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MINIMUM ARRAY ELEMENTS AND ANGULAR SEPARATION BASED ON SEVERAL WIDEBAND DIRECTION-OF-ARRIVAL ESTIMATION APPROACHES

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Abstract- This work presents the minimum array elements and angular separation for performance analysis of two wideband Angle of Arrival (AOA) or Direction of Arrival (DOA) estimation algorithms, namely, Test of Orthogonality of Projected Subspaces (TOPS) and Incoherent Multiple Signal Classification (IMUSIC). The efficacy of each wideband DOA algorithm is measured by its ability to resolve many spaced signals. Previous studies have been concentrated on determining the effects of design parameters on the outcomes of DOA approaches. These studies focus on the effects of two closely spaced sources that impinge on an antenna array using a Uniform Circular Array (UCA). There are various multipaths and DOA that interact with the original signal in the real world. As a result, the receiver site must be able to compute the DOA and comprehend the supplied transmitters' angular coordinates. This study considers the effects of interference and multipath. The study was prioritized upon the investigation of the minimum angular distance and number of array elements required to solve multiple conflicting signals for a variety of broadband AOA estimation techniques. The results reveal that the IMUSIC algorithm outperforms the TOPS algorithm.

Keywords: Direction-of-Arrival, Uniform Circular Array, Correlation Matrix, TOPS, IMUSIC.

1. INTRODUCTION

Array treatment is a scientific area of research that incorporates the processing of data of signals received by an array of antennas functioning in a specific environment, such as on the ground, above ground, or underwater [1]. An array is made up of two or more detectors arranged in a certain dimensional form. An arrangement of sensors outperforms a single sensor in terms of directional accuracy.

Antenna arrays have been used in radar (radio detection and range) [2-5], space exploration, sonar (sound navigating and ranging) [6], seismology, radiology, communications systems [7-9], mapping, source localization [10], wireless communications [11], and other disciplines. Depending on the requirements, detectors might be antennas, microphones, hydrophones, geophones, or ultrasonic probes. Sonar, for example, use hydrophone arrays; Sound waves bands are utilized to locate audio sources, piezoelectric sensors are used in medical ultrasonography, and geophone panels are employed in seismology, among other uses. Radar, remote sensing, telecommunications, positioning, radio astronomy, and navigating are just a few of the electromagnetic applications that use antenna arrays [10].

When the arriving sources are broadband, the most typical way is to disintegrate the broadband signal into narrowband items, and broadband AOA prediction is principally concerned with determining how to use various covariance matrices at various frequencies to generate a reliable AOA/DOA estimation [12]. Wideband AOA prediction approaches were divided into two parts, namely, incoherent signal subspaces method [13, 14], and coherent signal subspaces method [15, 16].

One of the most basic broadband DOA estimation approaches is the incoherent signal subspace approach. This technique employs multiple narrowband signals that have been incoherently decomposed from a wideband signal [17]. The method, in particular, uses narrowband DOA estimation methods, such as Incoherent Multiple Signal Classification (IMUSIC) [18], to narrowband signals separately. The DOAs of entering broadband signal sources are then calculated by averaging these values. Although the IMUSIC method improves estimation precision in low level noise areas, it suffers when the signal-to-noise ratio (SNR) of a specific frequency is poor. In another way, the accuracy of the final estimation will be harmed by poor estimations from certain frequency bands.

The coherent signal subspace method has been proposed to solve these limitations and enhance DOA estimation performance [15]. In the coherent signal subspaces method processing, transformation matrices concentrate the covariance matrix of every frequency range, and the concentrated arrays are combined to generate a new covariance matrix. The DOAs of arriving wideband signal sources are then estimated employing a AOA estimation approach for narrowband signals. This algorithm's main point is how to focus correlation matrices. Many methods for obtaining a proper focusing matrix have been proposed [19, 20].

