Design of an Efficient Wideband Beamformer using OPSO

Diksha Thakur, Vikas Baghel, Salman Raju Talluri

Abstract: Wideband beamforming is a technique which is used to produce frequency invariant beampatterns over a wide signal bandwidth. In this paper, orthogonal particle swarm optimization (OPSO) based wideband beamformer is designed to achieve wideband beamforming. Simulations are carried out for two different scenarios to illustrate the capability of the algorithm for wideband beamforming. The beampatterns obtained from three different methods that are standard Frost algorithm, particle swarm optimization (PSO) and OPSO are compared by various parameters such as level of interference, deviation in interference angle and peak side lobe level. It is shown that by using OPSO, SLL (Sidelobe Level), null depth as well as angle deviation in nulls direction can be reduced as compared to PSO and Frost algorithms.

Keywords: Orthogonal particle swarm optimization, PSO, wideband beamforming.

I. INTRODUCTION

Array signal processing [1] has wide variety of applications in many fields such as radar, sonar, wireless communication etc. It includes various elements in antenna array [2] which are located at different positions in the space. The signals received by elements of the antenna array are processed and multiplied by optimum weights in order to form the beam in specific direction while suppressing the interfering signals at the same time. Depending upon the bandwidth of the received signals, beamforming can be classified into two types such as narrowband beamforming and wideband beamforming [3].

Narrowband beamformer that forms narrowband beamforming operates with signals having fractional bandwidth less than 1%. In narrowband beamforming, before adding the received signals they are multiplied by optimum weights to produce the desired beampattern. With the increase in received signal bandwidth the performance of narrowband beamformer degrades [4]-[5]. In order to process wideband signals whose fractional bandwidth is greater than 1% to 25%, a series of tapped delay line (TDL) is used after each element of the array to compensate the phase difference for each of the frequency components.

To produce wideband beamforming, various methods have been proposed in the last few years. In [6], Frost's algorithm or linearly constrained minimum variance (LCMV) was described which calculate the optimum beamforming weights in order to suppress the interfering signals whilst maintaining the main beam direction for a particular frequency range. Various methods have been proposed in literature to improve the performance of LCMV algorithm. A response variation element was incorporated into LCMV in [7] to improve the performance with respect to desired direction errors and frequency invariance constraint over the specified frequency range. In [8], response variation element with norm bounded errors was used for further increase in robustness as well as more effective control on frequency invariance constraint. To reduce the computational complexity along with increase in robustness as well as frequency invariance constraint in LCMV algorithm, derivative constraint based method was proposed in [9]. Frost algorithm can be used in interference environment as it places null towards the interfering direction and main beam towards the desired direction. Recently, Frost algorithm was modified in [10] to deal with rapidly moving interfering signals. The nulls were broadened by adding virtual interferences around the original interference direction.

Due to various advantages of evolutionary algorithms over classical optimization methods [11], evolutionary optimizations can be used to form wideband beamforming. PSO was used in literature to design optimal beamforming. In [12]-[13] various examples of beamforming are presented and one of them is of wideband beamforming with single null in the beampattern. In the simulation results, there was deviation in angle of null as the frequency changes and in various application nulls should be placed at exact location as desired for the specified frequency range. In this paper, evolutionary algorithms such as OPSO and PSO with novel objective function are proposed to improve the performance of wideband beamforming. It is shown in the simulations that OPSO enhance the performance as compared to PSO with the same objective function.

The paper is organized as follows. In section II and III, a brief introduction of PSO and OPSO in described. The problem formulation and objective function that is used to form wideband beamforming are explained in section IV. In Section V, simulation results of numerical examples are discussed and finally conclusion is made in section VI.

II. PSO

PSO is an optimization technique [14] which is inspired by social behavior of swarms such as bird flock, fish school and bees swarm in the nature. The swarms continuously interact with each other and update

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their positions to find optimum solution in a solution space. The process of PSO is summarized in flowchart depicted in Fig.1.

