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Adaptive Beamforming for Vector-Sensor Arrays Based on Reweighted Zero-Attracting Quaternion-Valued LMS Algorithm

Mengdi Jiang, Wei Liu and Yi Li

Abstract—In this work, reference signal based adaptive beamforming for vector sensor arrays consisting of crossed dipoles is studied. In particular, we focus on how to reduce the number of sensors involved in the adaptation so that reduced system complexity and energy consumption can be achieved while an acceptable performance can still be maintained, which is especially useful for large array systems. As a solution, a reweighted zero attracting quaternion-valued least mean square algorithm is proposed. Simulation results show that the algorithm can work effectively for beamforming while enforcing a sparse solution for the weight vector where the corresponding sensors with zero-valued coefficients can be removed from the system.

Index Terms—vector sensor array, quaternion, adaptive beamforming, LMS, zero attracting.

I. INTRODUCTION

Adaptive beamforming has a range of applications and has been studied extensively in the past for traditional array systems [1], [2], [3], [4]. With the introduction of vector sensor arrays, such as those consisting of crossed-dipoles and tripoles [5], [6], [7], adaptive beamforming for such an array system has attracted more and more attention recently [6], [8], [9], [10].

In this work, we consider the crossed-dipole array and study the problem of how to reduce the number of sensors involved in the beamforming process so that reduced system complexity and energy consumption can be achieved while an acceptable performance can still be maintained, which is especially useful for large array systems. In particular, we will use the quaternion-valued steering vector model for crossed-dipole arrays [8], [9], [10], [11], [12], [13], [14], [15], [16], and propose a novel quaternion-valued adaptive algorithm for reference signal based beamforming.

In the past, several quaternion-valued adaptive filtering algorithms have been derived in [9], [16], [17], [18]. Notwithstanding the advantages of the quaternionic algorithms, extra cares have to be taken in their developments, in particular when the derivatives of quaternion-valued functions are involved, since quaternion algebra is non-commutative. Very recently, properties and applications of a restricted HR gradient operator for quaternion-valued signal processing were provided in [19]. Based on these recent advances in quaternion-valued signal processing, we here derive a reweighted zero attracting (RZA) quaternion-valued least mean square (QLMS) algorithm by introducing a RZA term to the cost function of the QLMS algorithm. Similar to the idea of the RZA least mean square (RZA-LMS) algorithm proposed in [20], the RZA term aims to have a closer approximation to the $l_0$ norm so that the number of non-zero valued coefficients can be reduced more effectively in the adaptive beamforming process. This algorithm can be considered as an extension of our recently proposed zero-attracting QLMS (ZA-QLMS) algorithm [21], where the $l_1$ norm penalty term was used in the update equation of the weight vector. We will show in our simulations that the RZA-LMS algorithm has a much better performance in terms of both steady state error and the number of sensors employed after convergence.

A review of adaptive beamforming based on vector sensor arrays is provided in Sec. II, and the proposed RZA-QLMS algorithm is derived in Sec. III. Simulations are presented in Sec. IV, and conclusions drawn in Sec. V.

II. ADAPTIVE BEAMFORMING BASED ON VECTOR SENSOR ARRAYS

A. Quaternionic Array Signal Model

A general structure for a uniform linear array (ULA) with $M$ crossed-dipole pairs is shown in Fig. 1, where these pairs are located along the y-axis with an adjacent distance $d$, and at each location the two crossed components are parallel to the x-axis and y-axis, respectively. For a far-field incident signal

1Here $H$ (Hamilton) denotes the quaternion domain and $R$ the real domain.
with a direction of arrival (DOA) defined by the angles $\theta$ and $\phi$, its spatial steering vector is given by

$$S_r(\theta, \phi) = \begin{bmatrix} 1, e^{-j2\pi d \sin \theta \sin \phi / \lambda}, \\
\ldots, e^{-j2\pi (M-1)d \sin \theta \sin \phi / \lambda} \end{bmatrix}T$$