Nevertheless, each focused approach, necessitates early values, that are the predetermined directions of entering sources, and the effectiveness of the coherent signal subspaces algorithm is dependent on the initial values [21]. The second approach in this work, Test of Orthogonality of Projected Subspaces (TOPS) [22], employs noise subspace and signal subspace from various frequencies to provide high DOA prediction efficiency with no need for starting inputs. TOPS lies between coherent and incoherent methods. This method has the following advantages [22]:

- no need for the focused degrees or a beamforming matrix;
- it integrates frequency bins better than incoherent methods at low SNR.

Nevertheless, the approach has a drawback that the spatial spectra contain several spurious peaks, making it difficult to determine the true AOA of signals.

In this paper, we are focused on the resolution capabilities of those methods described above for different wideband signal sources, in order to find the minimum array antenna elements and the shortest angular separation between two adjacent sources.

The following sections of this article are structured as follows. Section 2 presents the formulation of the wideband signal model using a UCA configuration and the fundamentals of direction estimation. Section 3 describes the wideband DOA estimation methods, while Section 4 displays the simulation results. Section 5 concludes with the conclusion and future work.

2. SIGNAL MODEL FOR UNIFORM CIRCULAR ARRAY

In circular arrays, the antennas are organized in a circle. The Figure 1 depicts a circular array of N antennas that are distributed equally in the *x*-*y* axis across the circle of radius r.

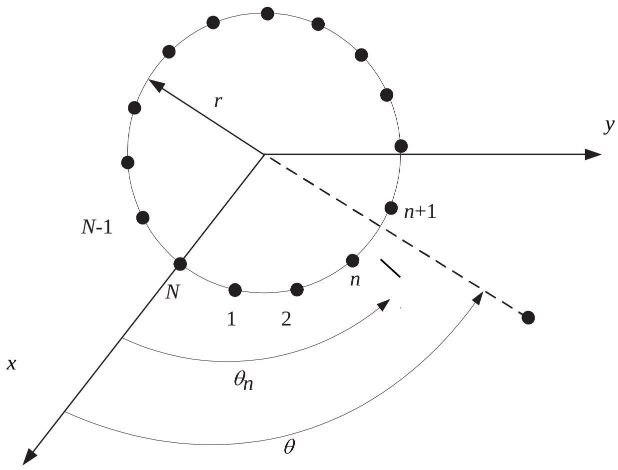

Figure 1. The *x*-*y* axis structure of an *N*-element of UCA [23]

The received broadband signals are divided into K narrowband signal sources. The Discret Fourier Transform (DFT) [23] of the received source at *n*th element for Uniform Circular Array (UCA) geometry is [24]:

$$x(\omega)=\sum_{m=1}^{M}s_m\exp\left(j\omega\frac{2\pi r}{\lambda}\cos(\theta_m-\theta_n)\right)+b(\omega) \tag{1}$$

where, M is the number of AOAs, and θ_n is the azimuthal position the *n*th sensor of the array and computed as follows [24]:

$$\theta_n=2\pi\left(\frac{n-1}{N}\right) \tag{2}$$

On the *x*-*y* axis, the steering vector is given by [25]:

$$a(\omega_i,\theta_n)=\begin{bmatrix}\exp\left(j\omega_i\frac{2\pi r}{\lambda}\cos\theta_m\right)\\ \exp\left(j\omega_i\frac{2\pi r}{\lambda}\cos(\theta_m-\theta_2)\right)\\ \vdots\\ \exp\left(j\omega_i\frac{2\pi r}{\lambda}\cos(\theta_m-\theta_N)\right)\end{bmatrix} \tag{3}$$

Then, the $N\times N$ covariance matrix is given by [22]:

$$\begin{aligned}R_{xx}(\omega_i)&=E\left\{x(\omega_i)x^H(\omega_i)\right\}=\\&=a(\omega_i,\theta_n)R_{ss}(\omega_i)a^H(\omega_i,\theta_n)+\sigma^2 I\end{aligned} \tag{4}$$

where, $E\{.\}$ represents the mean value, H represents the Hermetian (complex conjugate transpose), $R_{ss}(\omega_i)=E\left\{s(\omega_i)s^H(\omega_i)\right\}$, σ^2 is the noise, and I is the $N\times N$ unit array matrix.