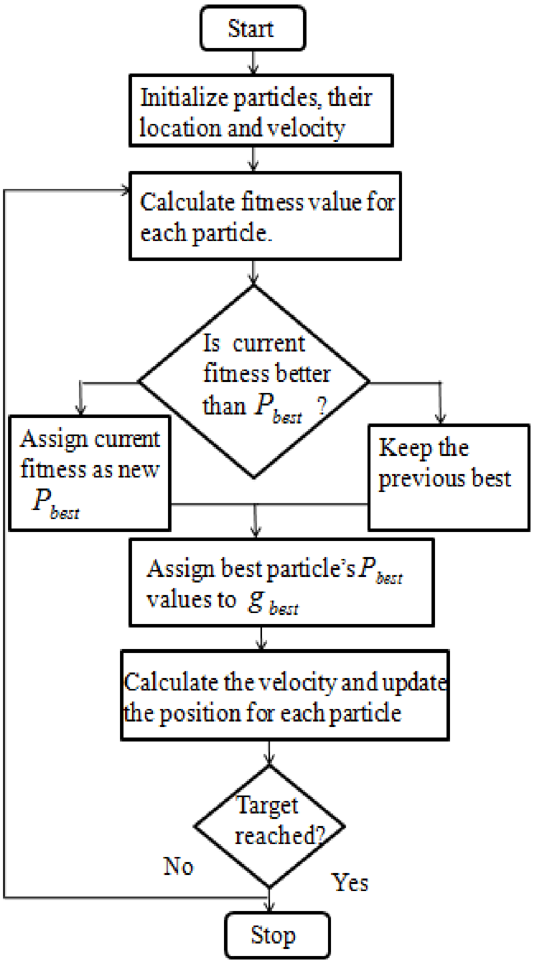

Fig. 1.Flowchart of PSO algorithm.

The update equations for velocity and position are given in (1) and (2) respectively.

$$v_i(t+1) = w_i v(t) + c_1 r_1 (x_p(t) - x_i(t)) + c_2 r_2 (x_g(t) - x_i(t)) \quad (1)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (2)$$

where w_i is the inertia weight, c_1 , c_2 are acceleration coefficients and r_1, r_2 are random numbers whose values are uniformly distributed between 0 to 1 and $x_i(t)$, $x_p(t)$ and $x_g(t)$ are particles initial, individuals best and global best positions respectively. After defining the appropriate values of velocity parameters, the position of the particle is updated using (2).

III. ORTHOGONAL PSO

The velocity and position of the particles in PSO are updated according to the particle's best and swarm's best positions. This can result in oscillation phenomenon [15] which degrades the search efficiency of PSO algorithm. The particles become confused as they are not able to decide the direction of movement. The objective of applying orthogonal concept in the basic PSO algorithm is to enhance its performance. Basically orthogonal means statistically independent [16]. The orthogonality in PSO is used to create the points of an initial population that are scattered over the possible solution space so that algorithm can evenly search the possible solution space in order to discover appropriate points for further exploration in the following iterations. An initial swarm consists of *n* particles from which *m* particles (*m*< *n*) are selected in OPSO that have the possible solutions. A process called orthogonal diagonalization [17] is used in which *m* numbers of orthogonal vectors are generated from *n* number of current position vectors. These orthogonal vectors are updated with each iteration and are used to guide the selected *m* particles to fly in one direction toward global minimum. Consider a swarm which consists of *n* particles and each particle maintains a vector of position $\overline{X_i}$ and velocity $\overline{V_i}$ which are given in (3) and (4) respectively.

$$\overline{X_i} = [x_{i1}, x_{i2}, ..., x_{in}] \quad (3)$$

$$\overline{V_i} = [v_{i1}, v_{i2}, ..., v_{in}] \quad (4)$$

The position and velocity of the particles are updated with each iteration in OPSO algorithm by using following steps:

i. Each particle in the swarm is evaluated by the fitness function and the position of particle with minimum value of fitness function is denoted by X_{best} . The remaining *n*-1 particles are evaluated in the similar way to get the best position vectors. The best n position vectors are arranged in ascending sequence of the value of fitness function.

