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ICT Express 2 (2016) 5–9
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Application of capon method to direct position determination☆,☆☆

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Received 25 October 2015; received in revised form 1 January 2016; accepted 5 February 2016
Available online 24 March 2016

Abstract

The direct position determination (DPD) approach is a single-step method which uses the Maximum Likelihood estimator to localize sources emitting electromagnetic energy using combined data from all available sensors. The DPD is known to outperform the traditional 2-step methods under low Signal to Noise Ratio (SNR) conditions. We propose an improvement to the DPD approach, using the well known minimum-variance-distortionless-response (MVDR) approach. Unlike Maximum Likelihood, the number of sources need not be known before applying the method. The combination of both the direct approach and MVDR yields unprecedented localization accuracy and resolution for weak sources. We demonstrate this approach on the problem of multistatic radar, but the method can easily be extended to general localization problems.
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1. Introduction

The localization of sources emitting electromagnetic or acoustic energy is needed in wild-life tracking, radio-astronomy, seismology, medical-diagnosis, communications, and other engineering applications. Common localization methods use two estimation steps. First, intermediate parameters are estimated. Intermediate parameters are usually time of arrival, direction of arrival, Doppler frequency shift or signal strength. These estimated parameters are then used, in a second step, to estimate the actual location of the emitter. The Direct Position Determination (DPD) approach has been recently proposed [1] as a single-step Maximum Likelihood localization technique. A single-step approach is a technique in which the estimator uses exactly the same data as used in two-step methods but estimates the source location directly, skipping the intermediate (first) step. This can be viewed as searching for the emitter location that best explains the collected data. From estimation theory point-of-view the two-step approach is inferior, since in the first step the parameters are measured independently, ignoring the constraint that the measurements relate to the same emitter location. Indeed, this method has been shown to be superior to the two-step methods for low SNR. In addition, the DPD method has been shown to be more robust by inherently selecting reliable observations without the need for a goodness-of-fit test (such as the chi-square test). This method was also extended to radar scenarios in [2], where the Maximum Likelihood target location estimation was developed as well as the Cramer–Rao lower bound for the estimation error.

When there are multiple sources the DPD is no longer equivalent to the Maximum Likelihood Estimator (MLE). The exact MLE can be derived but it requires a multi-dimensional search which is usually impractical. An alternative for the Maximum Likelihood parameter estimator is the Minimum Variance Distortionless Response (MVDR) estimator. It was originally proposed by Capon [3] for frequency–wavenumber power spectral density analysis, but has since been used extensively as a high resolution method. The idea is to adaptively select the weight vector in order to fix the response for the parameter value of interest while minimizing the output power. Unlike the Maximum Likelihood approach, the MVDR approach does not need to know a-priori the number of targets (or model order) and therefore it is a robust approach with good resolution and immunity to jamming and interference.

Our test case is multistatic radar, which is a generalization of the classical mono-static radar system. In a multistatic radar system multiple cooperative receivers are used for target localization. This could be generalized further with the addition of multiple transmitters (a scheme usually termed MIMO radar,

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Peer review under responsibility of The Korean Institute of Communications Information Sciences.

☆ This research was supported by Israel Science Foundation (grants 503/15, 965/15) and the Institute for Future Technologies Research named for the Medvedi, Shwartzman and Gensler.

☆☆ This paper is part of a special issue entitled "Positioning Techniques and Applications" guest edited by Prof. Sunwoo Kim, Prof. Dong-Soo Han, Prof. Chansu Yu, Dr. Francesco Potorti, Prof. Seung-Hyun Kong and Prof. Shiho Kim.

http://dx.doi.org/10.1016/j.icte.2016.02.010
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e.g. [4]), but we limit our demonstration to a single transmitter, thus ignoring difficulties caused by mutual interference of the transmitted signals.

