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Morphological image processing for FM source detection and localization

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ABSTRACT

We consider the problem of direction finding for frequency modulated signals impinging on an array of sensors. Making use of a time–frequency representation of the data, we are able to exploit the non-stationary nature of the source signals. We employ morphological image processing to estimate time–frequency signature segments of each source. For the direction finding we apply beamforming techniques on averaged spatial time–frequency distribution matrices. When they occur, overlapping segments are splitted and re-combined after direction finding. The re-combination of segments is based on a bootstrap test, which resamples time–frequency auto-term locations. The proposed method also allows direction finding for the underdetermined case, i.e. when there are more sources than the number of array sensors. Furthermore, it detects the number of sources present, and the detector performance is compared to information based criteria.

1. Introduction

Frequency modulated (FM) signals arise in a number of fields including sonar, radar and communications. The energy content of FM signals is restricted to well-defined regions in the time–frequency (TF) domain; the so-called TF signatures. Using spatial time–frequency distributions (STFDs), we are able to exploit the TF localization of the sources and improve the performance of direction finding algorithms [2]. The gain in performance with respect to traditional methods is significant when separately averaging over the TF signatures of each source [19]. It should be noted, however, that the performance gain demonstrated in [2,19] was obtained assuming perfect knowledge of the source TF signatures. The practical benefit of these approaches therefore depends on how well the TF signatures can be estimated from the observation data.

One approach to obtaining the required TF signatures of the sources is based on an estimation of the instantaneous frequency (IF) using the spatially averaged TF distributions (TFD) of the sensor data. Recently, the application of various image processing techniques has received attention in the TF and STFD literature. To name a few:

- Peak detection and component linking has been used for IF estimation [15].
- A line detection method, commonly used in road network extraction in SAR images, has been used for underdetermined blind source separation [1].
- Another approach for blind source separation considers vector classification based on the spatial structure of the signal eigenvectors [14].
- A generalized Hough transform has been used for the estimation of a parameterized IF trajectory [4]. This approach has also been applied for direction finding [3].

We propose to extract segments of TF signatures with image processing techniques, in particular morphological

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filtering and thinning. The extracted IF segments can be effectively used for direction finding, by means of STFD matrix averaging, if they belong to a single source [10].

This paper is organized as follows: Section 2 introduces the signal model. Underlying principles of STFD averaging in view of direction finding are summarized in Section 3. IF segment extraction, principally based on morphological filtering, thinning and component splitting, is treated in Section 4. The extracted IF segments may be described as connected sets of single-source TF points, approximately lying on the sources' IF. In Section 5, a sequential segment linking approach is applied to combine IF segments which originate from the same source. The segment linking uses a statistical test based on a bootstrap resampling technique. We note that in general each source may be represented by more than one IF segment. Therefore, the linking of segments may be beneficial in the following scenarios:

- The case of crossing IFs generally does not allow a unique signal decomposition, e.g. a crossing up- and down-chirp may be interpreted as various combinations of four IF segments. Using the spatial information of the STFD, we are able to link them correctly
- "Broken" segments, which may occur at low SNR, can be recombined.

Section 6 summarizes simulation results which show that our approach can be effectively used for source detection and localization and that it offers better accuracy than traditional approaches without TF processing. Section 7 includes discussion and conclusions drawn from this work.

2. Signal model

In narrowband array processing, the baseband signal model for d signals, arriving at an m-element array is given by

$$\mathbf{x}(t) = \mathbf{A}\mathbf{s}(t) + \mathbf{n}(t), \quad t \in \mathbb{R} \tag{1}$$

Here, $\mathbf{A}$ is the $m \times d$ mixing matrix, $\mathbf{x}(t)$ is the $m \times 1$ array output vector and $\mathbf{s}(t)$ is the $1 \times d$ source signal vector. The mixing matrix takes the form $\mathbf{A} = [\mathbf{a}(\theta_1), \ldots, \mathbf{a}(\theta_d)]^{\mathrm{T}}$ where $\mathbf{a}(\theta_k)$ is the k-th array steering vector and $\theta_1, \ldots, \theta_d$ are the source directions of arrival (DOA). The noise vector $\mathbf{n}(t)$ is assumed to be stationary, spatially and temporally white, zero-mean, circular complex Gaussian.

