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Multiple Direct Data Domain Genetic Algorithm Beamforming Approach to Space Time Adaptive Processing Using Real Array Elements

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Abstract: This study presents a new multiple direct data domain genetic algorithm beamforming approach to space time adaptive processing using real array elements. Using this new genetic-algorithm-based approach, multiple signals of interest could be handled at the same time. The proposed approach performance will be tested using uniformly spaced real antenna array elements. Hence, received signals by array elements are affected by mutual coupling. The method of moments is used to estimate these mutual coupling effects. Then, the transformation matrix method is used to compensate for these undesired effects. The matrix pencil method is used to estimate the directions of arrival of all coming signals. Finally, the genetic algorithm is used for array multiple beamforming. Numerical examples are used to demonstrate the efficient capability of formed beam patterns to reconstruct more than one signal of interest.

Keywords: Adaptive antennas; mutual coupling; matrix pencil; genetic algorithms; method of moments

I. INTRODUCTION

Adaptive antenna array systems constitute a multiple discipline technology field that has spanned a number of decades in the engineering and scientific community, due to advances in electromagnetic and signal processing [1]. These techniques are considered to be the best methods to handle sever dynamic interference as it has the ability to electronically direct the pattern main lobe to the target direction while also automatically placing deep pattern nulls in the directions of interferers [2].

In direct data domain (D^3) methods, which process the data on snapshot by snapshot basis, no assumption is made about the statistics of the environments. Hence, the effect of nonstationarity in the data could be mitigated [3]. D^3 methods could be used for space time adaptive processing (STAP). In this case, two dimensional data is collected on snapshot by snapshot basis by an antenna array utilizing space and time diversity for adaptively enhancing signals in a nonhomogeneous environment. The nonhomogeneous environment may consist of nonstationary clutters and could include blinking jammers [4].

Genetic algorithms (GAs) might be more efficient than gradient-based methods for improving the nulling performance of a linear antenna array since the gradient-based methods have following disadvantages:

a. The methods are highly sensitive to starting points when the number of variables, and hence the size of the solution space, increases.
b. The methods frequently converge to local suboptimum solutions.
c. The methods require a continuous and differentiable objective function.
d. The methods require piecewise linear cost approximation (for linear programming).
e. The methods have problems with convergence and algorithm complexity (for non-linear programming).

The main advantage of the direct data domain genetic algorithm (D^3GA) beamforming approach to STAP [5] is that, in addition to the method ability to maintain the array beam pattern value at the signal of interest (SOI) direction, it could minimize the side lobes level and hence reduce the energy which will leak from the array through these side lobes. However, D^3GA algorithm can handle only one SOI at a time. So, in this study, a new technique for multiple beamforming based on D^3GA approach is developed. Using this new algorithm, multiple SOIs could be handled at the same time.

In practical cases, the real antenna array elements spatially sample and reradiate the incident fields. The reradiated fields interact with the other elements causing the sensors to be mutually coupled. Mutual coupling severely degrade the interference nulling capabilities of the D^3 algorithms and hence these effects must be evaluated and compensated [2].

The rest of the paper is organized as follows: In section II, the using of the method of moments (MoM) to evaluate the mutual coupling in an array of uniformly spaced thin half-wavelength dipoles will be presented and the transformation matrix approach to the compensation for these mutual coupling effects will be also presented. Section III represents the matrix pencil (MP) method to estimate the directions of arrival (DOAs) of all coming signals. Section IV states a brief description of the D^3GA beamforming approach to STAP. Section V presents the new multiple direct data domain genetic algorithm (MD^3GA) beamforming approach. Section VI presents the main component of the GA used in this paper. Finally, in section VII, the performance of the proposed new approach will be evaluated using two numerical examples.

II. MUTUAL COUPLING EVALUATION AND COMPENSATION

The effect of mutual coupling on the performance of adaptive arrays has been a topic of considerable interest for the last three decades. The general conclusion of the work reported in the open literature is that mutual coupling degrades the performance of adaptive arrays as it hardly affects the nulling performance of adaptive antennas [1]. In the next two subsections, the evaluation of the mutual coupling effects in an array of uniformly spaced thin half-wavelength dipoles using the MoM will be presented. Then, the compensation for these effects using the transformation matrix method will be illustrated.

