Spatial-Smoothing-Based DOA Estimation of Coherent Jamming Signals for a Misaligned Antenna Array

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ABSTRACT

A signal processing technique based on spatial smoothing to estimate the direction of arrival (DOA) of incoming coherent jammers for a misaligned antenna array, where each antenna element is oriented in different directions, is investigated in this study. Because of the rank deficiency due to coherency, the conventional MUltiple SIgnal Classification (MUSIC) algorithm cannot distinguish the coherent signals despite its high resolution. For estimation of the coherent signals, the misaligned antenna array is divided into overlapping subarrays and the received model is derived by considering the misalignment. The obtained received signal model is applied to the constructed scanning vector system for finding peaks of the spatial spectrum whereas the conventional scanning vector of the existing spatial smoothing technique, which reflects only the phase difference of the received signals between the antenna elements, can undergo performance degradation due to the antenna element misalignment. For validation, a representative simulation result for comparing the performances between the proposed method and conventional spatial smoothing method is proposed.

Keywords: jammer, misaligned antenna array, MUSIC algorithm, DOA estimation, spatial smoothing

1. INTRODUCTION

Although various modern infrastructures are becoming increasingly dependent on position, navigation, and timing information provided by the Global Positioning System (GPS), vulnerability of the GPS receivers to jamming signals still remains a challenge because the received signal power of the GPS is extremely weak (Braasch & van Dierendonck 1999, Borre et al. 2007).

As a countermeasure to the GPS jammers, in addition to jammer mitigation (Seo et al. 2011, Chen et al. 2012, Park et al. 2017, 2018), intensive research has been performed on methods for direction of arrival (DOA) estimation of incoming jamming signals using antenna arrays. Among these methods, the MUltiple SIgnal Classification (MUSIC) algorithm (Schmidt 1981, Rao & Hari 1989, Stoica & Nehorai 1989, Friedlander 1990, Kundu 1996) is the most widely used subspace-based signal processing method and is known to provide very high resolution. However, when more than two incoming narrowband signals have the same center frequency, i.e., there is coherency between the signals, the classical MUSIC algorithm cannot show effectiveness because the rank of the signal subspace obtained after eigenvalue decomposition is not equal to the number of the incoming signals owing to coherency.

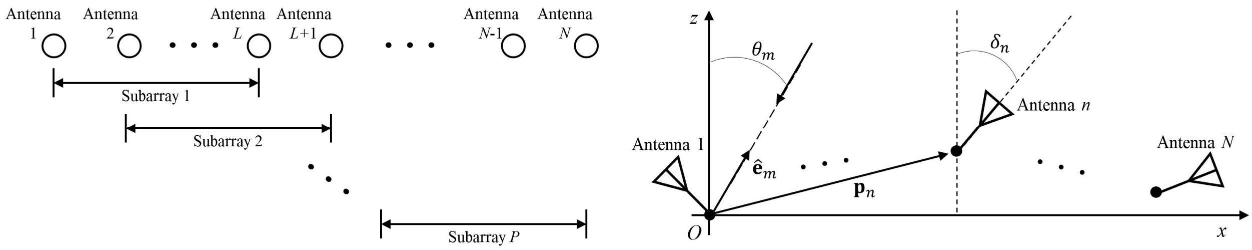
To solve this rank deficiency problem, a spatial smoothing technique (Shan et al. 1985, Williams et al. 1988, Pillai & Kwon 1989), which is an improved version of the MUSIC algorithm, was developed, and this method uses the concept of dividing the antenna array into overlapping subarrays for restoring the rank of the signal subspace. However, when constructing a vector scanning system for finding peaks of the spatial spectrum, the conventional spatial smoothing technique does not reflect the orientation of each antenna element, but only considers the phase differences between the received signals. Therefore, in case of antenna array misalignment, i.e., the antenna elements are oriented in different directions, the DOA estimation performance of the conventional spatial smoothing technique can decrease.

Therefore, in this study, a spatial-smoothing-based signal processing method is proposed for DOA estimation of coherent jamming signals in order to prevent performance degradation in case antenna array misalignment. The mathematic model of the coherent signals received by an arbitrarily misaligned antenna array is obtained by considering the orientations and polarizations of the antenna elements, and the polarizations of the coherent jamming signals. Subsequently, a modified scanning vector is calculated based on the obtained received signal model and is used to find the peaks of the spatial spectrum.

To demonstrate the DOA estimation performance of the proposed method, simulations are performed and a representative result is present to compare the performance between the proposed method and the conventional spatial smoothing technique.

2. SPATIAL-SMOOTHING-BASED DOA ESTIMATION METHOD FOR THE MISALIGNED ANTENNA ARRAY

The spatial smoothing technique (Shan et al. 1985, Williams et al. 1988, Pillai & Kwon 1989) utilizes the concept of subarrays, as depicted in Fig. 1a. The *N*-element antenna array is divided into overlapping L-element subarrays, and thus, total $P = N - L + 1$ subarrays are formed.



