Int. J. Electron. Commun. (AEÜ) 75 (2017) 124–129

Contents lists available at ScienceDirect

International Journal of Electronics and Communications (AEÜ)

journal homepage: www.elsevier.com/locate/aeue

Regular paper

Robust adaptive beamforming using multi-snapshot direct data domain approach

Lilong Qin [a,b,*], Manqing Wu [c], Zhen Dong [a]

[a] Institute of Space Electronics and Information Technology, School of Electronic Science and Engineering, National University of Defense Technology, China
[b] Department of Signal Processing and Acoustics, Aalto University, Finland
[c] China Academy of Electronics and Information Technology, China Electronics Technology Group Corporation, China

ARTICLE INFO

Article history:
Received 19 October 2016
Accepted 7 March 2017

Keywords:
Direct data domain
Array signal processing
Robust adaptive beamforming
Norm-constrained beamforming
Probability-constrained beamforming

ABSTRACT

For the realistic case where there is no secondary snapshot that does not contain the desired signal and exhibits the statistical characteristics similar to the snapshot under test, direct data domain (D^3) beamforming approaches have been proposed to estimate a desired signal in the presence of interference. However, the basic idea of the D^3 methods is realized by making significant sacrifices with respect to the number of degrees of freedom (DoFs). In this paper, we present a multi-snapshot approach for D^3 beamforming. Using the least-squares method with multiple snapshots, we can eliminate the interference without causing a severe reduction in the number of DoFs. In addition, to consider a mismatch between nominal and actual target steering vectors, we propose a D^3 approach combined with a probability constraint to prevent the self-nulling effect, and the relationship between the probability constraint and norm constraint is discovered. The simulations verify that the proposed method provides better performance and robustness than the conventional D^3 approaches.

1. Introduction

In many wireless communication, biomedical imaging, sonar, and radar applications, adaptive beamforming approaches can be used to effectively separate the target from interference (jammer, clutter, and noise) [1]. Ignoring the detailed working principle, these approaches can be classified into two classes: stochastic beamformers and deterministic beamformers [2].

Regarding the conventional stochastic beamforming approach, the interference statistics (e.g., the covariance matrix) need to be estimated from secondary snapshot data. Conventional stochastic beamformers can achieve good performance when secondary snapshots do not contain the desired signal and exhibit homogeneous statistical characteristics similar to the snapshot under test. According to the Reed-Mallet-Brennan rule, the required number of snapshots must be twice the system degrees of freedom (DoFs) [3]. In many realistic cases, however, it is impossible to obtain sufficient secondary snapshots that satisfy these requirements (e.g., in passive localization, wireless communication, passive sonar, and speech processing applications, signal-free data are unavailable), and the performance is significantly degraded [4].

Single-snapshot Direct data domain (D^3) approaches have been proposed to overcome the drawbacks of the conventional statistical techniques [5–7]. In contrast to conventional stochastic beamforming approaches, single-snapshot D^3 approaches do not require secondary snapshots to estimate the statistical characteristics. The snapshot under test is directly employed to design the beamformer. However, it is achieved by introducing a high side-lobe level and at the high cost of a reduction in the number of degrees of freedom (DoFs) [7]. In [8], a D^3 beamforming method is proposed to increase the number of DoFs while decreasing the side-lobe level, and the proposed method can provide better performance than the conventional single-snapshot D^3 approaches.

However, the performance of the D^3 approaches is significantly affected by the mismatch between the nominal and actual target steering vectors [9]. This imperfect steering vector mismatch will result in a target self-nulling effect that leads to severe performance degradations. Several approaches have been proposed to overcome this problem. The first approach is to establish multiple constraints that cover the region of uncertainty of the target parameters [10,11]. This solution can preserve the gain for the target at the expense of a reduced number of DoFs that are available to suppress the interference. The second approach aims to refine

* Corresponding author at: Institute of Space Electronics and Information Technology, School of Electronic Science and Engineering, National University of Defense Technology, China.

E-mail address: qin.lilong@outlook.com (L. Qin).

http://dx.doi.org/10.1016/j.aeue.2017.03.004
1434-8411/

the target parameter estimation, but an additional computational burden is introduced [12]. In addition, certain robust techniques that are used for the conventional Capon beamforming (e.g., the diagonal loaded technique [13,14], the beamformer optimizing the worst-case performance [15] and the signal-subspace projection method [16]) can be used to improve the robustness of the D^3 beamformer.