The focus of this paper is the demonstration of the single-step (direct) MVDR concept for source localization. As an example, we use a simplified multi-static radar model, neglecting radar clutter for brevity. Future work includes the full blown radar model. Note that MVDR is applied to the target's location estimation in a single step, and not for intermediate parameters estimation. Some previous publications touch upon our proposed approach but in no way cover the full potential of this method (see for example [5–7]). Other papers use MVDR for Angle of Arrival Estimation but titles that refer to localization [8]. We show that the estimation method proposed here can significantly improve target resolution compared with the single-source MLE. Fine target resolution can prove very useful for target localization within many dense decoys.

2. Problem formulation

Consider a transmitter and L widely separated receiving arrays. Each receiving array consists of M_r elements. The array aperture is typically a few signal wavelengths. The transmitted signal $s(t)$ is confined to the time interval $t \in [0, T]$. It is assumed that the signal $s(t)$ is perfectly known, which is usually the case when there is line of sight from the transmitter to the receiving array. In the following analysis the signal impinges on a single target whose coordinates vector is denoted by $\mathbf{p}_t$, and is reflected by the target towards the receiving arrays. We assume that the transmitter, arrays and target are all confined to a plane, and the transmitter and receiving arrays locations are known while the target location needs to be estimated.

The ℓ-th array output is given by the $M_r \times 1$ vector,

$$\mathbf{r}_\ell(t) = \mathbf{a}_\ell(\mathbf{p}_t)\alpha_\ell s(t - \tau_\ell(\mathbf{p}_t))e^{i2\pi f_{D,\ell}t} + \mathbf{n}_\ell(t) \tag{1}$$

where α_ℓ is the signal attenuation at the ℓ-th array, τ_ℓ is the signal delay associated with the propagation from the transmitter to the target and then to the ℓ-th array, which satisfies,

$$\tau_\ell(\mathbf{p}_t) = \frac{\|\mathbf{p}_t - \mathbf{p}_\ell\|}{c} + \frac{\|\mathbf{p}_t - \mathbf{p}_{\mathrm{Tx}}\|}{c} \tag{2}$$

where $\mathbf{p}_{\mathrm{Tx}}$ is the transmitter's location, $\mathbf{p}_\ell$ is the ℓ-th array location, and c is the speed of propagation. Further, $\mathbf{n}_\ell(t)$ is a $M_r \times 1$ wide-sense stationary, white, zero mean, complex Gaussian noise, $\mathbf{a}_\ell(\mathbf{p}_t)$ is a $M_r \times 1$ vector representing the ℓ-th array response to a target at $\mathbf{p}_t$, and $f_{D,\ell}$ is the Doppler frequency shift. We note that without loss of generality we can impose the constraint $\|\mathbf{a}_\ell(\mathbf{p}_t)\|^2 = 1$. Since the transmitter and arrays cooperate the signal transmission time is perfectly known. This can be accomplished by direct interception of the transmitted signal or by synchronization of the transmitter and receiving arrays. Finally, we assume the target is illuminated by M_p consecutive pulses. To simplify the exhibition, it is assumed that the target speed is small enough to neglect the Doppler effect. Note that this formulation can be modified to describe somewhat different localization problem. For example, in source localization, such as smart phones localization, assuming the transmitted signal is known, the only change is in the dependence of τ_ℓ on the target position. A similar derivation was performed in [9]. Further, if the signal is not known, it could be incorporated into the estimation problem, but this is beyond the scope of this work.

The DFT of the received jth pulse is given by

$$\bar{\mathbf{r}}_{\ell,k}(j) = \mathbf{a}_\ell(\mathbf{p}_t)\,\alpha_\ell(j)\,\bar{s}_k e^{-i2\pi f_k \tau_\ell(\mathbf{p}_t)} + \bar{\mathbf{n}}_{\ell,k}(j) \tag{3}$$

where $f_k = \frac{k}{K} f_s$ is the frequency associated with the kth coefficient, K is the number of samples, f_s is the sampling frequency, and $\bar{\mathbf{r}}_{\ell,k}$, $\bar{s}_k$ and $\bar{\mathbf{n}}_{\ell,k}$ are the kth Fourier coefficients of $\mathbf{r}_\ell(t)$, $s(t)$ and $\mathbf{n}_\ell(t)$, respectively, and where it is assumed that the observation time is longer than the received signal interval plus its delays at all sensors.