As source signals, we consider constant amplitude FM signals of the form

$$s_k(t) = \mathrm{e}^{\mathrm{j}2\pi\Phi_k(t)}, \quad k = 1, \ldots, d$$

and their corresponding IF given by $f_k(t) = \mathrm{d}\Phi_k(t)/\mathrm{d}t$. We confine our consideration to the case where the sources are "well distinguishable" in the TF domain, i.e. separated by at least the resolution limit of the chosen TFD representation. The source waveforms are assumed to lie within the same baseband frequency range, and have been demodulated using a common carrier frequency. The dynamic range of the sources is accounted for in the steering matrix. The objective is to detect d sources and estimate their DOAs, given N snapshots of $\mathbf{x}(t)$.

3. STFD matrices and direction finding

We make use of the idea by Amin et al. [2] for direction finding based on a spatial TFD matrix, defined in terms of the auto- and cross-TFDs of the sensors as

$$[\mathbf{D}_{\mathbf{xx}}(t,f)]_{ij} = D_{x_i x_j}(t,f;\varphi) \tag{2}$$

where $D_{x_i x_j}(t,f;\varphi)$ is assumed to be a bilinear TFD of Cohen's class, for which the kernel function is φ. We have used a discrete-time form of Cohen's class of TFDs as can be found in [5],

$$D_{xx}(t_n,f) = \sum_{l,m=-\infty}^{\infty} \varphi(m,l) R_{xx}(t_n,m,l) \mathrm{e}^{-\mathrm{j}4\pi fl} \tag{3}$$

where $R_{xx}(t_n,m,l) = x(t_{n+m+l})x^*(t_{n+m-l})$ is commonly referred to as the local auto-correlation function and $\varphi(m,l)$ is the kernel function in the time-lag domain. By averaging the STFD matrix over a subset of signal IF signatures, the source direction can be estimated, e.g. using beamforming techniques.

Our proposed approach performs IF signature estimation by means of morphological image processing. The extracted IF segments are non-overlapping sets of TF points $(t_n,f_n) \in \mathscr{S}_k$ for $k = 1, \ldots, p$. Note that each source may be represented by one or more IF segments. For each segment, the averaged STFD matrix is computed as

$$\mathbf{D}_k = \frac{1}{\#\mathscr{S}_k} \sum_{(t_n,f_n)\in\mathscr{S}_k} \mathbf{D}_{\mathbf{xx}}(t_n,f_n) \tag{4}$$

where $\#\mathscr{S}_k$ is the number of TF points in $\mathscr{S}_k$. The direction of the source signal represented by the IF segment $\mathscr{S}_k$ is estimated by the maximum of the well-known beamformer spectrum applied to $\mathbf{D}_k$

$$\hat{\theta}_k = \arg\max_{\theta} \frac{\mathbf{a}^H(\theta)\mathbf{D}_k\mathbf{a}(\theta)}{\mathbf{a}^H(\theta)\mathbf{a}(\theta)}, \quad k = 1, \ldots, p \tag{5}$$

which can be shown to be equivalent to the deterministic maximum likelihood solution for the single-source case [12]. Note that while the sample covariance matrix was used for direction estimation in the original beamformer algorithm, the averaged STFD matrix given in (4) leads to an enhanced effective SNR, and therewith to an improved accuracy of the direction estimate. The fact that IF segments only comprise single sources also allows the case of underdetermined direction finding.

As discussed in Section 1, segment linking is beneficial for non-unique signal decompositions or broken segments at low SNR. One can also attempt to link segments which originate from the same source and re-do the direction finding, thereby improving the DOA estimates. An overview of the proposed approach for FM source detection and localization is given in Fig. 1, where the combined segments are denoted by $\mathscr{C}_l$ for $l = 1, \ldots, \hat{d}$. Assuming the IF extraction and the segment linking was carried out successfully, $\hat{d}$ constitutes an estimate of the number of sources. The next two sections provide more details on