ii. Create a matrix *K* of size *n*×*m* such that every row attains one of the n best position vectors in the same order. Then, *L* symmetric matrix of size *m*×*m* is created from *K* matrix using a procedure given in [18].

iii. The symmetric matrix L is now converted to orthogonal matrix *M* using Gram–Schmidt orthogonalization method [17].

iv. An orthogonal diagonal matrix *N* of size *m*×*m* is constructed from matrices *K, L* and *M* which is given in (1) by using orthogonal diagonalization (OD) process.

$$N = MLM^T \quad (5)$$

v. The best position and velocity are updated using (6) and (7) respectively.

$$v_i(t+1) = w_i v(t) + cr(N_i(t) - x_i(t)) \quad (6)$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (7)$$

where w_i , *c* and *r* are the inertia weight ,acceleration coefficients and random number respectively. The values of r are uniformly distributed between 0 to 1, i =1, 2, 3 ...m and N_i is the i^{th} row of the matrix *N*. After defining the appropriate values of velocity parameters, the position is updated according to (7). As there is only one guide in the velocity equation so the particles move towards the target instead of trapping in the oscillation phenomenon. The procedure for OPSO [19] is depicted in Fig.2.

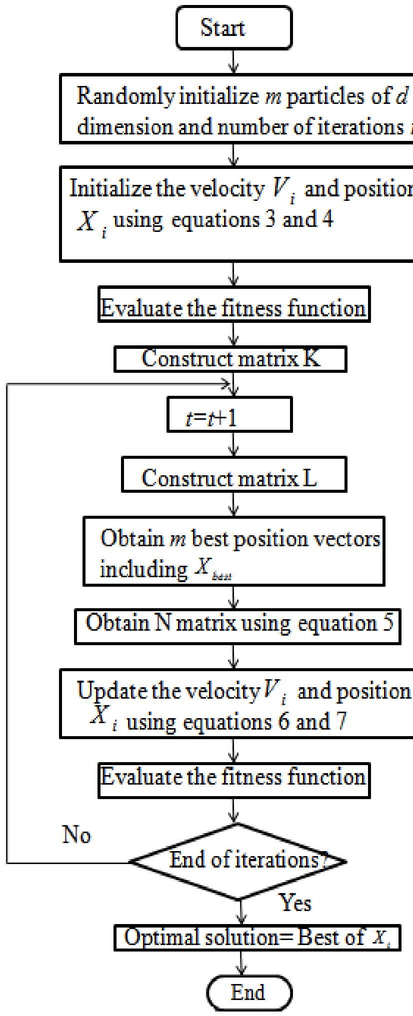

Fig. 2.Flowchart of OPSO algorithm.

IV. PROBLEM FORMULATION

The basic structure of wideband beamformer using tapped delay lines for *L* elements in the antenna array with *K* number of taps associated with each element is shown in Fig.3. The output of wideband beamformer is expressed as:

$$y(t) = \sum_{m=0}^{L-1}\sum_{k=0}^{K-1} w_{m,k} x_m (t-(\tau_m + kT_s)) \qquad (8)$$

where τ_m is the delay between m^{th} antenna element and reference antenna element and T_s is the delay between adjacent taps of the tapped delay lines. For sinusoidal signals, beamformer's output is given in (9).

$$y(t) = \sum_{m=0}^{L-1}\sum_{k=0}^{K-1} w_{m,k} \exp - j\omega(\tau_m + kT_s) \qquad (9)$$

As the wideband beamformer provides similar response over a specified range of frequencies so its output as a function of frequency and direction of arrival (DOA) angle θ is expressed in (10).

