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Optimal quiescent vectors for wideband ML beamforming in multipath fields

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Abstract

In this work,[1] the behavior of the recently developed wideband maximum likelihood steered beamformer (ML-STBF) is analyzed under multipath conditions. In particular, the importance of an optimal choice of the quiescent vector to initialize the ML-STBF is pointed out.

Some quiescent vectors, optimized on the basis of the previous analysis, are developed for the joint use with the ML-STBF and compared in simulation. It is shown that their use can significantly improve the output signal-to-noise ratio, the multipath suppression capability and the robustness with respect to focusing errors of the ML-STBF.

Keywords: Acoustics; Quiescent vector; Matched-field beamforming; Maximum likelihood; Minimum variance; Multipath; Propagation; Reverberation; Scattering; Sensor arrays; Steered adaptive beamforming; Wideband coherent focusing

1. Symbols and notation

Throughout the present work, matrices will be indicated by capital boldface letters, and vectors by lower-case boldface letters. Other frequently used symbols are

$(.)^*$	matrix conjugate
$(.)^H$	Hermitian matrix transpose
$\lvert . \rvert$	absolute value of a scalar
$\lVert . \rVert$	L_2 norm of a matrix or a vector
$\lVert . \rVert_F$	Frobenius norm of a matrix [8]
$(.)^\dagger$	Moore–Penrose pseudo-inverse of a matrix [8]
Re(.)	real part of the argument
$\mathbf{I}_m$	the $(m \times m)$ identity matrix
$\mathbf{0}$	all-zero matrix
ω	angular frequency in discrete time
i	imaginary unit
$F^{-1}(.)$	Inverse Discrete Fourier Transform (IDFT) [18]
$E[.]$	statistical expectation operator

To avoid ambiguities, sample estimates will be marked by a *tilde* superscript.

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2. Introduction

Adaptive beamforming of sensor arrays is frequently used to recover an *undistorted copy* of a wideband[2] *signal of interest* (SOI) radiated by a wave-field source [23], for purposes of localization [10], recording, speech recognition, digital data transmission [19] and biomedical imaging [14].

In many environments, high levels of multipath and reverberation [2] are present. In these cases, non-adaptive beamforming is inefficient in suppressing reflections and independent interference with a reasonable number of sensors, while classical adaptive beamforming, based on minimum variance (MV) or maximum likelihood (ML) criteria [23], may suffer of *SOI cancellation* at the beamformer output, because of the finite data misadjustment [21] and the mismatch with respect to the assumed single-path propagation model [20].

In addition, cancellation may result as an effect of the *SOI temporal correlation*, which induces *multipath coherence* well beyond the length of the SOI impulse response [5].

Several approaches have been developed to cope with this nasty phenomenon:

1. specification of a proper set of *linear or quadratic constraints* on the weight vector after a preliminary wave-field analysis [1,20];
2. *matched-field* (MF) adaptive beamforming, which takes into account the contributes from *all propagation modes*, estimated by a numerical wave-field simulator, to minimize effects of random model errors [15];
3. *wideband beamforming*, capable of destroying multipath coherence by frequency averaging [5,16,21].

In particular, the wideband *steered adaptive beamformer* (STBF), first introduced in [16], is characterized by the preliminary SOI focusing [13] and the use of a single weight vector for the entire analysis bandwidth. Thanks to the low number of free parameters and the high rate of independent observations delivered, the STBF exhibited valid performance even with short data records [21].

Experiments with real world data using the recent stochastic ML-STBF [5] demonstrated that focusing, based on the *analytical or empirical modeling* of the direct (e.g., the *shortest*) path only, coupled with proper robustness constraints on the weight vector, can suppress multipath and avoid SOI cancellation, even in the presence of significant propagation uncertainties.

The scope of this work is to analyze and optimize the performance of the ML-STBF in the presence of multipath. It is shown that the ML-STBF is largely insensitive to the SOI spectrum if the output signal-to-noise ratio (SNR), measured *after adaptation*, is sufficiently high. In addition, reflections, whose delay roughly exceeds the reciprocal of the SOI bandwidth, are cancelled by the ML-STBF just as independent interference and noise.

On the contrary, it is shown that reflections arriving with a smaller delay (*coherent modes*) and sensor mismatches can still cause SOI cancellation. A cure, suggested by past work on adaptive narrowband MF beamforming [15], has been found in the choice of an optimal *quiescent vector* [9] to initialize the ML-STBF, which explicitly takes multipath into account.

So, exploiting the properties of the ML-STBF and a simplified model of coherent modes, some optimal quiescent vectors are devised in order to prevent SOI cancellation and enhance the output SNR of the beamformer. Their synthesis requires a rough preliminary focusing of the direct path and a consistent estimate of the *overall array response* (including multipath) over a grid of source locations of interest.

The paper is organized as follows. The signal model and the ML-STBF are briefly recalled in Section 3. In Section 4 the analysis of the ML-STBF in the presence of multipath is carried out. On this basis, some optimal quiescent vectors are derived in Section 5. Finally, in Section 6, computer simulations in difficult scenarios demonstrate the significant performance gains achieved by the ML-STBF [5] (and also by the classical MV-STBF [16]), when coupled with the proposed quiescent vectors.

[2] A signal is considered here as *wideband* when its bandwidth exceeds a few percent of its central frequency [21].