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A new DOA estimation algorithm for wideband signals in the presence of unknown spatially correlated noise

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ABSTRACT

In this paper, a new high resolution direction-of-arrival (DOA) estimation technique is proposed for wideband signals in the presence of spatially correlated noise with unknown covariance matrix. The proposed technique is based on the (matrix) difference between the forward–backward averaged covariance matrix of the observations and the Hermitian of the backward covariance matrix of the observations. This differencing operation eliminates the noise covariance matrix from the difference matrix. The propagator method is then applied to the difference matrix to find the DOA. This proposed technique does not require any initial estimate of the DOAs and is effective for both correlated and partially correlated sources. In this paper, the proposed technique is applied to a uniform linear array and an L-shaped array for both one- and two-dimensional DOA estimation. Simulations results comparing the performance of the proposed method with that of the coherent propagator method are presented.

1. Introduction

Direction-of-arrival (DOA) estimation is one of the important research areas of array signal processing [1], which has been attracting the attention of the signal processing community for more than three decades. DOA is one of the most important parameters that needs to be estimated in many applications. For radar, DOA estimation is the most important operation performed to localize targets. For communications, DOA estimation can give spatial diversity to the receiver to enable multi-user scenarios. There exists at present a large number of algorithms for DOA estimation. Signal subspace methods are very well known DOA estimation techniques with high performance and relatively low computational cost. MUSIC (MUltiple Signal Classification) [2] and ESPRIT [3] fall into this category. Most of these methods take advantage of the fact that there is only a phase difference among the different sensor outputs, when the signals are narrowband. Therefore, the subspace methods work exclusively under this narrowband assumption.

Recently, wideband signals have attracted considerable attention because of their inherent advantages over narrowband signals in applications such as radar, sonar, seismology, and spread spectrum communications. For example, ultra wideband (UWB) radar can provide high resolution images [4], and UWB wireless communication can counteract the effects of channel fading due to multipath [5]. Wideband signals are also used to track moving objects from acoustic measurements [6] or to find buried objects with the help of seismic sensors [7]. Use of wideband signals results in high data rates in communication.

Direct exploitation of raw wideband signals for DOA estimation using the traditional narrowband technique leads to failure. The reason is that the narrowband

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methods, which require the bandwidth to be small, exploit the fact that time delays directly translate to phase differences so long as the phase remains approximately constant over the bandwidth. On the other hand, for wideband signals, whose bandwidth is not small compared to the centre frequency, this direct proportionality between time delays and phase differences does not hold.

One simple way to deal with wideband signals is to decompose the wideband signal into many narrowband signals centered around frequencies with large power concentration using filter banks or the discrete Fourier transform in the temporal domain [8–10]. Narrowband methods can then be applied to each narrowband component of the decomposed signal. However, this kind of approach does not take advantage of the signal's full frequency band because of the possibility of rejecting some frequency bins, which might have had information about the DOA, on the basis of the power-concentration criterion. These methods, which apply narrowband processing to the selected frequency bins independently, are called incoherent methods. Several different approaches that make full use of all the frequency components of a wideband signal in a coherent fashion have been published in the literature [11–15]. Most of these coherent methods involve a conversion of wideband data or statistics into narrowband forms, either directly or indirectly, so that narrowband subspace methods become applicable. One of the most well-known of coherent methods is the coherent signal subspace method (CSSM) [16] from which many other variants derive their roots [17–19]. CSSM requires a preprocessing step called focusing. The focusing step requires an initial estimate of the DOAs which should be as close as possible to the true DOAs. If the initial values are substantially different from the true DOAs, the DOA estimate could exhibit a bias that does not vanish as the number of data samples approaches infinity [20].

Most of the high resolution techniques for estimating DOAs have been applied to spatially white noise models [2,3]. For the case of non-white (correlated) noise, the noise-covariance matrix is assumed to be known, but in reality, estimating the noise covariance matrix may be a problem. Many algorithms [21] have been proposed to solve this problem assuming uncorrelated sources. The drawbacks of these algorithms, in the presence of spatially correlated noise fields, are (i) an increase in the bias of the DOA estimate and hence a degradation in performance and (ii) the need for a computationally intensive eigen-decomposition of the covariance matrix of the observations to find the DOAs. In this context, the so-called propagator method, which does not require eigen-decomposition, proposed by Marcos et al. [22], is quite attractive from the computational point of view. But the performance of the propagator method (PM) is poor when the signal-to-noise ratio (SNR) is low. The PM cannot significantly reduce the effects of unknown noise because the PM requires noise covariance matrices to be known.

In this paper, a high resolution DOA estimation technique based on differencing the forward–backward (FB) averaged covariance matrix and the Hermitian of backward covariance matrix [20] for a uniform linear array (ULA) and an L-shaped array for wideband sources in the presence of unknown spatially correlated noise is presented. The PM is then applied to the difference matrix and the resulting incoherent propagator matrices are then transformed using certain focusing matrices. Finally, a coherent propagator matrix is obtained by averaging the transformed incoherent propagator matrices. The coherent propagator matrix is then used to estimate the DOAs of wideband sources.

For the DOA estimation problem in the presence of an unknown correlated noise field addressed in this paper, the noise-covariance matrix is assumed to be in the Hermitian symmetric Toeplitz form as in [23,24]. This assumption is justified when the noise field is cylindrically or spherically isotropic around the array elements. Such a situation is typically encountered when the noise field is radiated by a set of point sources distributed symmetrically about the array broadside [23]. This is the type of noise that would be encountered in a passive sonar environment when wind-generated noise is dominant [25].

The paper is organized as follows: In Section 2, the data models for a uniform linear array and an L-shaped array are presented. In Section 3, the proposed DOA algorithm for wideband signals is derived. In Section 4, we present numerical simulations that illustrate the mean-square error reduction and resolution improvement achieved by the proposed method as compared to the coherent propagator method. Finally, Section 5 concludes the paper.

Throughout this paper, vectors are denoted by lowercase bold letters and matrices by uppercase bold letters. The superscripts *, T and H denote, respectively, complex conjugation, transposition, and conjugate transposition.

2. Formulation of data models

2.1. Data model for a uniform linear array

Consider a uniform linear array consisting of M sensors, with inter-element spacing d, that receives the wave field radiated by K wideband sources in the presence of an arbitrary noise field. It is assumed that the number K of such sources has already been estimated using one of the standard methods [26–28]. The received signals are assumed to be zero-mean, wide-sense stationary random processes band-limited to W over the finite observation interval. The DOA of the kth source signal is θ_k for $k=1, 2, \ldots, K$, with respect to the array normal. The observation interval is subdivided into D disjoint intervals. The received signal $\tilde{z}_m(t)$ at the mth sensor, in each subinterval, can be written as

$$\tilde{z}_m(t) = \sum_{k=1}^{K} \tilde{s}_k(t - \tau_m(\theta_k)) + \tilde{\eta}_m(t), \tag{1}$$

where $\tilde{s}_k(t)$ is the kth source signal, $\tilde{\eta}_m(t)$ is the noise observed at the mth sensor, and $\tau_m(\theta_k) = ((m-1)d\cos\theta_k/c)$ is the relative delay where c is the constant propagation speed of the source signals.