(a) (b)

Fig. 1. (a) *N*-element antenna array divided total *P* subarrays of size *L* for spatial smoothing, (b) Coordinate systems for the *N*-element misaligned antenna array.

As proved by Shan et al. (1985), the three conditions, $P \geq M$, $L \geq M + 1$ and $N \geq 2M$, should be satisfied to estimate the DOAs of all the *M* coherent jamming signals. When comparing the above three conditions to $N \geq M + 1$ in case of non-coherent jammers, the capability to deal with the coherent jammers is achieved at the expense of a reduced effective aperture (Shan et al. 1985).

In the current study, an antenna array that consists of *N*-element antennas oriented in different directions is considered, as depicted in Fig. 1b. For simplicity, it is assumed that all the antenna elements are Hertzian dipoles and located in the xz-plane. The location and antenna orientation with respect to the z-axis of the n^{th} $(n = 1, 2, \cdots, N)$ antenna element are denoted by $\mathbf{p}_n$ and δ_n $(-90° \leq \delta_n \leq 90°)$, respectively. In addition, all the *M* incoming coherent jammers, with an incident angle of θ_m $(-90° \leq \theta_m \leq 90°, m = 1, 2, \cdots, M)$ with respect to the z-axis, are assumed to be linearly polarized sinusoidal plane waves. A unit vector indicating the direction of each jamming signal, which is denoted by $\hat{\mathbf{e}}_m$, is also contained in the *xz*-plane for simple analysis. Moreover, it is assumed that the frequencies of the *M* coherent jammers are known, and the first antenna element is located at the origin. If we let $\mathbf{x}_p[k]$ denote the received signal vector at the p^{th} subarray, $\mathbf{x}_p[k]$ can be given as follows:

$$\begin{gathered}\mathbf{x}_p[k] = \mathbf{A}_p\mathbf{s}[k] + \boldsymbol{\eta}_p[k] \\ \mathbf{A}_p = K'[\mathbf{a}_{p,1}(\theta_1) \quad \mathbf{a}_{p,2}(\theta_2) \quad \cdots \quad \mathbf{a}_{p,M}(\theta_M)] \\ \mathbf{a}_{p,m}(\theta_m) = \left[F(\delta_p,\theta_m)\exp[j\Delta\tau_{p,m}] \quad \cdots \quad F(\delta_{p+L-1},\theta_m)\exp[j\Delta\tau_{p+L-1,m}]\right]^T \\ \mathbf{s}[k] = [s_1[k] \quad s_2[k] \quad \cdots \quad s_M[k]]^T,\ \boldsymbol{\eta}_p[k] = [\eta_p[k] \quad \eta_{p+1}[k] \quad \cdots \quad \eta_{p+L-1}[k]]^T \\ K' = j\frac{K}{\sqrt{2}},\ F(\delta_n,\theta_m) = \sin(\delta_n - \theta_m),\ \Delta\tau_{n,m} = \frac{2\pi\mathbf{p}_n\cdot\hat{\mathbf{e}}_m}{\lambda}\end{gathered} \tag{2}$$

where $\mathbf{s}[k]$ is the vector of incoming jamming signals and $\boldsymbol{\eta}_p[k]$ the noise vector of the p^{th} subarray, respectively. All $\eta_n[k]$ are assumed to be additive white Gaussian noises, independent of each other, and have the same power σ_η^2. Subsequently, the spatially smoothed covariance matrix can be obtained by averaging the covariance matrices of all the subarrays as follows:

$$\widetilde{\mathbf{R}} = \frac{1}{P}\sum_{p=1}^{P}\mathbf{R}_p,\ \mathbf{R}_p = E\{\mathbf{x}_p[k]\mathbf{x}_p^H[k]\} \tag{3}$$

The spatially smoothed covariance matrix can be factorized as follows by eigenvalue decomposition:

$$\begin{gathered}\widetilde{\mathbf{R}} = \widetilde{\mathbf{U}}\widetilde{\mathbf{\Lambda}}\widetilde{\mathbf{U}}^H \\ \widetilde{\mathbf{U}} = [\mathbf{u}_1 \quad \cdots \quad \mathbf{u}_L] \\ \widetilde{\mathbf{\Lambda}} = \begin{bmatrix}\lambda_1 & & \\ & \ddots & \\ & & \lambda_L\end{bmatrix}\end{gathered} \tag{4}$$

where $\{\lambda_1,\cdots,\lambda_L\}$ are the eigenvalues of $\widetilde{\mathbf{R}}$ in descending order and $\{\mathbf{u}_1,\cdots,\mathbf{u}_L\}$ are the corresponding eigenvectors orthogonal to each other. In the presence of *M* jamming signals, $\{\lambda_1,\cdots,\lambda_M\}$ and $\{\mathbf{u}_1,\cdots,\mathbf{u}_M\}$ are the eigenvalues and eigenvectors of the signal subspace, respectively, whereas the other eigenvalues and eigenvectors correspond to the noise subspace. In addition, each of the eigenvalues corresponding to the noise subspace is equal to the noise power, i.e., $\lambda_i = \sigma_\eta^2$ $(i = M+1,\cdots,L)$. Because the signal subspace is spanned by $\{\mathbf{a}_{p,1}(\theta),\cdots,\mathbf{a}_{p,M}(\theta)\}$ for any *p* and orthogonal to the noise subspace, the following orthogonality can be obtained:

$$\mathbf{A}_p^H\widetilde{\mathbf{U}}_\eta = \mathbf{0},\ \widetilde{\mathbf{U}}_\eta = [\mathbf{u}_{M+1} \quad \cdots \quad \mathbf{u}_L] \tag{5}$$

Using Eq. (5), a spatial spectral function that can be used for estimating the DOA of the coherent jamming signals impinging on the misaligned antenna array can be obtained using a scanning vector $\mathbf{a}_p(\theta)$ corresponding to any p^{th} subarray as follows:

$$\begin{gathered}Q(\theta) = \frac{1}{\mathbf{a}_p^H(\theta)\widetilde{\mathbf{U}}_\eta\widetilde{\mathbf{U}}_\eta^H\mathbf{a}_p(\theta)} \\ \mathbf{a}_p(\theta) = \left[F(\delta_p,\theta)\exp[j\Delta\tau_p] \quad \cdots \quad F(\delta_{p+L-1},\theta)\exp[j\Delta\tau_{p+L-1}]\right]^T\end{gathered} \tag{6}$$

where $\Delta\tau_p$ is the phase difference between signals received by the first and the p^{th} antenna elements with respect to a signal impinging on the origin. The values of angle θ corresponding to the peaks of $Q(\theta)$ are chosen as the estimated DOAs of the coherent jammers.

3. SIMULATION RESULTS

For performance demonstration of the proposed method, a simulation result for a representative scenario in presence of coherent jammers is presented in this section. The misaligned antenna array consists of 10 antenna elements, and each antenna element is assumed to be located on a globular-shaped surface, as shown in Fig. 2.

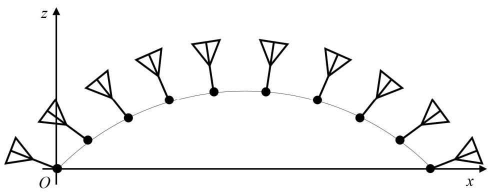


Fig. 2. Ten-element misaligned antenna array deployed on a globular-shaped surface.

The distance between any two adjacent antenna elements is set to be half wave length of the GPS L1 signal, i.e., approximately 9.5 cm, and the orientation of the antenna elements $\{\delta_1, \delta_2, \delta_3, \delta_4, \delta_5, \delta_6, \delta_7, \delta_8, \delta_9, \delta_{10}\}$ is set to be $\{-72°, -56°, -40°, -24°, -8°, 8°, 24°, 40°, 56°, 72°\}$. The above antenna array is divided into five six-element subarrays, i.e., $P = 5, L = 6$.

In the jamming scenario, three coherent jammers, each having a jammer to noise power ratio of 25 dB, have intermediate frequencies equal to 1.25 MHz, and their directions are assumed to be $\theta_1 = -35°, \theta_2 = 10°, \theta_3 = 55°$. Fig. 3 shows the comparison between two spatial spectral functions obtained by using the conventional spatial smoothing method without misalignment consideration and the proposed method. In Fig. 3, the solid line represents the spatial spectral function of the proposed method, whereas the dashed line represents the spatial spectral function of the conventional spatial smoothing method.

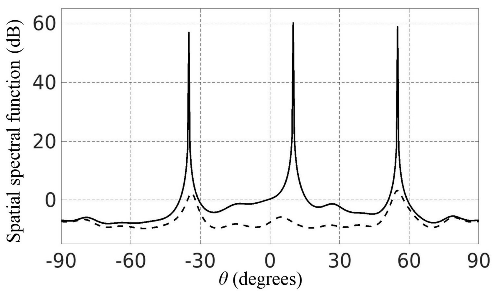


Fig. 3. Comparison between the spatial spectral functions obtained by using the proposed method and the conventional spatial smoothing technique.

As expected, obvious peaks are present in the spatial spectral function of the proposed method, whereas the conventional spatial smoothing technique cannot generate peaks in the directions of the coherent jammers. It can be concluded that this result validates the performance of the proposed method.

4. CONCLUSIONS

In this study, a signal processing technique for DOA estimation of coherent jammers in case of a misaligned antenna array was investigated. We assumed an antenna array consisting of dipole antennas oriented in different directions and the mathematical model of the received signal was derived. Using the received signal model, a modified spatial smoothing method for antenna array misalignment was presented in this article. For performance demonstration, a representative simulation result was presented so as to compare the DOA estimation performances of the proposed technique and conventional spatial smoothing method, and it was validated that the proposed method shows better estimation performance.

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