Signal Processing 93 (2013) 2103–2107

Contents lists available at SciVerse ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

Fast communication

Target localization using MIMO electromagnetic vector array systems

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ARTICLE INFO

Article history:
Received 25 September 2012
Received in revised form
25 January 2013
Accepted 4 February 2013
Available online 13 February 2013

Keywords:
MIMO array
Target localization
Electromagnetic vector antenna
Polarization diversity
ESPRIT

ABSTRACT

Recently developed MIMO array systems, which use spatially separated but colocated scalar-antennas in both transmit and receive modes, can fully exploit waveform diversity and spatial diversity to offer significant performance improvement over traditional phased-array based systems. Unlike these structure, in this paper, we present a MIMO array system that is composed of electromagnetic vector antennas (EMVA). Parameterizing the target locations by azimuth-elevation arrival angles and adopting the ESPRIT algorithm, the presented MIMO array system provides closed-form automatically paired azimuth-elevation angle estimation, resolves up to six targets with distinct locations, requires no restrictions on transmit antennas placement, and offers a performance better than the MIMO array system with spatially separated scalar-antennas of comparable receive data size. All these advantages are achieved by additional polarization diversity offered by the EMVA.

1. Introduction

In recent years, activities with respect to investigation on multiple-input–multiple-output (MIMO) array systems have increased, especially focusing on radar target detection and localization (e.g., [1–7]). A MIMO array system transmits, via its transmit antennas, multiple correlated or uncorrelated probing signals and via its receive antennas, receives targets' reflected signals. Thus, a MIMO array system with spatially separated but colocated antennas can fully exploit waveform diversity as well as spatial diversity to offer significant performance improvement over traditional phased-array systems [1].

Most existing target localization techniques with MIMO array systems [2–6] use scalar-antennas in both transmit and receive modes, and as a result, can only measure the scalar quantities of the reflected signals. However, target reflections of active sensing systems, such as radar and sonar, are in fact contain vector components. For example, the reflections of radar targets are electromagnetic (EM) signals that consist of electric and magnetic components [8], whereas the reflections of sonar targets are acoustic signals that consist of pressure and velocity components [9]. Measurements from the scalar-antennas cannot embody the entire vector information.

Recently, underwater acoustic target localization using MIMO velocity vector array has been addressed in [7]. Motivated by [7], in this paper, we investigate target localization using MIMO EMVA systems. Indeed, EMVA array and waveform polarization diversities are widely used in wireless communications and signal processing [10–18]. Target and array polarization properties are used to improve the capacity of communication systems [12] and performance of parameter estimation [13–18]. Furthermore, given the wealth knowledge on MIMO arrays and EMVA arrays, it would be of significance to

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http://dx.doi.org/10.1016/j.sigpro.2013.02.005

develop new target localization methods, where the waveform and polarization diversities are concurrently utilized. We introduce a MIMO array system with full-component EMVAs, each of which consists of three orthogonal electric dipoles and another three orthogonal magnetic loops, co-located in space. The transmit antennas emit orthogonal signals, and the receive antenna receives all three electric signals and three magnetic signals at a point. Unlike the existing MIMO array systems, the presented MIMO array system can exploit the polarization diversity in addition to the spatial diversity and waveform diversity to improve target localization performance. Parameterizing the target locations by azimuth-elevation arrival angles and adopting ESPRIT algorithm [19], the presented MIMO array system can provide closed-form automatically paired azimuth-elevation angle estimation, resolve up to six targets with distinct locations, and require no restrictions on transmit antennas placement. Simulation results show that the presented MIMO array system outperforms the MIMO array system with spatially separated scalar-antennas of comparable receive data size and computational load.

The paper is organized as follows. Section 2 formulates the problem of interest. Section 3 develops the target localization algorithm. Section 4 presents the remarks on the proposed algorithm. Section 5 provides the simulation results demonstrating the efficacy of the proposed methods. Section 6 concludes the paper.

Throughout the paper, scalar quantities are denoted by lowercase letters. Lowercase bold letters are used for vectors, while uppercase bold letters for matrices. Superscripts T, H, $\dagger$ and $*$ represent the transpose, conjugate transpose, pseudo inverse and complex conjugate, respectively.