A. Mutual Coupling Evaluation:

First, Consider an incident field E^{inc} impinging on a receiving linear antenna array of N parallel thin uniformly spaced dipoles. Each element of the array is identically point loaded at the center with the load impedance Z_L. The dipoles are z-directed, of length L and radius a, and are placed along the x-axis, separated by distance Δx. The array lies in the X-Z plane. Thus the integral equation that relates the incident field to the current on the wires could be written as [2], [3]

$$E_z^{inc} = -\mu_0 \int I(z') \frac{e^{-jkR}}{4\pi R} dz' + \frac{1}{\epsilon_0} \frac{\partial}{\partial z} \int \frac{\partial I(z')}{\partial z'} \frac{e^{-jkR}}{4\pi R} dz' \quad (1)$$

Equation (1) could be solved using MoM. By Considering B (chosen odd) piecewise sinusoids basis functions per element, (1) could be reduced to the matrix equation [6]:

$$V = Z\, I \rightarrow I = Y\, V \quad (2)$$

Where I is the MoM current vector, V is the MoM voltage vector. Z and Y are the MoM impedance and admittance matrices respectively. Assuming that the incident field is linearly polarized; the i^{th} entry in the MoM voltage vector V, corresponding to the q^{th} basis function on the m^{th} antenna, is given by the analytic form [3]

$$V_i = \frac{E_0 e^{ikx_m cos(\emptyset)\sin(\theta)}}{k sin(k\Delta z) sin^2(\theta)}\ 2e^{jkz_{q,m}\cos(\theta)}. [\cos(k\Delta z cos(\theta)) - \cos(k\Delta z)] \quad (3)$$

Where x_m is the x-coordinate of the axis of the m^{th} antenna, $i = (m-1)B + q$, and Δz is the distance between two successive basis functions' centers. An analytic form for the entries of the MoM impedance matrix could be found in [6]. The mutual coupling affected measured voltage at the m^{th} antenna port, V_{meas_m}, could be computed by [2]

$$V_{meas_m} = Z_L I_{(B+1/2),m} \quad (4)$$

B. Mutual Coupling Compensation:

In this subsection, the transformation matrix approach to compensate for the undesired electromagnetic effects in a non-uniformly spaced antenna array whose received elements' signals are affected by the presence of near-field scatterers and the mutual coupling between the array elements is presented. However, in this study, only mutual coupling effects will be considered.

In this technique, the non-uniformly spaced array is transformed into a uniform linear virtual array (ULVA) in the absence of mutual coupling and other undesired electromagnetic effects using a transformation matrix[3], [7]. Hence, it is required to find the optimal transformation matrix T_m between the real array manifold $A(\emptyset)$ and the array manifold corresponding to a ULVA, $A_v(\emptyset)$, such that

$$A_v(\emptyset) = T_m A(\emptyset) \quad (5)$$

In order to find the transformation matrix T_m, we start by dividing the field of view of the array into sectors. Next, we define a set of uniformly defined angles to cover each sector such that:

$$\Phi_q = [\phi_q, \phi_q + \Delta, \phi_q + 2\Delta, \dots, \phi_{q+1}] \quad (6)$$

Where Δ is the step size. Then we measure/ compute the real array manifold $A(\Phi_q)$ corresponding to the set Φ_q and compute the ULVA array manifold $A_v(\Phi_q)$ corresponding to the same set Φ_q. Now the transformation matrix T_{mq} is computed for each sector q such that $A_v(\Phi_q) = T_{mq} A(\Phi_q)$ using the least squares method. The least squares solution for the transformation matrix could be written as

$$T_{mq} = A_v(\Phi_q) A(\Phi_q)^H (A(\Phi_q) A(\Phi_q)^H)^{-1} \quad (7)$$

Where the H superscript represents the conjugate transpose of a complex matrix. The processed input voltage in which the mutual coupling effects and the effects of various near field scatterers have been eliminated, $x_c(t)$, could be written as

$$x_c(t) = T_{mq} x(t) \quad (8)$$

Where $x(t)$ is the measured mutually coupling affected voltage vector.

III. MATRIX PENCIL METHOD

The MP method is a D^3 method to estimate the DOAs of various signals impinging on an antenna array [3], [8]. For a uniformly spaced linear array composed of N+1 element, the voltage induced in the array n^{th} element, x_n, could be written as:

$$x_n = \sum_{k=1}^{P} s_k\, e^{\left(\frac{j2\pi nd \cos(\phi_k)}{\lambda}\right)} + \xi_n = \sum_{k=1}^{P} s_k\, a_k^n + \xi_n \quad (9)$$

Where ξ_n is the noise at the n^{th} array element, P is the number of incident signals, S_k is the complex amplitude of the k^{th} incident signal, λ is the wavelength, d is the distance between two adjacent elements, ϕ_k is the DOA of the k^{th} signal, and a_k are the poles to be estimated.