(1)

where $\lambda$ is the wavelength of the incident signal and $\{\cdot\}^T$ denotes the transpose operation. For a crossed dipole the parallel to the x-axis and one to the y-axis. The complex number/vector, respectively. Given a set of coefficients, the response of the array is given by

$$r(\theta, \phi, \gamma, \eta) = w^H S_q(\theta, \phi, \gamma, \eta)$$

(10)

where $w$ is the quaternion-valued weight vector.

$$S_p(\theta, \phi, \gamma, \eta) = \begin{bmatrix} -\cos \gamma, \cos \theta \sin \gamma e^{j\eta} \\
\cos \gamma, -\cos \theta \sin \gamma e^{j\eta} \end{bmatrix}$$

(2)

where $\gamma$ is the auxiliary polarization angle with $\gamma \in [0, \pi/2]$, and $\eta \in [-\pi, \pi]$ is the polarization phase difference.

The array structure can be divided into two sub-arrays: one parallel to the x-axis and one to the y-axis. The complex-valued steering vector of the x-axis sub-array is given by

$$S_x(\theta, \phi, \gamma, \eta) = \begin{bmatrix} -\cos \gamma S_q(\theta, \phi) \phi = \frac{\pi}{2} \\
\cos \gamma S_q(\theta, \phi) \phi = \frac{\pi}{2} \end{bmatrix}$$

(3)

and for the y-axis it is expressed as

$$S_y(\theta, \phi, \gamma, \eta) = \begin{bmatrix} \cos \theta \sin \gamma e^{j\eta} S_q(\theta, \phi) \phi = \frac{\pi}{2} \\
-\cos \theta \sin \gamma e^{j\eta} S_q(\theta, \phi) \phi = \frac{\pi}{2} \end{bmatrix}$$

(4)

Before we present the quaternion-valued steering vector model, we first very briefly review some basics about quaternion. A quaternion $q$ can be described as

$$q = q_1 + (q_2 i + q_3 j + q_4 k),$$

(5)

where $q_1, q_2, q_3,$ and $q_4$ are real-valued [24], [25]. In this paper, we consider the conjugate operator of $q$ as $q^* = q_1 - q_2 i - q_3 j - q_4 k$. The three imaginary units $i, j,$ and $k$ satisfy

$$ij = k, \quad jk = i, \quad ki = j, \quad \text{and} \quad ijk = k^2 = -1;$$

(6)

where the exchange of any two elements in their order gives a different result. For example, we have $ji = -ij$ rather than $ji = ij$. For a general quaternion-valued function $f(q)$, the derivative $\frac{df(q)}{dq}$ with respect to $q$ can be expressed as [19], [21], [26]

$$\frac{df(q)}{dq} = \frac{1}{4} \left[ \frac{\partial f(q)}{\partial q_1} - \frac{\partial f(q)}{\partial q_2} i - \frac{\partial f(q)}{\partial q_3} j - \frac{\partial f(q)}{\partial q_4} k \right],$$

(7)

while the derivative of $f(q)$ with respect to $q^*$ is given by

$$\frac{df(q)}{dq^*} = \frac{1}{4} \left[ \frac{\partial f(q)}{\partial q_1} + \frac{\partial f(q)}{\partial q_2} i + \frac{\partial f(q)}{\partial q_3} j + \frac{\partial f(q)}{\partial q_4} k \right].$$

(8)

Combining the two complex-valued subarray steering vectors together, an overall quaternion-valued steering vector with one real part and three imaginary parts can be constructed as

$$S_q(\theta, \phi, \gamma, \eta) = \Re\{S_x(\theta, \phi, \gamma, \eta)\} + j\Im\{S_y(\theta, \phi, \gamma, \eta)\} + \gamma S_q(\theta, \phi, \gamma, \eta) + k\Im\{S_y(\theta, \phi, \gamma, \eta)\},$$