If the M sources are uncorrelated and $R_{ss}(\omega_i)$ have full rank, the signal subspace matrix $V_s(\omega_i)$ and the noise subspace matrix $V_n(\omega_i)$ at frequency ω_i may be constructed using the Eigenvalues Decomposition (EVD) of the covariance matrix as follows [12, 22]:

$$V_s(\omega_i)=\left[v_1(\omega_i),v_2(\omega_i),\cdots,v_M(\omega_i)\right] \tag{5}$$

$$V_n(\omega_i)=\left[v_{M+1}(\omega_i),v_{M+2}(\omega_i),\cdots,v_N(\omega_i)\right] \tag{6}$$

where, $v_1(\omega_i),v_2(\omega_i),\cdots,v_N(\omega_i)$ are the perpendicular eigenvectors of $R_{xx}(\omega_i)$ sorted in decreasing order by their eigenvalues.

3. WIDEBAND DOA ESTIMATION ALGORITHMS

3.1. IMUSIC Method

This method is known as Incoherent Multiple Signal Classification (IMUSIC), because the same narrowband MUSIC approach is used for all frequency bins at the same time. IMUSIC, among the most important AOA estimation approaches for broadband sources, applies narrowband signal subspaces algorithms (e.g., MUSIC) to every frequency range individually [12]. The IMUSIC then calculates the AOA of broadband signals employing the given formula [12]:

$$P(\theta)=\frac{1}{\sum_{i=1}^{K}a^H(\omega_i,\theta)V_n(\omega_i)V_n^H(\omega_i)a(\omega_i,\theta)} \tag{7}$$

The noise subspace matrix $V_n(\omega_i)$ is computed from the spatial covariance matrix $R_{xx}(\omega_i)$ in the Equation (6).

Since this AOA predicted by the Equation (7) are means of the results of every frequency spectrum, wrong predictions from a single band of frequencies reduce the overall estimation performance. The Incoherent MUSIC is typically successful in the whole SNR range, as well as when the signals are well separated from one to another, but it suffers from errors and produces side peaks at incorrect angles when the SNR is low and the sources are closely spaced, which is common in many cases. Furthermore, the noise level is expected to be flat across the frequency range, which is not normal condition [22].

3.2. TOPS Method

TOPS calculates the AOA/DOA of arriving broadband sources by utilizing both the signal and noise subspaces of every frequency band [22]. As indicated in the previous section, we first extract the signal subspaces $V_s(\omega_i)$ and the noise subspaces $V_n(\omega_i)$ from the EVD of the covariance matrix of every frequency range. Then, one frequency band ω_i should be chosen, and the signal subspace $V_s(\omega_i)$ of the chosen frequency range should be converted to other bands.

TOPS is superior to coherent signal subspaces in that it eliminates the need for early AOA predictions for the frequencies conversion procedure, as seen below. TOPS employs a diagonally unit transform. The *m*th item on the frequencies transform matrix's diagonal $\varphi(\omega_i,\theta)$ is defined as [12, 22]:

$$\left[\varphi(\omega_i,\theta)\right]_{(m,m)} = \exp\left(j\omega_i \frac{2\pi r}{\lambda}\cos(\theta_m - \theta_n)\right) \quad (8)$$

The signal subspaces $V_s(\omega_i)$ of the frequency range ω_i are converted into the other frequency band ω_i using $\varphi(\omega_i,\theta)$, in which the transformed signal subspaces $U_{ij}(\theta)$ are defined as follows [22]:

$$U_{ij}(\theta) = \varphi(\Delta\omega,\theta)V_s(\omega_i) \quad (9)$$

where, $\Delta\omega = \omega_j - \omega_i$. Then, the Equation (9) can be expressed as [12]:

$$U_{ij}(\theta) = \varphi(\Delta\omega,\theta)a(\omega_i,\theta)G(\omega_i) = a(\omega_j,\widehat{\theta})G(\omega_i) \quad (10)$$

where, $\widehat{\theta}$ represents the converted θ by employing the frequency transform matrix $\varphi(\omega_i,\theta)$, and $G(\omega_i)$ is a full-rank square matrix that validates $U_{ij}(\omega_i) = a(\omega_i,\theta)G(\omega_i)$.