The poles a_k could be estimated by constructing and processing a Hankel matrix as illustrated in [3], [8]. Then, the DOAs of various signals could be obtained as follows:

$$\phi_k = \cos^{-1}[\frac{\lambda \ln(a_{es\,k})}{j2\pi d}] \quad (10)$$

Where $a_{es\,k}$ is the k^{th} estimated pole. The complex amplitudes vector of the P signals, AMP, could be obtained by:

$$AMP = (P_0{}^H P_0)^{-1}\, P_0{}^H x \quad (11)$$

Where P_0 is the matrix containing the pole of each incident signal at each antenna element and x is a vector containing the induced voltages at the array elements.

IV. D^3GA BEAMFORMING APPROACH TO STAP

In this section, the D^3GA beamforming approach to STAP will be presented [5]. A pulsed Doppler radar STAP system situated on an airborne platform which is moving at a constant velocity is considered. The system consists of a linear antenna array with uniformly spaced N elements where each element has its own independent receiver channel and it is also assumed that the system processes M coherent pulses within a coherent processing interval (CPI). Hence, there are NM complex weights to be used for beamforming. Given the DOAs for all the coming signals, a genetic algorithm (GA) will be used to find the optimal values of these weights which fulfill the algorithm objectives [10], [11]. The objectives of the GA are:

a. Minimizing the beam pattern average value in order to minimize the pattern side lobes level.

b. Maximizing the pattern value in the direction of the SOI (P_S) in order to radiate maximum possible power in this direction.

c. Placing deep nulls in directions of interferers and also the nulls' depths will be proportional to the interference incident signals' intensities.

The fitness function which is supposed to achieve the above objectives could be written as:

$$Fit = w\sum_{i=1}^{i=J}\left|\left|\frac{P_i}{P_s}\right| - N_i\right| + \left|\frac{P_{av}}{P_s}\right| \qquad (12)$$

Where J is the number of interferers (jammer) signals, P_i is the array beam pattern complex value in the direction of the i^{th} jammer, P_S is the array beam pattern complex value in the direction of the SOI, N_i is the i^{th} normalized pattern null value corresponding to the i^{th} jammer, and w is the weighting factor used to increase the amplitude of the fitness function's 1st term, subtraction term, and hence balance the GA optimization between the two terms of the fitness function. P_{av} is the pattern average value and | | denotes the absolute (magnitude) of the complex quantities.

The pattern value at any direction, $P(\theta,\emptyset)$, could be computed using the following equation:

$$P(\theta,\emptyset) = W^T A(\theta,\emptyset) \qquad (13)$$

Where W is the complex weights vector obtained by the D^{3}GA beamforming approach, T denotes the transpose of the vector, and $A(\theta,\emptyset)$is the spatial-temporal steering vector in the direction of$(\theta,\emptyset)$ which, for the case that all coming signals are in the azimuth plane (θ = 90°), could be expressed as the successive rows of the steering matrix A_{st}, where

$$A_{st} = [A_s,\ A_s e^{j2\pi\frac{f_d}{f_r}}, \ldots\ldots, A_s e^{j2\pi\frac{(M-1)f_d}{f_r}}]^T \qquad (14)$$

Where f_d is the Doppler frequency, f_r is the pulse repetition frequency (PRF), and A_s is the spatial steering vector given by

$$A_s = [1, e^{j2\pi\frac{d}{\lambda}cos\emptyset}, e^{j2\pi\frac{2d}{\lambda}cos\emptyset}, \ldots, e^{j2\pi\frac{(N-1)d}{\lambda}cos\emptyset}]^T \qquad (15)$$

Where N is the number of array elements and λ is the radar signal wavelength. The pattern average value, P_{av}, could be computed as follows:

$$P_{av} = \frac{\sum_{k=1}^{k=N_p}|P_k|}{N_p} \qquad (16)$$

Where N_p is the number of directions in which the pattern values are calculated and P_k is the pattern value computed at the k^{th} direction. The i^{th} normalized pattern null value corresponding to the i^{th} jammer, N_i, could be computed by

$$N_i = (|S_i| * C)^{-1} \qquad (17)$$

Where S_i is the i^{th} incident jammer intensity and C is the cancelling factor (CF) used to make the nulls depth enough to cancel the interference signals effectively. It is worth mentioning that all pattern values and complex weights will be normalized with respect to P_s. The weights could be used to reconstruct the SOI using

$$RSOI = W_n^T\, x \qquad (18)$$

Where $RSOI$ is the reconstructed SOI, W_n is the normalized weights vector, and x is the received signals' vector.

