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Fuzzy inference based robust beamforming ☆

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Abstract

This paper presents a new approach to robust beamforming based on fuzzy logic theory that is suitable for both point and scattered sources. The presented technique is based on the optimum beamformer and makes it robust to an imperfect estimate of the direction of arrival (DOA) even when powerful interferences are within the uncertainty range of the desired source. This robust approach solves the deficiencies of the classical non-robust space reference beamformers (SRB) in which the real DOA and the presumed one are taken as equal, although they are not. At low signal-to-noise ratio (SNR) the fuzzy inference-based beamformer relies on the fuzzy description of the DOA estimation, and at high SNR it places more emphasis on the estimated DOA. Interference rejection is well achieved for Interference to noise ratios (INRs) over the SNR. When the number of antennas is large, the fuzzy inference based beamformer can be implemented by means of a general side lobe canceller (GSLC) architecture and stability improves while the beamformer is still capable of suppressing weak interferences. The proposed schemes are compared with existing techniques, showing that the fuzzy inference beamformer can be an alternative when considering scenarios with

Abbreviation: AOA, angle of arrival; DOA, direction of arrival; FLS, fuzzy logic system; GSLC, generalized side lobe canceller; INR, interference-to-noise ratio; MMSE, minimum mean squared error; MPDR, minimum power distortionless response; MSE, mean squared error; MV, minimum variance; MVDR, minimum variance distortionless response; SIR, signal-to-interference ratio; SMI, sample matrix inversion; SNIR, signal-to-noise plus interference ratio; SNR, signal-to-noise ratio; SRB, space reference beamformers

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DOA uncertainty and interferences. The main goals of the proposed scheme are: DOA robustness, adjustability, and numerical stability, which shortens the distance between theory and implementation.

Keywords: Fuzzy inference; Approximation theory; Array signal processing; Interference suppression; DOA estimation; Robust adaptive beamforming

1. Introduction

Adaptive array beamformers are utilized to discriminate the desired signal from unwanted interferers. Classical beamforming techniques, such as space reference beamformers (SRB), need to know the steering vector associated with the desired signal. The goal is to provide a constant response towards this steering direction while rejecting the interfering spatial directions. However, significant performance degradation occurs when the array response vector for the desired signal is not known exactly [1–7]. This degradation is especially noticeable when the number of available snapshots is low (i.e. the so-called sample support problem) and gets worse for high signal-to-noise plus interference ratio (SNIR). In this situation, mismatch between the estimated spatial signature and the real one may tend to suppress the desired signal. Imperfect knowledge of the array response vector may be due to improper modelling, uncertainty in the source DOA or sensor characteristics, and variations in the propagation medium between the source and the array. In this paper we mainly focus on the problem of DOA uncertainty and low number of snapshots (e.g. in non-stationary scenarios). As interference leakage is more harmful than that produced by thermal noise due to its non-Gaussian nature, special attention is paid to scenarios with interference.

Numerous methods have been proposed to improve robustness to pointing errors. We classify them depending on the knowledge that they require from the uncertain desired DOA. Many of the traditional approaches need a nominal DOA and its corresponding uncertainty range. These approaches include linearly constrained minimum variance beamforming, diagonal loading [8] and its generalization to cope with non-stationary interferences [9], worst-case performance optimization [10], Bayesian approaches [11], quadratic constrained beamforming, and combinations of these. In these techniques, robustness to DOA uncertainty is increased at the expense, sometimes, of a reduction in noise and interference suppression, and, usually, they do not address the problem of interference within the uncertainty range of the desired signal. A different approach consists in increasing the computational complexity by using samples from the sensor data to estimate the signal DOA or signal subspace. These direction-finding-based techniques estimate the DOA of the desired and interference signals and proceed as if they are exact [12,13]. Subspace techniques, as in [14] or reference therein, estimate the signal plus interference subspace aiming at reducing the mismatch. These techniques can have nearly optimal performance when the data length is high enough to yield good estimates of the DOA or subspace. However, they suffer significant performance degradation when the estimates are not reliable. Techniques that improve the robustness of data-driven beamformers in the presence of moving and spatially spread sources by incorporating additional linear constraints have also been proposed in [4].

The above-mentioned techniques resort to different robust signal processing schemes, as for instance: regularization, minimax/worst-case design, or Bayesian approaches. This paper uses fuzzy logic as another tool that can be useful when imprecise a priori knowledge of input characteristics makes the sensitivity of performance to deviations from assumed conditions an important factor in the design of good signal processing schemes [15].

In this work two direction-finding-based beamformers that describe DOA imprecision by means of fuzzy sets [16] are developed. They do not rely on any statistical assumption either on interference or noise and, therefore, its application is quite more direct than the Bayesian approaches, in