the case of $SNR \leq 15\ dB$, the EIT and EGM algorithms outperform both MDL and AIC methods.

Experiment 2. In this case, the uniform linear array with 10 sensors is used. Two wideband signals with equal powers impinge on the array. The bandwidth of the sources equals to $40Hz$ and $f_c = 100Hz$. Probability of detection the number of sources for $SNR = 20\ dB$underdifferent angular differences, from 1 to 10 degrees, are shown in Fig 2. As depicted in this figure, for different angular differences, RSS-EIT has the ability to determine the correct number of sources. For small differences between the incident angles (lower than 5°), RSS-MDL has a much better detection performance than RSS-EGM.

Experiment 3. In this case, to evaluate the effect of frequency bandwidth on the RSS algorithm, the performance of RSS-EIT algorithm under different bandwidths for two wideband sources is investigated. It is assumed that $f_{low} = 20\ Hz$ and f_{high} changes from 21Hz to 60Hz with step size 5Hz. Also, $SNR = 20\ dB$ and $\eta(p, N) = 2$.

As illustrated in Fig. 3, when bandwidth reduces from 40 Hz to 1Hz, the proposed RSS-EIT algorithm shows much better performance (from 78% to 98%).

B. Performance Evaluation of ISM-based Algorithm

Experiment 4. We consider two wideband sources impinging on a 10 element ULA from 5° and 20°. The sampling frequency is chosen to be twice the highest frequency. The sensor spacing is chosen to be $\lambda/2$ where λ is the wavelength corresponding to the highest frequency of signal. $f_c = 100Hz$ and $BW = 40\ Hz$. The SNR in different cases is varying from $-20dB$ to $20dB$with a step of $5dB$. Under each SNR, 500 independent trials are run. The output of each sensor is divided into 100 snapshots, each one consists of 33 samples. The performance of EGM, MDL and EIT algorithms is depicted in Fig. 4. According to this figure, ISM-MDL offers higher performance with respect to ISM-EGM and ISM-EIT methods for SNRs greater than 0 dB. In contrast, for small SNRs (lower than 0 dB), EGM offers much better detection performance than the EIT algorithm and MDL is completely in effective.

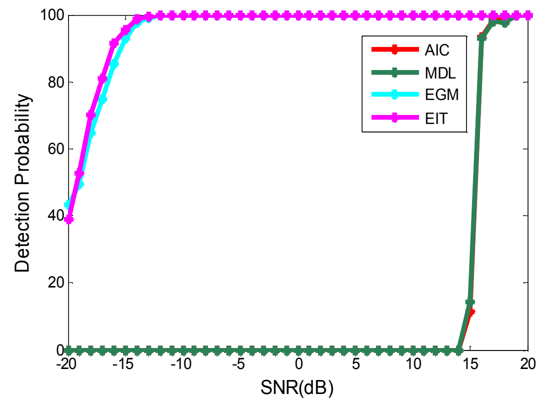

Figure 1: The detection probability versus SNR for experiment 1.

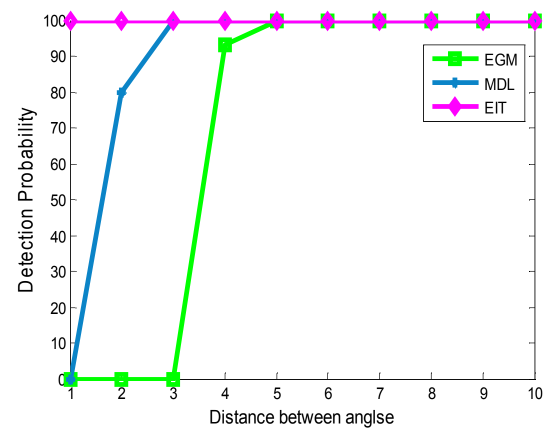

Figure 2: The detection probability versus angular difference for experiment 2.

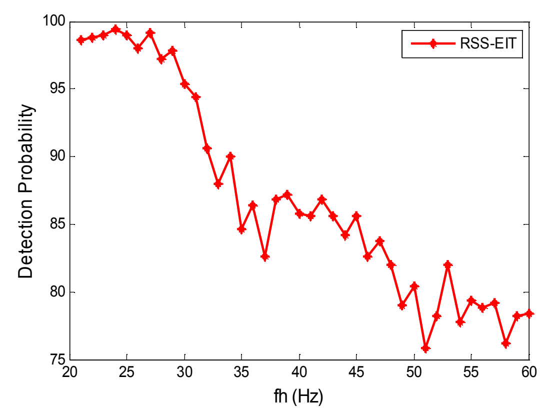

Figure 3: The detection probability versus fhighfor experiment 3.

Experiment 5. In this part, the performance of the proposed ISM-based algorithms under different angular differences for two wideband signals with $SNR = 20\ dB$ is investigated. As depicted in Fig. 5, in small differences between the incident angles (lower than 10°), MDL and EIT have a much higher detection probability than EGM. As depicted in this figure, EIT method shows 100% success for all incident angles and MDL offers a bit lower than 100% .

Experiment 6. In this experiment, the performance of ISM-EIT algorithm under different bandwidths for two wideband sources is evaluated. $f_{low} = 20$ and f_{high} changes from 21Hz to 60Hz with step size 5Hz. Also, $SNR = 20\ dB$ and $\eta(p, N) = 2$. As shown in Fig. 6, when bandwidth reduces from 40 Hz to 1Hz, the proposed ISM-EIT algorithm offers much better performance (82% compared to 65%).