V. MULTIPLE DIRECT DATA DOMAIN GENETIC ALGORITHM BEAMFORMING APPROACH

In this section, a new multiple direct data domain genetic algorithm (MD^{3}GA) beamforming approach to STAP will be presented. This approach is based on the D^{3}GA approach [5] which is capable of maintaining the beam pattern value in the direction of SOI, placing deep nulls in directions of interferers, and minimizing the side lobes level. Hence, this approach outperforms the methods presented in [3], [4], [9], and [12] which have no means to control the side lobes levels. However, the D^{3}GA approach is capable of handling only one SOI at a time. In this study, the D^{3}GA approach will be extended to be capable of handling more than one SOI at the same time.

The MD^{3}GA beamforming algorithm objectives will be the same as in D^{3}GA approach, which are presented in the previous section, but one more objective will be added: the beam pattern values at the directions of the SOIs must have the same complex value. Suppose that there are I SOIs impinging on the array, the fitness function which is supposed to achieve the algorithm objectives will be the same as (12) with an addition of a third term. Hence, the fitness function could be written as

$$Fit = w\sum_{i=1}^{i=J}\left|\left|\frac{P_i}{P_{S1}}\right| - N_i\right| + \left|\frac{P_{av}}{P_{S1}}\right| + w\frac{\sum_{u=2}^{u=I}|P_{S1}-P_{Su}|}{|P_{S1}|} \qquad (19)$$

Where P_{s1},P_{s2},….,P_{SI} are the I SOIs impinging on the array. Note that, all beam pattern normalization are done with respect to the 1st SOI, P_{S1}.

A pulsed Doppler radar system situated on an airborne platform which is moving at a constant velocity will be considered as it is one of the most important STAP applications. Hence, given the DOAs of all the coming signals, a number of NM complex weights values which minimizes the fitness function in (19) will be found using the GA. When all SOIs have the same carrier frequency, (18) could be used to reconstruct the sum of all of them. In order to estimate each SOI individually, consider the other SOIs as interferers as it will be demonstrated in the next examples [9], [13], [14], [15].

VI. GENETIC ALGORITHM COMPONENTS

GA is a powerful optimization technique based on the concept of natural selection and natural genetics [10]. GA repeatedly modifies a population of individual solutions. At each step the GA selects individuals at random from the current population to be parents and uses them to produce the children of the next population. Over successive generations, the population "evolves" toward an optimal solution which is considered to be the solution which gives the minimum of the fitness function [10], [11]. In this paper, GAs are implemented based on the built-in genetic algorithm of R2013a MATLAB software package. The basic GA components, used in this paper, are reviewed briefly as follows [10]:

- ***a. Genetic representation of solution:*** Real number encoding is used to represent individual solutions or chromosomes.
- ***b. Population initialization:*** uniform random initialization is used and the population size is selected to be ten times the number of the antenna array elements taking into consideration that two chromosomes are used to represent each array element complex weight one for the real part and the other for the imaginary part [11].
- ***c. Evaluation of the fitness function:*** The GA should find the global minimum of the fitness function.
- ***d. Fitness scaling:*** The ranking method in which the scaling of raw scores is based on the rank of each individual instead of its score is used [11].
- ***e. Selection methods:*** Stochastic uniform selection method is used. Stochastic uniform selection method lays out a line in which each parent corresponds to a section of the line of length proportional to its scaled value. The algorithm moves along the line in steps of equal size. At each step, the algorithm allocates a parent from the section it lands on. The first step is a uniform random number less than the step size. Also, Elitism forces GA to retain some number of the best individuals at each generation [10], [11]. In this paper, the most fit two chromosomes survive directly to the next generation as elite chromosomes.
- ***f. Genetic operators:*** genetic operators are used to produce new individuals. Crossover and mutation are the most frequently used genetic operators and are described as follows: 1- The crossover operator is the exchange of genes between parent's chromosomes to produce offspring. The scattered crossover method is used. In this method, crossover is done by creating a random binary vector and selecting the genes where the vector's elements are ones from the first parent, and the genes where the vector's elements are zeros from the second parent, and combines the genes to form the child [10], [11]. The fraction of each population, other than elite children, that are made up of crossover children is set to 0.8. The remaining chromosomes are mutation children. 2- Mutation is done by the addition of a random number which is chosen from a Gaussian distribution to each entry of the parent vector.
- ***g. Termination condition:*** a maximum number of 500 generations is used to terminate GA.