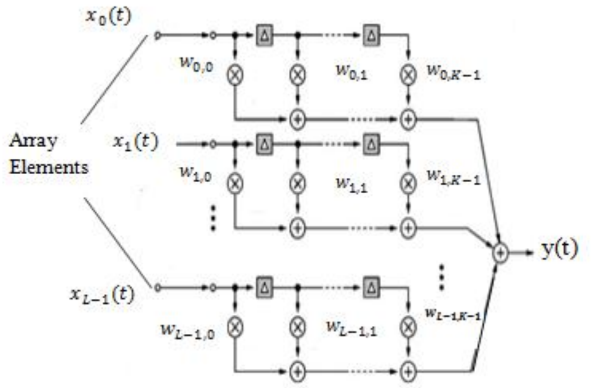

Fig. 3.General structure for wideband beamforming

$$Y(\omega,\theta) = \sum_{m=0}^{L-1}\sum_{k=0}^{K-1} w_{m,k} \exp - j\omega(\tau_m + kT_s) \qquad (10)$$

The vector form of (10) is given as:

$$Y(\omega,\theta) = w^T S(\omega,\theta) \qquad (11)$$

where w is the weight vector given in (12) and the steering vector is given in (13).

$$w = \left[w_{0,0} \ldots w_{L-1,0} \ldots w_{0.K-1} \ldots w_{m-1,k-1}\right]^T \qquad (12)$$

$$S(\omega,\theta) = \left[e^{-j\omega\tau_0}, .e^{-j\omega\tau_{L-1}}, .e^{-j\omega(\tau_0+(K-1)T_s}, .e^{-j\omega(\tau_{L-1}+(K-1)T_s}\right]^T \qquad (13)$$

The steering vector is the Kronecker product of received signal and sampled signal after taps [10] which are given in (15) and (16) respectively.

$$S(\omega,\theta) = x_{T_s}(\omega) \otimes x_{\tau_m}(\omega,\theta) \qquad (14)$$

$$x_{T_s}(\omega) = \left[1, \ldots\ldots e^{-j\omega(K-1)T_s}\right]^T \qquad (15)$$

$$x_{\tau_m}(\omega,\theta) = \left[1, \ldots\ldots e^{-j\omega(L-1)d\sin\theta/c}\right]^T \qquad (16)$$

where d is the distance between adjacent antenna elements and c is the speed of the wave.

The response of the wideband beamforming which is given in (10) and (11) is completely depending upon the weight vector *w*. The optimum weights to produce wideband beamforming can be obtained with evolutionary algorithms such as PSO as well as OPSO.

To achieve wideband beamforming using OPSO and PSO, mean square error (MSE) is used as fitness function. MSE is calculated between array pattern obtained from uniform weights i.e. weight vector (*w*=1) and array pattern obtained from OPSO/PSO such that position of nulls remains in the specific direction for each specified frequency. The fitness function used to achieve wideband beamforming is formulated as:

$$Y_{best}(\omega,\theta) = MSE[Y_{OPSO/PSO}(\omega,\theta) - Y_{uniform}(\omega,\theta)]$$

(17)

where $Y_{uniform}(\omega,\theta)$ is the reference pattern with uniform weights and nulls in the desired direction for each frequency given in (18) and $Y_{OPSO/PSO}(\omega,\theta)$ is the array pattern obtained from OPSO/PSO given in (19).

$$Y_{uniform}(\omega,\theta) = X(\omega,\theta)W_{uniform} \ \forall\ \theta \text{ and } \omega \text{ except } \theta_j \quad (18)$$

where θ_j are the angles at which nulls are required.

$$Y_{OPSO/PSO}(\omega,\theta) = X(\omega,\theta)W_{OPSO/PSO} \quad (19)$$

The weights calculated by OPSO/PSO are updated with each iteration and these are calculated such that it minimizes the MSE. The weight vector which provides the lowest MSE is used to produce the output of wideband beamformer and is called optimum weight vector.