A modular array at any frequency and DOA can be transformed into a distinct modular array at a different frequency using this transformation process. As a result, the converted array matrix is a complete rank array matrix and could be employed for the discussing orthogonality test between the converted array matrix and the noise subspaces, which is detailed in [12, 22]. Considering that the frequency band of interest is ω_1, the array matrix $D(\theta)$ is given as [25]:

$$D(\theta) = \left[U_{12}^H(\theta)V_n(\omega_2), U_{13}^H(\theta)V_n(\omega_3), \cdots, U_{1K}^H(\theta)V_n(\omega_K)\right] \quad (11)$$

where, θ is one of the DOA incoming wideband signal sources, the rank of the matrix $D(\theta)$ also reduces.

The accuracy of the calculated correlation matrix, which is primarily determined by the number of snapshots and the SNR of the received signal, determines the performance of DOA estimation. The subspace projection technique is used in TOPS signal processing to decrease signal subspace component leakage in the estimated noise subspace. Then, the projection matrix $P_i(\theta)$ is calculated by [26]:

$$P_i(\theta) = I - (a^H(\omega_i,\theta)a(\omega_i,\theta))^{-1}a(\omega_i,\theta)a^H(\omega_i,\theta) \quad (12)$$

where, I is a $M \times M$ unit array matrix. The noisy robustness matrix $D'(\theta)$ is then obtained by substituting the item $U_{ij}(\theta)$ of the Equation (11) by a newly converted signal subspaces array matrix $U'_{ij}(\theta)$, as follows [22]:

$$U'_{ij}(\theta) = P_j(\theta)U_{ij}(\theta) \quad (13)$$

$$D'(\theta) = \left[U_{12}'^H(\theta)V_n(\omega_2), U_{13}'^H(\theta)V_n(\omega_3), \cdots, U_{1K}'^H(\theta)V_n(\omega_K)\right] \quad (14)$$

TOPS performs better when using the Equation (14) with $D'(\theta)$ because the projection matrix $P_i(\theta)$ removes subspace estimation errors. Then, estimate $\hat{\theta}$ by [12,22]:

$$\hat{\theta} = \arg\max_{\theta} \frac{1}{\sigma_{\min}(\theta)} \quad (15)$$

where, $\sigma_{\min}(\theta)$ is the lowest singular value of $D'(\theta)$.

The output signal of the DFT is not necessarily a perfect narrowband signal. The accuracy of the DOA estimation might be harmed by the filtered signals.

TOPS can decrease these degradations by employing a specific signal subspace derived through the computed covariance matrix rather than the frequency band's steering vector. It implies that the approach used to choose the frequency range from wherein the signal subspace would be converted into other frequency ranges using the Equation (9) has an impact on the DOA estimation. On the other side, the inherent error of the subspaces results in certain undesired rank decreases of the estimator $D'(\theta)$ As a result, TOPS approach has a significant drawback of producing fake peaks in the pseudo spectrum generated by employing the Equation (15).

4. PERFORMANCE SIMULATIONS

To demonstrate the wideband IMUSIC and TOPS implementation using a UCA geometry, several computer simulations have been presented. MATLAB software (2020a) is used to examine the performance of these algorithms, then to determine the minimum array elements and angular distance between sources for both methods. The simulation results of IMUSIC and TOPS employing UCA geometry will be investigated with details, to determine which is the most performing. In order to compare the two methods, we assume that the SNR is equal to 5dB elements. In addition, the radius of the circle r is supposed to be $\lambda/(4\sin(\pi/N))$. Furthermore, the number of snapshots set to 200.

4.1. Array Elements

Some of the experimental findings that we have obtained are shown in the Figures 2 and 3 and Table 1. We illustrate the responsiveness of every approach at the noise level of SNR=5 dB for two values of the number of array elements, before and after correction. To test the performance of each method we use four sources coming from directions $\theta_1 = 4°$, $\theta_2 = 10°$, $\theta_3 = 79°$, $\theta_4 = 85°$.

