Information Sciences 266 (2014) 160–170

Contents lists available at ScienceDirect

Information Sciences

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

An adaptive robust fuzzy beamformer for steering vector mismatch and reducing interference and noise

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ARTICLE INFO

Article history:
Received 25 April 2012
Received in revised form 31 May 2013
Accepted 4 October 2013
Available online 17 October 2013

Keywords:
Fuzzy system
Beamformer
Genetic algorithm
Antenna array
Minimum variance distortionless response

ABSTRACT

This paper presents an efficient beamformer design that accounts for both signal steering vector mismatches and the trade-off between interference and noise reduction. The empirical results show that substantial performance degradation occurs when the exact signal steering vector for the desired signal is not known. Furthermore, total rejection of interference may increase noise, and vice versa. Therefore, an adaptive robust fuzzy beamformer was designed by adopting the method of fuzzy systems to modify both the value of the signal steering vector and the interference-to-noise ratio. This method uses the first-order Taylor expansion of the object function to modify the mismatches of the signal steering vector, and uses the signal covariance matrix eigendecomposition to adjust the ratio of interference reduction to noise reduction. Simulations confirm that the proposed scheme performance is substantially improved and more robust if the effects of the signal steering vector mismatches and the interference to noise ratio are considered in the beamformer design which is based on expert knowledge.

1. Introduction

The issue of extracting a desired signal that is buried in noise and interference is crucial [1,24]. The minimum variance distortionless response (MVDR) beamformer, also known as the Capon beamformer [3,11,12], is commonly used to reduce noise and interference energy without distorting the desired signal. This method uses the correlation matrix of the received signal and the desired signal direction-of-arrival (DOA), which must be known. A small error in the DOA estimation causes mismatches in the steering vector and results in cancellation of the desired signal [6,16]. However, in many practical applications, multipath propagation resulting from reflections and local scattering of the source signals causes a spreading of the signal energy around the nominal DOA. A small local scattered angle spread can cause substantial performance degradation when the exact array response vector for the desired signal is not known [6,16].

To address this problem, researchers have introduced various robust beamforming methods [7,10,12,20] to improve the mismatches in the steering vector. Diagonal loading [12] is a technique for adaptive robust beamforming. In this method, a sample covariance matrix determines the required diagonal loading by using user parameters that might not be available in practice; a strong disadvantage is that there is no reliable method for selecting the diagonal loading [12]. A linearly constrained minimum variance (LCMV) beamformer [7] provides robustness against uncertainty in the signal direction. This method accounts for the signal steering vector mismatches, and additional constraints can be imposed to improve the

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0020-0255/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.ins.2013.10.004

robustness of the adaptive beamforming to achieve various goals [8,26]. However, the beamformer loses degrees of freedom because of interference suppression [24]. The generalized sidelobe canceler (GSC) [10] can render the implementation of the LCMV much more efficient. The theoretical equivalence between the LCMV and its GSC counterpart was demonstrated by [10]. The purpose of this study is to improve the robustness of adaptive beamforming by considering the mismatches in the steering vector, previously assumed to be constant, as a time-varying function. Consequently, fuzzy systems could be a judicious choice for analyzing dynamic processes that feature the mismatch of steering vector values. In addition, it is assumed that interference and noise coexist with the desired signal. The authors of [2] proved that a trade-off between noise reduction and interference rejection is necessary. Total rejection of the interference may increase noise, and vice versa. Thus, a fuzzy system is used to consider the ratio of interference reduction to noise reduction for a robust beamformer.

Throughout the past two decades, fuzzy systems have been used to describe complicated nonlinear systems from the viewpoint of expert knowledge and have been widely and successfully applied in industrial control systems [5,18–20,23]. This paper proposes a new class of beamformer based on fuzzy systems. The distinguishing feature of this method is that it can express nonlinear systems linguistically. Based on knowledge of the adjustment of the mismatch of the steering vector values and the ratio of interference reduction to noise reduction, a fuzzy model can be constructed using expert input.