2. Problem formulation

2.1. Transmit signal

The introduced MIMO array system has M EM vector transmit antennas. We consider EMVA consisting of three orthogonal electric dipoles and three orthogonal magnetic loops. Each EMVA produces the following 6×2 response [8]:

$$\mathbf{Q}(\theta,\phi)=\begin{bmatrix}\cos\theta\cos\phi & -\sin\phi\\ \cos\theta\sin\phi & \cos\phi\\ -\sin\theta & 0\\ -\sin\phi & -\cos\theta\cos\phi\\ \cos\phi & -\cos\theta\sin\phi\\ 0 & \sin\theta\end{bmatrix} \tag{1}$$

where $0\le\theta<\pi$ denotes the elevation angle and $0\le\phi<2\pi$ represents the azimuth angle. The 2×1 baseband normalized electrical field signal emitted from the mth antenna can be expressed as

$$\mathbf{E}_m(t)=\underbrace{\mathbf{Q}^T(\theta,\phi)\mathbf{w}_m}_{[\xi_H,\xi_V]^T}s_m(t) \tag{2}$$

where $\mathbf{w}_m$ is a 6×1 weights controlling the transmit waveform polarization [20] and $s_m(t)$ is the waveform of the mth transmit signal. ξ_H and ξ_V, respectively, represent the H- and V-components of the waveform, which also determines the waveform polarization. Specially, every nonzero $\boldsymbol{\xi}=[\xi_H,\xi_V]^T$ has the following unique representation [8]:

$$\boldsymbol{\xi}=\|\boldsymbol{\xi}\|e^{j\psi}\begin{bmatrix}\cos\alpha & -\sin\alpha\\ \sin\alpha & \cos\alpha\end{bmatrix}\begin{bmatrix}\cos\beta\\ j\sin\beta\end{bmatrix} \tag{3}$$

where $\psi\in(-\pi,\pi]$, $\alpha\in(-\pi/2,\pi/2]$ is the orientation angle, and $\beta\in[-\pi/4,\pi/4]$ is the ellipticity angle. Moreover, ψ, α, β are uniquely determined if and only if $\xi_H^2+\xi_V^2\neq 0$.

Let us assume that the mth EMVA has the location $\mathbf{p}_m=[x_m,y_m,z_m]^T$, and the vector $\mathbf{r}=[u,v,w]^T=[\sin\theta\cos\phi,\sin\theta\sin\phi,\cos\theta]^T$ to be a unit vector pointing towards the spatial direction (θ,ϕ). Further assume that the M transmit signal have the same polarization. Then, the transmit signal of the EMVA array can be expressed as

$$\mathbf{b}(t)=\boldsymbol{\xi}\sum_{m=1}^{M}s_m(t)e^{j2\pi/\lambda\mathbf{p}_m^T\mathbf{r}}=\boldsymbol{\xi}\mathbf{a}^T\mathbf{s}(t) \tag{4}$$

where $\mathbf{a}=[e^{j2\pi/\lambda\mathbf{p}_1^T\mathbf{r}},\ldots,e^{j2\pi/\lambda\mathbf{p}_M^T\mathbf{r}}]$ denotes the transmit array spatial response, and $\mathbf{s}(t)=[s_1(t),\ldots,s_M(t)]^T$ represents the transmit waveform vector.

2.2. Receive signal

We assume that a single receive EMVA is deployed and K targets are located in far-field. The kth target is parameterized by (θ_k,ϕ_k). Then, the pth pulse data collected by the receive EMVA can be modeled as the following 6×1 vector:

$$\mathbf{x}(p,t)=\sum_{k=1}^{K}\gamma_k(p)\underbrace{\mathbf{Q}(\theta_k,\phi_k)\overbrace{\mathbf{S}_k\boldsymbol{\xi}}^{\boldsymbol{\eta}_k}}_{\mathbf{c}_k}\mathbf{a}^T(\theta_k,\phi_k)\mathbf{s}(t)+\mathbf{n}(p,t) \tag{5}$$

where $\gamma_k(p)$ is the complex reflection coefficient of the kth target at the pth pulse, $\mathbf{S}_k$ represents the 2×2 scattering matrix, which describe completely the polarization transforming property of the kth target [21], $\boldsymbol{\eta}_k$ is the receive polarization vector of the kth target, $\mathbf{c}_k$ is the 6×1 EMVA response of the kth target, and $\mathbf{n}(p,t)$ is the 6×1 noise vector. Note that the reflection coefficient $\gamma_k(p)$ for each target is assumed to be constant during the whole pulse, but varies independently from pulse to pulse, i.e., it obeys the Swerling II target model [22]. Note also that the EMVA response $\mathbf{c}_k$ can be expressed as $\mathbf{c}_k=[\mathbf{e}_k^T,\mathbf{h}_k^T]^T$, where the two 3×1 vectors $\mathbf{e}_k$ and $\mathbf{h}_k$, respectively, denote the electric field vector and the magnetic field vector.

With a total of $P\ge K$ pulses, the objective here is to determine the angles $\{\theta_k,\phi_k,k=1,\ldots,K\}$ of the targets from the data $\{\mathbf{x}(1,t),\ldots,\mathbf{x}(P,t)\}$.

3. Target localization

The presented MIMO array system transmits, via its transmit antennas, M unit-power orthogonal coding emitting signals, which satisfy the orthogonality condition:

$$\int_{T_0}\mathbf{s}(t)\mathbf{s}^H(t)\,dt=\mathbf{I}_M \tag{6}$$