V. RESULTS AND DISCUSSIONS

The simulations are carried out for a linear array of 16 isotropic antenna elements and 5 taps per antenna element. The number of iterations is 500 which are large enough to guarantee the convergence of algorithm. The frequency range used for simulations is 1.2GHz to 1.4GHz with bandwidth of 200MHz. The simulations are carried out for two different scenarios. In the first scenario only one interference is considered whereas two interferences are considered in the second scenario. The value of inertia weight w_i is linearly decaying from 0.8 to 0.4 with each iteration and $c_1 = c_2 = 1.042$ for both PSO and OPSO. Wideband beamforming is implemented using Frost algorithm, PSO and OPSO. The results obtained from these are compared by various parameters such as MSE, peak SLL (Sidelobe Level), deviation in interference angle and the level of interference.

A. Scenario 1: Single interference

The direction of main beam is 0° with single null at an angle of 26° for all frequencies. The training of OPSO and PSO is done for only three frequencies that are 1.2GHz, 1.3GHz and 1.4GHz but testing is done for all the frequencies in the specified range. Fig. 4 shows the convergence curves of PSO as well as OPSO and it can be said that OPSO converges faster and gives low MSE as compared to PSO.

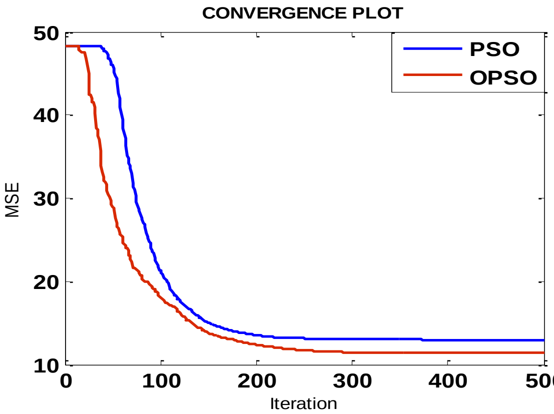

Fig. 4.Comparison of convergence curve of MSE with number of iterations

Firstly the trained PSO and OPSO based beamformers for wideband beamforming are tested for only three frequencies. The array beampattern obtained from Frost algorithm, PSO and OPSO are shown in Fig.5, 6 and 7 respectively.

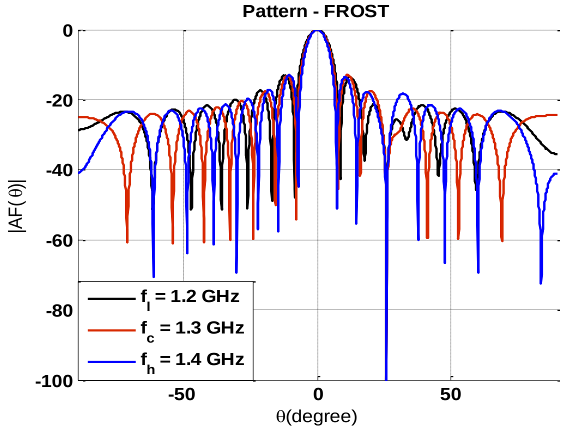

Fig. 5.Array pattern obtained from Frost

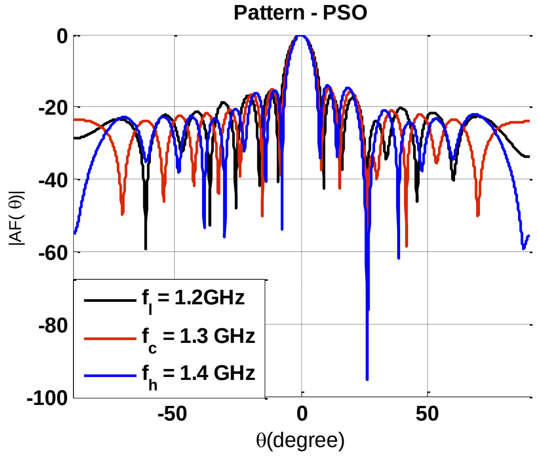

Fig. 6.Array pattern obtained from PSO.