Figure 2 depicts the spatial spectra before and after correction, as well as the amount of array elements employed in TOPS method. We remark that, The TOPS approach has shown to be effective. As seen in Figure 2, the two close targets are well distanced when we employ 12 array antenna elements.

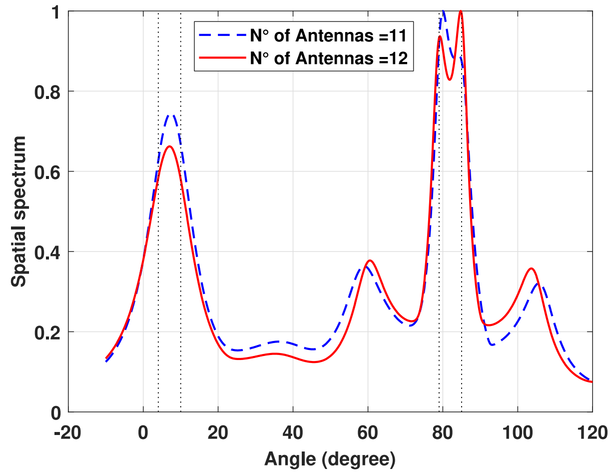

Figure 2. Wideband DOA estimation outcomes for various numbers of sensors using TOPS method

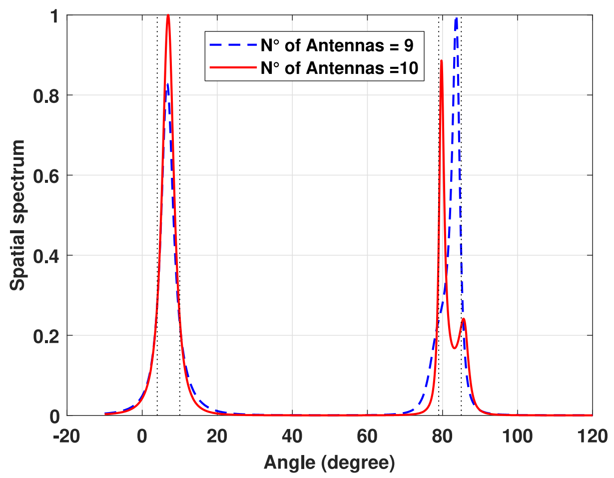

Figure 3. Wideband DOA estimation outcomes for various numbers of sensors using the IMUSIC method

Figure 3 depicts the outcome of the IMUSIC technique. In this noise level, we were capable to maximize the performance using IMUSIC by employing only 10 array antenna elements. Furthermore, we can see that the spatial spectrum is devoid of secondary lobes, indicating that IMUSIC is among the most effective wideband AOA localization methods.

Table 1. Summary of the results for the number of antennas

Wideband DOA estimation methods	Before resolution (degree)	After resolution (degree)
Incoherent MUSIC method	9	10
TOPS method	11	12

4.2. Angular Separation

The results of the remaining simulations that we have reviewed are shown in the Figures 4 and 5 and Table 2. We show the efficiency of both approaches for two distinct angle spacing values, before and after correction, at a noise level of SNR = 5dB. The number of sensors is $N = 10$.

Figure 4 depicts the pseudo spectrum before and after resolution and the angular separation used for the TOPS method. As illustrated in Figure 4, to obtain better accuracy employing the TOPS approach, we should separate well between the two closest sources (7°).