(9)

where $\Re\{\cdot\}$ and $\Im\{\cdot\}$ are the real and imaginary parts of a complex number/vector, respectively. Given a set of coefficients, the response of the array is given by

$$\nabla_w J_0[n] = -\frac{1}{2} e[n] x^*[n],$$

(16)

and the update equation for the weight vector with step size $\mu$ is given by

$$w[n+1] = w[n] - \mu \nabla_w J_0[n],$$

(17)
leading to the following QLMS algorithm [16, 17, 26]

\[ w[n + 1] = w[n] + \frac{1}{2}\mu (e[n]x^*[n]). \]  

(18)

III. THE RZA-QLMS ALGORITHM

Using the QLMS algorithm, we can find the optimal coefficient vector in terms of minimum mean square error (MSE) and obtain a satisfactory beamforming result. However, to reduce the complexity and also power consumption of the system, in particular for a large array, we can reduce the number of sensors involved, at the cost of the final beamforming performance. To achieve this, we here derive a novel quaternion-valued adaptive algorithm by introducing an RZA term to the original cost function of the QLMS algorithm. In this way, we can simultaneously minimise the number of sensors involved while suppressing the interferences during the beamforming process.

First, to minimise the number of sensors, we could add the \( l_0 \) norm of the weight vector \( w \) to the cost function \( J_0[n] \) to form a new cost function

\[ \hat{J}_0[n] = (1 - \delta_1)e[n]\|e[n]\| + \delta_1 \|w[n]\|_0, \]  

(19)

where \( \delta_1 \) is a weighting term between the original cost function and the newly introduced term. In this way, the number of non-zero valued coefficients in \( w \) will be minimised too, where the similar idea has been applied in [28].

In practice, we could replace the \( l_0 \) norm by the \( l_1 \) norm. However, \( l_1 \) norm would uniformly penalise all non-zero valued coefficients, while \( l_0 \) norm penalises smaller non-zero values more heavily. To have a closer approximation to \( l_0 \) norm, we can introduce a larger weighting term to those coefficients with smaller values and a smaller weighting term to those with larger values. This weighting term will change according to the resultant coefficients at each update of the algorithm. This general idea has been implemented as a reweighted \( l_1 \) minimization [29], [30] and employed in the sparse array design problem [31], [32], [33].

The modified cost function for the proposed RZA-QLMS algorithm with the reweighting term is given by

\[ J_1[n] = (1 - \delta_1)e[n]\|e[n]\| + \delta_1 \sum_{m=1}^{M} (\varepsilon_m|w_m[n]|), \]  

(20)

where \( \varepsilon_m \) is the reweighting term for \( w_m \). Then using the chain rule in [19], we can obtain the gradient of \( J_1[n] \) with respect to \( w^*_m \). In particular, the differentiation of the second part of \( J_1[n] \) with regards to \( w^*_m \) is given by

\[
\frac{\partial}{\partial w^*_m} \left( \varepsilon_m|w_m[n]| \right) = \frac{1}{4} \varepsilon_m \left( \frac{a_m}{|w_m[n]|} + \frac{b_m}{|w_m[n]|} i + \frac{c_m}{|w_m[n]|} j + \frac{d_m}{|w_m[n]|} k \right) \\
= \frac{1}{4} \varepsilon_m \frac{w_m[n]}{|w_m[n]|} = \frac{1}{4} \varepsilon_m \left( \text{sign}(w_m[n]) \right) .
\]

(21)

where \( \text{sign}(\cdot) \) is a component-wise sign function

\[ \text{sign}(w_m[n]) = \begin{cases} 
\frac{w_m[n]}{|w_m[n]|} & w_m[n] \neq 0 \\
0 & w_m[n] = 0 
\end{cases} \]

The overall gradient result is given by

\[ \nabla w_m J_1[n] = -\frac{1}{2} (1 - \delta_1)e[n]x^*_m[n] + \frac{1}{4} \delta_1 \varepsilon_m \text{sign}(w_m[n]). \]  

(22)