In contrast to the robust deterministic D^3 beamforming approaches that utilize a single snapshot (e.g., [10–12]), in this paper, a robust stochastic D^3 beamforming approach with multiple snapshots is proposed. Similar to conventional single-snapshot D^3 approaches, the proposed multi-snapshot D^3 beamforming algorithm does not require secondary snapshots, and snapshots under test can be directly employed. The proposed multi-snapshot D^3 beamforming algorithm can provide a better output SINR with a slight loss of DoFs [17]. Moreover, the relationship between the probability constraint and the norm constraint is derived in this paper.

Notation: In this paper, a variable, a column vector, and a matrix are represented by a lowercase letter, a lowercase bold letter, and a capital bold letter, respectively. The operations of transposition and conjugate transposition are denoted by $(\cdot)^{\mathrm{T}}$ and $(\cdot)^{\mathrm{H}}$, respectively. The symbol $\|\cdot\|$ denotes the ℓ_2-norm operator, and $|x|$ obtains the absolute value of x. x_n denotes the nth entry of vector $\mathbf{x}$, and $\mathbf{x}_{n_1:n_2} \triangleq [\,x_{n_1} \quad x_{n_1+1} \quad \cdots \quad x_{n_2}\,]^{\mathrm{T}}$.

2. Formulation

The adaptive beamforming technique is known to be effective for suppressing the interference energy while receiving the useful signal. Consider an array system equipped with a uniform linear array (ULA) consisting of N omni-directional elements. The narrowband signal received at the fast time $\tau_k$can be represented as [4]

$$\mathbf{x}(\tau_k) = \alpha_s(\tau_k)\mathbf{a}(\theta_s) + \sum_{i=1}^{P}\alpha_i(\tau_k)\mathbf{a}(\theta_i) + \boldsymbol{\upsilon}(\tau_k) \tag{1}$$

where $\alpha_s(\tau_k)$ and $\alpha_i(\tau_k)$ are the unknown complex amplitudes of the desired signal (if it exists) and the interference, respectively. P is the number of interferences impinging on the array, and $\boldsymbol{\upsilon}(\tau_k)$ is the thermal noise vector with noise power σ_n^2 on each channel. $\mathbf{a}(\theta) \triangleq \left[1 \quad e^{j\frac{2\pi d}{\lambda}\sin(\theta)} \quad \cdots \quad e^{j\frac{2\pi d(N-1)\sin(\theta)}{\lambda}}\right]^{\mathrm{T}}$ is the associated steering vector corresponding to the direction of arrival (DOA) θ, where d is the inter-element distance between the elements of the array and λ is the carrier wavelength.

Note that (1) can be rewritten as

$$\mathbf{x}(\tau_k) = \alpha_s(\tau_k)\mathbf{a}(\theta_s) + \sum_{i=1}^{P}\alpha_i(\tau_k)\mathbf{a}(\theta_i) + \sum_{\theta_j\in\Theta}\beta_j(\tau_k)\mathbf{a}(\theta_j) \tag{2}$$

where Θ is the set of whole spatial angles, with the exception of the angles of signal and interferences, and $\beta_j(\tau_k)$ are the corresponding complex amplitudes. In (2), the thermal noise is essentially regarded as a summation of the noises from all spatial directions [18].

Let us define $f_\theta \triangleq 2\pi d\sin(\theta)/\lambda$ as the spatial frequency. It is clearly observed that

$$\begin{aligned}\tilde{x}_n(\tau_k) &= x_n(\tau_k) - e^{-jf_{\theta_s}}x_{n+1}(\tau_k)\\ &= \sum_{i=1}^{P}\alpha_i(\tau_k)\left(1 - e^{j\left(f_{\theta_i}-f_{\theta_s}\right)}\right)a_n(\theta_i)\\ &\quad + \left(\upsilon_n(\tau_k) - e^{-jf_{\theta_s}}\upsilon_{n+1}(\tau_k)\right)\end{aligned} \tag{3}$$

contains no components of the signal of interest (SOI). Then we have

$$\begin{aligned}\tilde{\mathbf{x}}_n(\tau_k) &\triangleq [\tilde{x}_n(\tau_k),\cdots,\tilde{x}_{n+M-1}(\tau_k)]^{\mathrm{T}}\\ &= \sum_{i=1}^{P}\alpha_i(\tau_k)e^{j(n-1)f_{\theta_i}}\left[1 - e^{j\left(f_{\theta_i}-f_{\theta_s}\right)}\right]\mathbf{a}_{1:M}(\theta_i)\\ &\quad + \sum_{\theta_j\in\Theta}\beta_j(\tau_k)e^{j(n-1)f_{\theta_j}}\left[1 - e^{j\left(f_{\theta_j}-f_{\theta_s}\right)}\right]\mathbf{a}_{1:M}(\theta_j)\end{aligned} \tag{4}$$