This paper proposes a new beamforming method, which is called the adaptive robust fuzzy beamformer. The major contribution of this method is twofold. First, it uses fuzzy systems to modify both the value of the signal steering vector and the ratio of interference reduction to noise reduction. Second, adaptive array techniques are used to enhance the efficiency of the beamformer, and a genetic-based algorithm is proposed that yields the most accurate global parameter estimation.

The rest of this paper is organized as follows. Section 2 briefly outlines the problem. Section 3 presents the proposed method. Several simulation examples demonstrating the effectiveness of the proposed estimator are presented in Section 4. Section 5 offers a conclusion.

2. Problem description

2.1. Signal model

Consider a uniform linear array (ULA) with M elements illuminated by D uncorrelated far-field narrowband signal sources. Let $\mathbf{x}(t) = [x_1(t) \quad x_2(t) \quad \cdots \quad x_M(t)]^T$ denote the data received by the array elements at the tth snapshot. The data vector $\mathbf{x}(t)$ can be expressed as

$$\begin{aligned} \mathbf{x}(t) &= \sum_{i=1}^{D} \mathbf{a}(\theta_i) s_i(t) + \mathbf{n}(t) \\ \mathbf{a}(\theta_i) &= [1 \quad \exp(-j2\pi d \sin\theta_i/c) \quad \cdots \quad \exp(-j2\pi(M-1)d\sin\theta_i/c)]^T \end{aligned} \tag{1}$$

where $t = 1,2,\ldots,N$; N is the number of snapshots; $\mathbf{a}(\theta_i)$ is the steering vector with a size of $M \times 1$ in a complex manifold; d is the sensor spacing; c is the wavelength of the signal carrier; $s_i(t)$ is the signal amplitude; $\mathbf{n}(t)$ is the spatially white Gaussian noise with zero mean and variance σ_n^2 that is uncorrelated with all of the source signals; and the superscript T indicates transposition. Furthermore, assume that the source signals travel through a narrowband multipath fading channel. The signal with a scattered multipath can be closely approximated by a single point source with an angle spread of $\Delta\theta$ and within an angle interval centered at the line-of-sight (LOS) angle θ_i, $i = 1,2,\ldots,D$ [15,24]. Eq. (1) can be expressed as

$$\mathbf{x}(t) = \sum_{i=1}^{D}\sum_{j=1}^{K} \alpha_{i,j}\mathbf{a}(\theta_{i,j}) s_i(t) + \mathbf{n}(t) \tag{2}$$

where K is the number of locally scattered multipaths; $\theta_{i,j} = \theta_i + \Delta\theta_j$; $\Delta\theta_j$ is the angle spread with uniform distribution over the interval $[-0.5 \times \Delta\theta \quad 0.5 \times \Delta\theta]$; $\Delta\theta$ is defined as the angle spread; and $\alpha_{i,j}$ is the associated complex gain, which can be treated as constant over the processing period of interest because of the slow fading assumption. For convenience, assume that the first user of interest inputs the data. The array output can be expressed as

$$\mathbf{x}(t) = \sum_{j=1}^{K} \alpha_{1,j}\mathbf{a}(\theta_{1,j}) s_1(t) + \sum_{i=2}^{D}\sum_{j=1}^{K} \alpha_{i,j}\mathbf{a}(\theta_{i,j}) s_i(t) + \mathbf{n}(t) = \mathbf{g}_1 s_1(t) + \mathbf{i}(t) + \mathbf{n}(t) \tag{3}$$

where $\mathbf{g}_1$ is the nominal steering vector with a composition of K paths for the signal of interest and $\mathbf{i}(t)$ is the interference by the signal sources expected for the signal of interest. The parameter $\mathbf{g}_1$ is a function of the signal DOA θ_1 and the angle spread $\Delta\theta$. The DOA estimation methods can bias the estimation of DOA because of the existence of multipath environments. This type of scattered DOA phenomenon can cause a substantial degradation of the DOA estimation performance, even at low levels [16,17,27].