VII. NUMERICAL EXAMPLES

In this section, two numerical examples illustrating the effectiveness of the proposed MD^{3}GA beamforming technique will be presented. The examples use a 10-element array of thin half-wavelength long wire dipoles. The *z*-directed dipoles each have radius $\lambda/200$ and are spaced a half-wavelength apart along the *x*-axis. Each wire is centrally loaded with a 50 Ω resistance. Seven unknowns per wire are used in the MoM analysis. The array is operating at 900 MHz and the array vision range is limited to $0° \leq \emptyset \leq 180°$ measured starting from the *x*-axis. We consider that all the coming signals are in the azimuth plane (θ= 90°) and these signals are composed of two jammers and two SOIs, also *w* and *M* are chosen to be 100 and 16 respectively. The Doppler frequency is f_d= 900 Hz, the PRF is 4000Hz, and the CF is chosen to be 1000 m/V. White Gaussian noise of 26 dB below the 1st SOI is added to the received signals.

After mutual coupling evaluation, the transformation matrix method is used to compensate for these mutual coupling effects. Then, the MP method is used to estimate the incident signals' DOAs and the amplitudes of all impinging signals will be also estimated. Finally, the proposed multiple beamforming approach is used to find the weights' optimal values and then the SOIs are reconstructed using (18).

A. *Example One: Constant Signals:*

In the first example, the incident SOIs are assumed to have complex amplitudes of SOI1=2+i and SOI2=1+i V/m arriving from the directions $\emptyset = 120°$ and $\emptyset = 45°$ respectively. The two jammers have intensities of 50dB, 30dB over SOI1 and arriving from $\emptyset = 90°$ and 100° respectively.

The normalized beam pattern in dB is shown in Fig. 1. Deep nulls are placed correctly in the directions of the jammers and their depths are proportional to the incident jammers' intensities and the normalized beam pattern values in the directions of the SOIs are maintained at 0dB. The reconstructed signal, which represents the sum of the incident SOIs, is found to be 2.9862 + 2.0196i. It is also clear that all the side lobes levels, all are below 0dB, are significantly minimized with respect to the results obtained by the multiple beamforming approaches presented in [9], [13], [14], and [15].

In order to reconstruct one SOI at a time, the other one should be considered as an interferer. Fig. 2 shows the normalized beam pattern in dB when SOI2 is considered as an interferer; one deep null is placed in its direction. Hence, this pattern could be used to reconstruct the 1st SOI, SOI1, which is found to be 1.975+1.0357i V/m. Similarly, Fig. 3 shows the normalized beam pattern in dB when SOI1 is considered as an interferer, and hence this pattern could be used to reconstruct the 2*nd* SOI, SOI2, which is found to be 1.0134+0.99408i V/m.