C. Comparison Study

In order to compare the performance of RSS-based and ISM-based algorithms, 3 wideband signals impinging on a 12 element array from 2°, 15° and 33° are simulated. The SNR varies from $-20dB$ to $20dB$ with a step of $5dB$. 500 Monte Carlo runs is considered. Simulation results are shown in Fig. 7. In both RSS and ISM algorithms, MDL, AIC, EGM and EIT are run to determine the number of wideband sources. According to Fig. 7, in low SNRs, RSS-based algorithm offer higher detection probability rather than ISM-based one. Moreover, ISM-MDL and ISM-AIC determine the number of sources exactly when the SNR is greater than 5 dB. Also, RSS-MDL and RSS-AIC offer 100% detection probability for SNRs greater than 20 dB.

To compare the computational complexity of the proposed RSS-based and ISM-based algorithms, the number of additions, subtracts, multiplications and divisions are given in TABLE I. It is obvious that, RSS has more computational complexity than ISM. Among the methods, RSS-MDL has the most computational complexity and ISM-EGM has the least one.

6. Conclusion

In array signal processing field, estimating the number of sources from observed data is a fundamental problem. Since the methods of detecting the number of narrowband signals cannot determine the number of wideband sources, a new approach that combines the RSS or ISM criteria with one of the MDL, AIC, EGM and EIT criteria was proposed which can estimate the number of wideband sources.

In the proposed RSS-based algorithm, RSS was applied to obtain the universal correlation matrix and then, the number of wideband signals was determined by using narrowband methods. In the proposed ISM-based algorithm, after decomposing wideband signals into narrowband signals via DFT, an appropriate detection method such as MDL, AIC, EGM and EIT was applied on each frequency bin. Then, by averaging the results, the number of sources was determined.

The effectiveness of the proposed RSS-based and ISM-based algorithms was verified through numerical examples. Simulation results showed that the proposed methods estimate the number of wideband as well as narrowband signals.

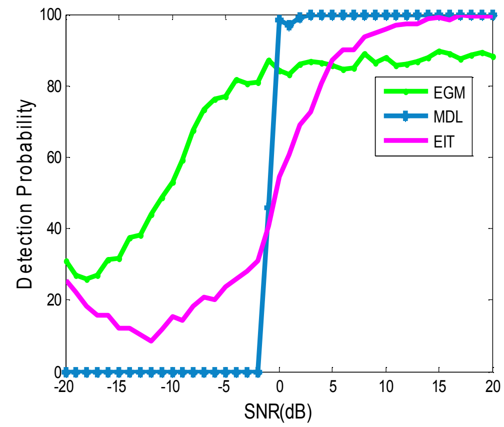

Figure 4: The detection probability versus SNR for experiment 4.

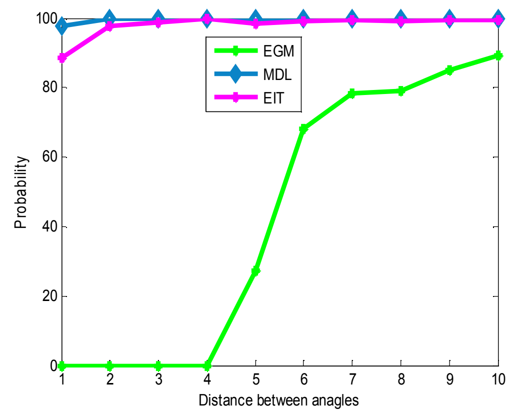

Figure 5: The detection probability versus angular differences for experiment 5.

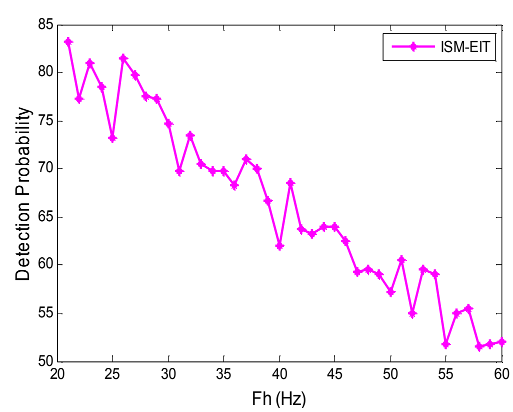

Figure 6: The detection probability versusfhighfor experiment 6.

TABLE 1
COMPUTATIONAL COMPLEXITY OF THE PROPOSED RSS-BASED AND ISM-BASED ALGORITHMS

Algorithm	No. of Comparisons to Threshold	No. of Minimizations	No. of Additions and Subtractions	No. of Multiplications and Divisions
RSS-MDL	0	p	$Np^2(3p-2)+p-K+4$	$(pK+12)+N\big((pK+4)+p^2K+3p^3\big)+p-K$
RSS-EGM	$p-1$	0	$Np^2(3p-2)+p+1$	$(pK+5)+N((pK+4)+p^2K+3p^3)$
RSS-EIT	$p-1$	0	$Np^2(3p-2)+p+1$	$(pK+9)+N((pK+4)+p^2K+3p^3)$
ISM-MDL	0	pN	$N(p-K+5)$	$N(p-K+8)+1$
ISM-EGM	$N(p-1)$	0	$N(p+2)$	$N+1$
ISM-EIT	$N(p-1)$	0	$N(p+2)$	$4N+1$

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BIOGRAPHIES

Somaye Jalaei received the B.Sc. degree from Shahed University, Tehran, Iran and M.Sc. degree from Shahid Rajaee Teacher Training University (SRTTU), Tehran, Iran, both in Electrical Engineering. In 2009 and 2013, respectively. Her research interests include determining the number of narrowband and wideband wireless radio sources.

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