We choose the reweighting term \( \varepsilon_m \) as

\[ \varepsilon_m = 1/(\sigma + |w_m[n]|), \]  

(23)

with \( \sigma \) being roughly the threshold value below which the corresponding sensor will not be included in the update. Then, with the step size \( \mu_1 \), we finally obtain the following update equation for the RZA-QLMS algorithm in vector form

\[ w[n + 1] = w[n] + \frac{1}{2} (\mu_1 - 4\rho_1) (e[n]x^*[n]) - \rho_1 \left( \text{sign}(w[n]),/(\sigma + |w[n]|) \right), \]  

(24)

where \( \rho_1 = \frac{1}{4} \mu_1 \delta_1, \ |w_m[n]| \) is a vector formed by taking the absolute value of the coefficients in \( w[n] \), \( \cdot \) is a component-wise division between two vectors, and \( \text{sign}(w[n]) \) is defined as

\[ \text{sign}(w[n]) = \begin{cases} 
\frac{w[n] \cdot |w[n]|}{|w[n]|} & w[n] \neq 0 \\
0 & w[n] = 0 
\end{cases} \]

When \( \sigma + |w_m[n]| \) is removed from the above equation, it will be reduced to the ZA-QLMS algorithm in [21], with its cost function given by

\[ J_2[n] = (1 - \delta_2)e[n]\|e[n]\| + \delta_2 \|w[n]\|_1, \]  

(25)

where \( \delta_2 \) is a trade-off factor. The update equation for the ZA-QLMS algorithm is

\[ w[n + 1] = w[n] + \frac{1}{2} (\mu_2 - 4\rho_2) (e[n]x^*[n]) - \rho_2 \cdot \text{sign}(w[n]), \]  

(26)

where \( \rho_2 = \frac{1}{4} \mu_2 \delta_2, \) and \( \mu_2 \) is the step size.

We now discuss the computational complexity of the algorithms. The results are shown in Tab. I, where \( M \) is the number of vector sensors of the array. Obviously, the RZA-QLMS algorithm has the highest complexity. However, as we will see in simulations, this additional cost is paid back by a resultant much smaller number of sensors, and especially at a later stage of the adaptation, when the number of sensors involved becomes smaller, the overall complexity of the RZA-QLMS algorithm could be lower than the other two algorithms.

<table>
<thead>
<tr>
<th>Complexity</th>
<th>RZA-QLMS</th>
<th>ZA-QLMS</th>
<th>QLMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-valued addition</td>
<td>28M+</td>
<td>35M+</td>
<td>52M+</td>
</tr>
<tr>
<td>Real-valued multiplication</td>
<td>32M+</td>
<td>44M+</td>
<td>52M+</td>
</tr>
</tbody>
</table>

(INCLUDING SQUARE ROOT OPERATION)

TABLE I

COMPARIson of computational complexity.
where $\Delta M$ is the number of removed sensors, and $\Delta \mathbf{w}$ is the change of $\mathbf{w}$ after some of its sensors are removed (the corresponding coefficients on the positions of removed sensors have a magnitude smaller than $\sigma$ and are then set to zero). As a result, the maximum possible change in array response, due to removal of some sensors, is given by $\sigma \cdot \Delta M \cdot \sqrt{M}$.