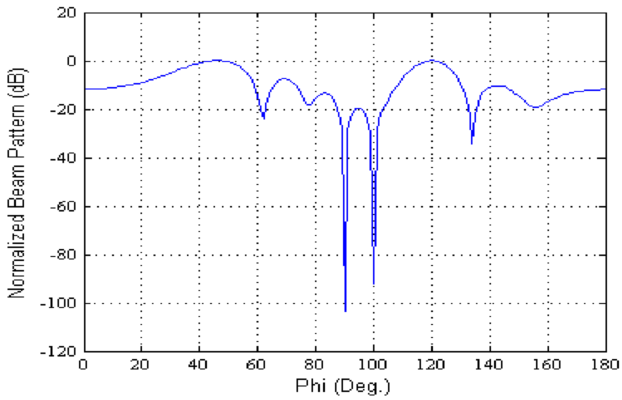

Figure 1. Normalized beam pattern used to reconstruct the SOIs magnitude

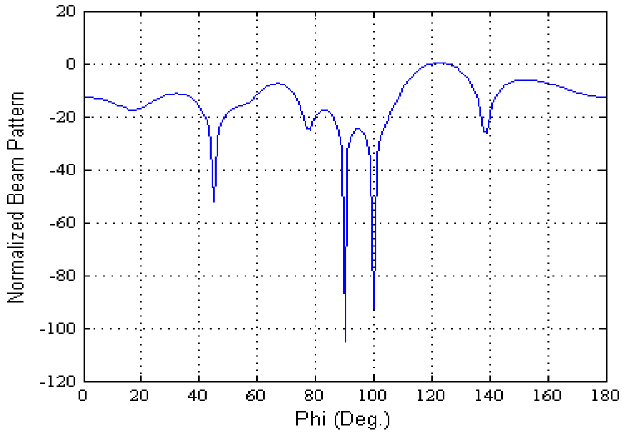

Figure. 2. Normalized beam pattern used to reconstruct SOI #1

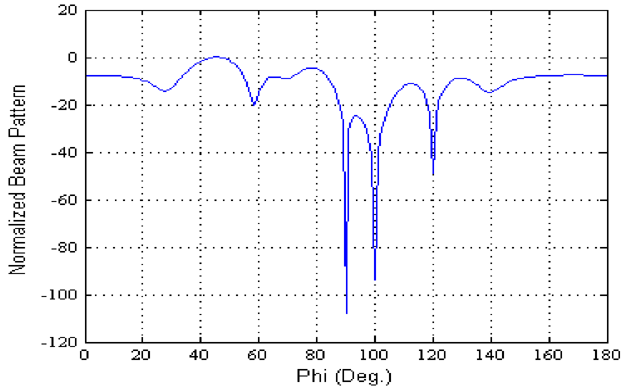

Figure 3. Normalized beam pattern used to reconstruct SOI #2

B. Example Two: Varying Signals:

In the second example, the 1st incident SOI intensity is 1 V/m and arriving from the direction $\emptyset = 45°$ and the 2nd incident SOI intensity is varied from 0.2 V/m to 10 V/m and its DOA is varied from $\emptyset$=120° to $\emptyset$=170°. The 1st jammer intensity is fixed at 50dB over the 2nd SOI and arriving from a fixed direction of $\emptyset = 90°$while for the 2nd jammer the intensity is varied from 0dB to 50 dB over the 2nd SOI and its DOA is varied from $\emptyset$=100° to $\emptyset$=110°. All the variations in the amplitudes and the DOAs of the 2nd SOI and 2nd jammer are done over 50 equal steps.

Fig. 4 plots the magnitudes of the actual and the reconstructed SOIs, i.e. the sum of the incident SOIs. As it can be seen, the reconstructed SOIs magnitudes are almost coincide with the actual values. The reconstruction root mean square error (RMSE) is found to be 0.0059V/m; the reconstruction errors are plotted in Fig. 5.

The 1st SOI could be reconstructed by considering the 2nd SOI as an interferer. Fig. 6 shows the actual and the reconstructed 1st SOI magnitudes. The reconstruction RMSE is found to be 0.0049 V/m. Similarly, the 2nd SOI could be reconstructed by considering the 1st SOI as an interferer. Fig. 7 shows the 2nd SOI actual and reconstructed magnitudes and the corresponding reconstruction errors are shown in Fig. 8. The 2nd SOI reconstruction RMSE is found to be 0.0054 V/m.

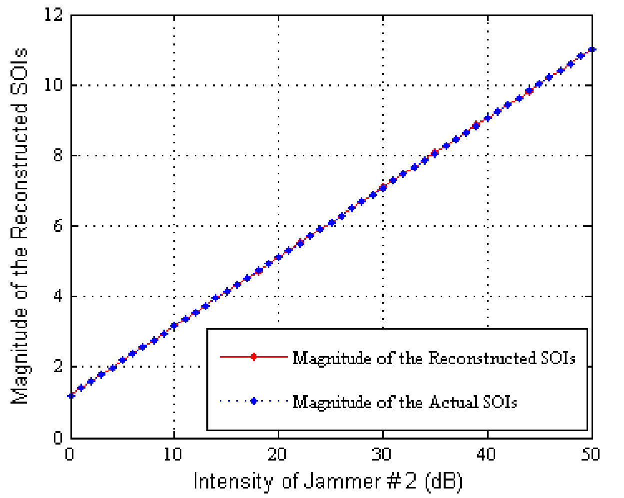

Figure 4. Magnitudes of actual and reconstructed SOIs (V/m)