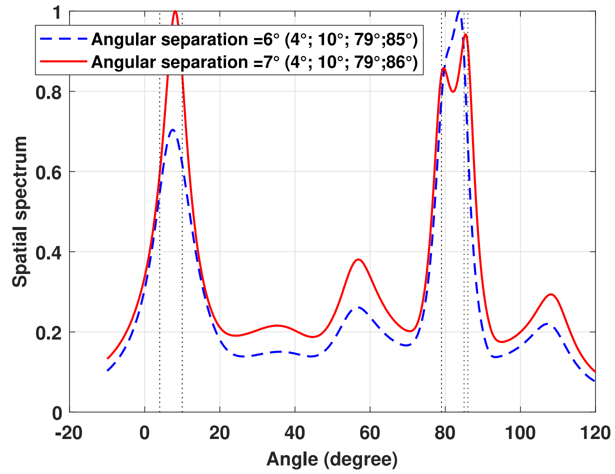

Figure 4. Wideband DOA estimation for different angular separation using TOPS method

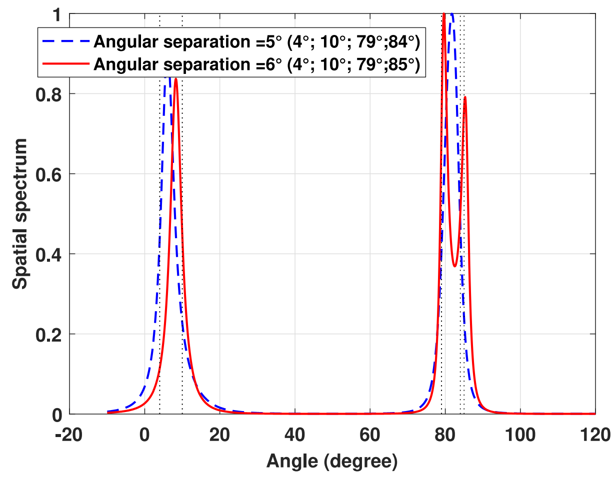

Figure 5. Wideband DOA estimation for different angular separation using IMUSIC method

Figure 5 illustrates the result obtained by using the IMUSIC technique and the angular separation used. IMUSIC only needs 6° of difference to offer a precise estimation of the second and third direction of arrival, as shown in Figure 5.

As proven by the computer outcomes, the IMUSIC outperforms TOPS in terms of array elements and angular distance. Moreover, from these results, it is crucial to note that the two wideband methods, when we use the UCA geometry, are unable to identify the right AOA; this is owing to the fact that power system reduces when the received signals are distant from the borders of a uniform linear sensors architecture $(\theta = \pm 90°)$.

Table 2. Summary of the results for the angular separation

Wideband DOA estimation methods	Before resolution (degree)	After resolution (degree)
Incoherent MUSIC method	5	6
TOPS method	6	7

5. CONCLUSION

In this paper, the performance evaluation and resolution capabilities of several wideband DOA estimation approaches have been described. The performance resolution of the wideband DOA methods has been given by looking for the minimum number of antennas required to detect two close sources and the smallest angular distance between two adjacent sources. The results showed that IMUSIC surpasses TOPS algorithm; the simulation results suggest that the IMUSIC algorithm is the best and requires the fewest array antennas to separate between two close targets, and the smallest distance between them.

Further research, is required as future work, including alternative approaches with varying stimulation settings, along with additional statistical analysis of the data.

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BIOGRAPHIES

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Said Safi was born in Beni Mellal, Morocco, in 1971. He received the B.Sc. degree in Physics (option: Electronics) from Cadi Ayyad University, Morocco in 1995, the M.Sc. and the Ph.D. degrees from Chouaib Doukkali University and Cadi Ayyad University, Morocco in 1997 and 2002, respectively. He has been a Professor of information theory and telecommunication systems at the National School for applied Sciences, Tangier, Morocco, from 2003 to 2005. Since 2006, he is a Professor of applied mathematics and programming at Polydisciplinary Faculty, Sultan Moulay Slimane University, Beni Mellal, Morocco. In 2008, he received the Ph.D. degree in Telecommunication and Informatics from the Cadi Ayyad University. In 2015, he received the degree of Professor in Sciences at Sultan Moulay Slimane University. His general interests span the areas of communications and signal processing, estimation, time-series analysis, and system identification subjects on which he has published more than 50 journal papers and more than 70 conference papers. His current research topics focus on transmitter and receiver diversity techniques for single- and multi-user fading communication channels, and wide-band wireless communication systems.