IV. SIMULATION RESULTS

Simulations are performed based on an array with 16 crossed-dipoles and half-wavelength spacing for the three algorithms: QLMS, ZA-QLMS and RZA-QLMS. The stepsizes $\mu$, $\mu_1$ and $\mu_2$ are set to be $2 \times 10^{-4}$, $4 \times 10^{-4}$ and $2 \times 10^{-3}$, respectively, which are chosen empirically to make sure these algorithms have a similar convergence speed. A desired signal with 20 dB signal to noise ratio (SNR) impinges from the broadside of the array ($\theta = 0^\circ$) and two interfering signals with a signal to interference ratio (SIR) of -10 dB arrive from the directions $(20^\circ, 90^\circ)$, and $(30^\circ, -90^\circ)$, respectively. All the signals have the same polarisation of $(\gamma, \eta) = (30^\circ, 0)$. For the RZA-QLMS and ZA-QLMS algorithms, the coefficients of the zero attractor $\rho_1$ and $\rho_2$ are set to be $7 \times 10^{-7}$ and $2.8 \times 10^{-5}$, respectively and $\sigma = 0.001$. Their learning curves obtained by averaging results from 200 simulation runs are shown in Fig. 3 and the resultant beam patterns are shown in Fig. 4, where for convenience positive values of $\theta$ indicate the value range $\theta \in [0^\circ, 90^\circ]$ for $\phi = 90^\circ$, while negative values of $\theta \in [-90^\circ, 0^\circ]$ indicate an equivalent range of $\theta \in [0^\circ, 90^\circ]$ with $\phi = -90^\circ$.

First, the two nulls at the directions of the interfering signals can be observed in all three beam patterns, clearly indicating a satisfactory beamforming result for all algorithms. However, from Fig. 3, we see that although these three algorithms have a similar convergence speed, the original QLMS algorithm has the smallest steady state error, which is not surprising since it has the most degrees of freedom among them. On the other hand, the proposed RZA-QLMS algorithm has achieved a lower steady state error than the ZA-QLMS algorithm. In terms of output signal to interference plus noise ratio (SINR), it is 23.48 dB for the QLMS algorithm, 18.32 dB for the RZA-QLMS algorithm, and 7.36 dB for the ZA-QLMS algorithm.

The amplitudes of steady state weight coefficients for the three algorithms are shown in Fig. 5, where for the QLMS algorithm, the amplitudes of the coefficients are spread over the sixteen sensors with some small variations, while for the ZA-QLMS algorithm, some degree of sparsity has also been achieved with four of the coefficients are close to zero. However, with 0.001 as the threshold value, they can not be discarded. For the RZA-QLMS algorithm, the variation is significantly larger and seven of them are almost zero-valued, which means the corresponding sensors can be removed and only 9 sensors are needed to give a satisfactory beamforming result, rather than 16 sensors. Moreover, the difference response between the original array and the one with 7 sensors removed is extremely small, and no difference can really be observed by a naked eye, as shown in Fig. 6. Based on the steady-state sensor number, the computational complexity of the three algorithms is listed in Tab. II, where we can see that the RZA-QLMS algorithm has the lowest complexity.

TABLE II

<table>
<thead>
<tr>
<th>Comparison of Computational Complexity in Simulations</th>
<th>QLMS</th>
<th>ZA-QLMS</th>
<th>RZA-QLMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-valued addition</td>
<td>452</td>
<td>564</td>
<td>346</td>
</tr>
<tr>
<td>(Including square root operation)</td>
<td>516</td>
<td>708</td>
<td>472</td>
</tr>
</tbody>
</table>

Fig. 3. Learning curves of the three algorithms.

Fig. 4. Beam patterns of the three algorithms.

Fig. 5. Amplitudes of the steady state weight coefficients.
valued coefficients can be removed from the system. The corresponding crossed-dipole sensors with almost zero-
while enforcing a sparse solution for the weight vector where
the proposed algorithm can work effectively for beamforming
for large array systems. Simulation results have shown that
the proposed algorithm can work effectively for beamforming
while enforcing a sparse solution for the weight vector where
the corresponding crossed-dipole sensors with almost zero-
valued coefficients can be removed from the system.

V. CONCLUSION
An RZA-QLMS algorithm has been proposed for adaptive
beamforming based on vector sensor arrays consisting of
crossed dipoles. It can reduce the number of sensors involved in
the beamforming process so that reduced system complexity
and energy consumption can be achieved while an acceptable
performance can still be maintained, which is especially useful
for large array systems. Simulation results have shown that
the proposed algorithm can work effectively for beamforming
while enforcing a sparse solution for the weight vector where
the corresponding crossed-dipole sensors with almost zero-
valued coefficients can be removed from the system.

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