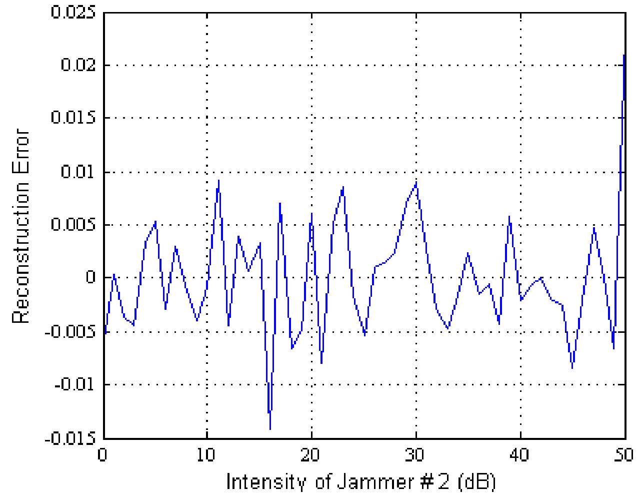

Figure 5. SOIs magnitudes' reconstruction errors (V/m)

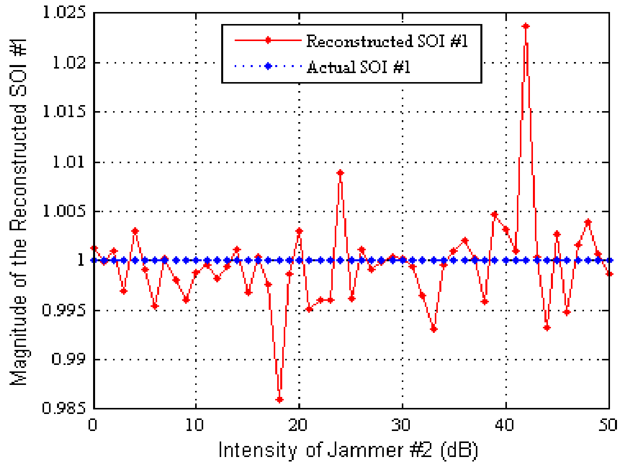

Figure 6. Magnitudes of actual and reconstructed SOI #1 (V/m)

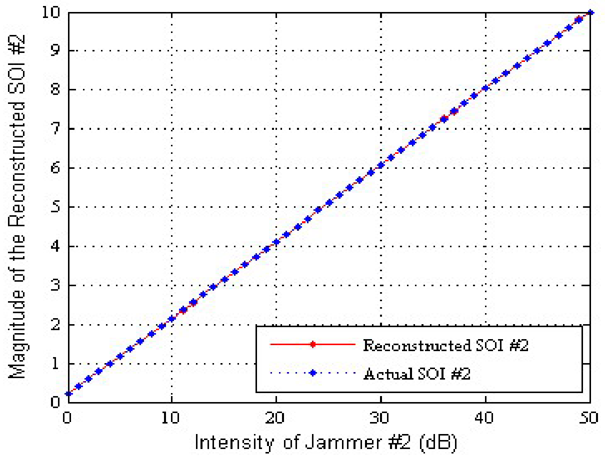

Figure 7. Magnitudes of actual and reconstructed SOI #2 (V/m)

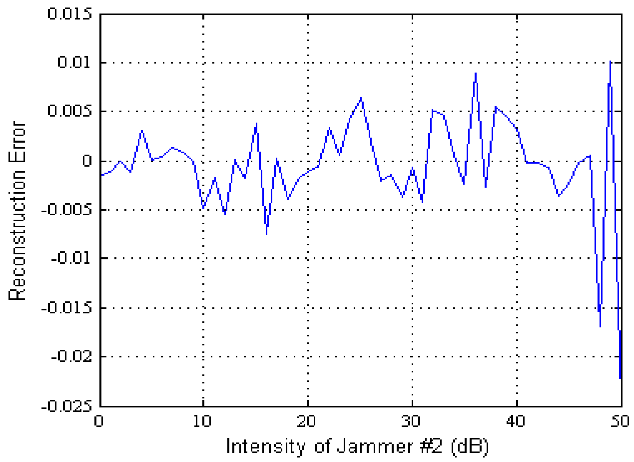

Figure 8. SOI #2 magnitudes' reconstruction errors (V/m)

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