Define

$$\begin{aligned}
\bar{\mathbf{r}}_\ell(j) &\triangleq [\bar{\mathbf{r}}_{\ell,1}^T(j), \bar{\mathbf{r}}_{\ell,2}^T(j), \ldots, \bar{\mathbf{r}}_{\ell,K}^T(j)]^T \\
\bar{\mathbf{n}}_\ell(j) &\triangleq [\bar{\mathbf{n}}_{\ell,1}^T(j), \bar{\mathbf{n}}_{\ell,2}^T(j), \ldots, \bar{\mathbf{n}}_{\ell,K}^T(j)]^T \\
\mathbf{A}_\ell(\mathbf{p}_t) &\triangleq \mathrm{diag}(e^{-j2\pi f_1 \tau_\ell}, \ldots, e^{-j2\pi f_K \tau_\ell}) \otimes \mathbf{a}_\ell(\mathbf{p}_t) \\
\bar{\mathbf{s}} &\triangleq [\bar{s}_1, \ldots, \bar{s}_K]^T
\end{aligned} \tag{4}$$

where the dependence of τ_ℓ on $\mathbf{p}_t$ is suppressed and where $\otimes$ denotes the Kronecker product. We can now write (3) in a vector form

$$\bar{\mathbf{r}}_\ell(j) = \alpha_\ell(j)\,\mathbf{A}_\ell(\mathbf{p}_t)\,\bar{\mathbf{s}} + \bar{\mathbf{n}}_\ell(j)\,. \tag{5}$$

In the next section we derive the (single-source) Maximum Likelihood estimator for $\mathbf{p}_t$, where $\{\alpha_\ell(j)\}$ are treated as unknown parameters. As explained in the introduction, it is possible to derive an exact Maximum Likelihood estimator. However, such an estimator needs to know a-priori the number of targets, and it requires a multi-dimensional search. In Section 2.2 we use the single-source Maximum Likelihood estimator to obtain the multi-source MVDR estimator, which is our main goal.

2.1. Target localization using the maximum likelihood estimator

Using (5) and the fact that $\{\bar{\mathbf{n}}_\ell(j)\}$ are statistically independent complex Gaussian vectors, the Maximum Likelihood cost function is

$$Q(\mathbf{p}_t) = \sum_{\ell=1}^{L}\sum_{j=1}^{M_p} \|\bar{\mathbf{r}}_\ell(j) - \alpha_\ell(j)\,\mathbf{A}_\ell(\mathbf{p}_t)\,\bar{\mathbf{s}}\|^2\,. \tag{6}$$

The signal attenuation $\{\alpha_\ell(j)\}$ is assumed to be independent from pulse to pulse, as is suggested by the well known Swerling II and IV target models, which assume the target radar-cross-section (RCS) is independent from pulse to pulse (see [10]). The attenuation coefficient that minimizes the cost function (6) is given by

$$\begin{aligned}
\hat{\alpha}_\ell(j) &= \left(\bar{\mathbf{s}}^H \mathbf{A}_\ell^H(\mathbf{p}_t)\,\mathbf{A}_\ell(\mathbf{p}_t)\,\bar{\mathbf{s}}\right)^{-1} \bar{\mathbf{s}}^H \mathbf{A}_\ell^H(\mathbf{p}_t)\,\bar{\mathbf{r}}_\ell(j) \\
&= (\bar{\mathbf{s}}^H \bar{\mathbf{s}})^{-1} \bar{\mathbf{s}}^H \mathbf{A}_\ell^H(\mathbf{p}_t)\,\bar{\mathbf{r}}_\ell(j)
\end{aligned} \tag{7}$$

where we used

$$\mathbf{A}_\ell^H(\mathbf{p}_t)\,\mathbf{A}_\ell(\mathbf{p}_t) = \mathbf{I}_{M_r K}\|\mathbf{a}_\ell\|^2 = \mathbf{I}_{M_r K}\,. \tag{8}$$

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