where M is the number of DoFs which should be less than N. As shown, the complex amplitude of the interferences has been modulated by the coefficient $e^{j(n-1)f_{\theta_i}}\left[1 - e^{j\left(f_{\theta_i}-f_{\theta_s}\right)}\right]$, whereas the associated steering information is unchanged, i.e., the subspace of interference $\mathbf{a}_{1:M}(\theta_i)$ is unchanged. In the conventional single-snapshot D^3 approach, we form a cancellation matrix $\mathbf{F}(\tau_k) = [\tilde{\mathbf{x}}_1(\tau_k), \tilde{\mathbf{x}}_2(\tau_k), \cdots, \tilde{\mathbf{x}}_{N-M}(\tau_k)]$, where the weighted sum of all its column elements would be zero. Moreover, we fix the gain of the sub-array by forming the weighted sum $\boldsymbol{\omega}^{\mathrm{H}}\mathbf{v}$ to a pre-specified value C, where $\boldsymbol{\omega}$ denotes the designed filter coefficient vector, and $\mathbf{v} \triangleq \left[1, e^{jf_{\theta_s}}, \cdots, e^{j(M-1)f_{\theta_s}}\right]^{\mathrm{T}}$ is the pre-determined gain direction, i.e., [7]

$$\boldsymbol{\omega}^{\mathrm{H}}[\,\mathbf{v} \quad \mathbf{F}(\tau_k)\,] = [\,C \quad \mathbf{0}\,]. \tag{5}$$

In [12], it is shown that after the linear Eq. (5) is solved, an estimate of the signal complex amplitude can be derived as $\hat{\alpha}_s(\tau_k) = \boldsymbol{\omega}^{\mathrm{H}}\mathbf{x}_{1:M}(\tau_k)$.

In the single-snapshot D^3 beamforming approaches, $M \cong (N+1)/2$. Hence, the number of DoFs for suppressing interference is $(N-1)/2$, which is considerably smaller than that in conventional stochastic beamforming $(N-1)$. Moreover, the conventional D^3 beamforming approach has a weak noise gain (due to the high side-lobe level of the beampattern).

D^3 beamforming approaches that use multiple snapshots have been proposed to overcome the drawbacks of the conventional single-snapshot approaches. The cancellation matrix in the multi-snapshot D^3 beamforming approach can be directly constructed as

$$\mathbf{F} = [\mathbf{F}(\tau_1), \mathbf{F}(\tau_2), \cdots, \mathbf{F}(\tau_K)] \tag{6}$$

where K is the number of used snapshots. According to (4), the filter coefficient vector $\boldsymbol{\omega}$ designed to minimize (not to null the interference energy) $\left\|\boldsymbol{\omega}^{\mathrm{H}}\mathbf{F}\right\|^2$ can not only suppress the interferences, but also decrease the side-lobe level to mitigate the thermal noise.

It is known that the D^3 beamforming approach is adversely affected by the mismatch between the nominal and actual target steering vectors [11]. In the next section, we propose a novel D^3 beamforming approach that uses multiple snapshots and a probability constraint to overcome the drawbacks of conventional approaches.

3. Solutions

Consider the possibility of mechanical vibrations, calibration errors, or atmospheric refractions of the incident electromagnetic waves. The assumed DOA may not be very accurate [19–22]. Hence, the filter pulse response should be designed such that it minimizes the output interference power while robustly maintaining a pre-determined array gain.

3.1. Norm-constrained optimization

The array gain can be defined as [23]

$$G \triangleq \frac{\alpha_s^2\left|\boldsymbol{\omega}^{\mathrm{H}}\tilde{\mathbf{v}}\right|^2}{\boldsymbol{\omega}^{\mathrm{H}}\mathbf{F}\mathbf{F}^{\mathrm{H}}\boldsymbol{\omega}} = \frac{\alpha_s^2\left(\boldsymbol{\omega}^{\mathrm{H}}\mathbf{v}\mathbf{v}^{\mathrm{H}}\boldsymbol{\omega} + \boldsymbol{\omega}^{\mathrm{H}}\mathbf{C}_{\tilde{\mathbf{v}}}\boldsymbol{\omega}\right)}{\boldsymbol{\omega}^{\mathrm{H}}\mathbf{F}\mathbf{F}^{\mathrm{H}}\boldsymbol{\omega}}. \tag{7}$$