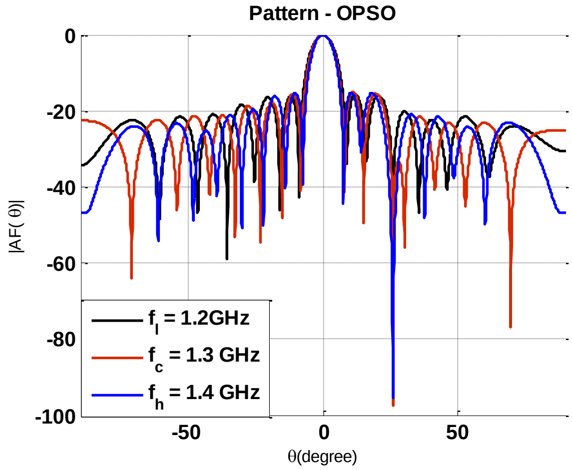

Fig. 7.Array pattern obtained from OPSO.

From the Fig. 5, 6 and 7, it is found that the nulls and main beam is towards the desired direction for all the three different frequencies. The comparison of performance parameters is depicted in Table-I. It is found out that the SLL is reduced for all frequencies and the null is located at exact location as desired because there is no deviation in null's position.

Table- I: Comparison of performance parameters

Frequency↓	*Method* ↓	*Parameter*	
		SLL(dB)	*Deviation in null angle (Degree)*
1.2GHz	Frost	-13.04	0
	PSO	-15.74	0
	OPSO	-15.63	0
1.3GHz	Frost	-12.94	0
	PSO	-14.74	0
	OPSO	-14.92	0
1.4GHz	Frost	-12.98	0
	PSO	-14.07	0
	OPSO	-15.21	0

In order to test the three methods for all the frequencies between 1.2GHz-1.4GHz, array beampatterns are obtained for 100 frequencies between the chosen range. The results obtained from Frost, PSO and OPSO are shown in Fig.8, 9 and 10 respectively.

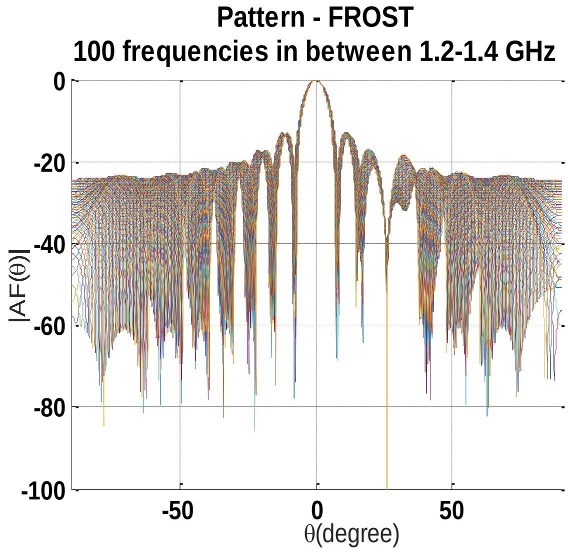

Fig. 8.Array pattern obtained from Frost for 100 frequecies.

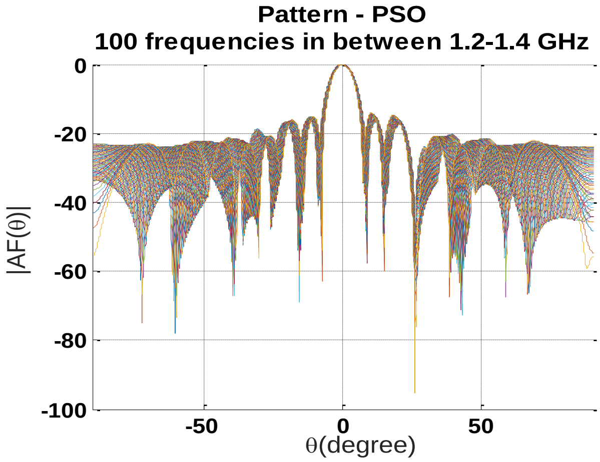

Fig. 9.Array pattern obtained from PSO for 100 frequecies.

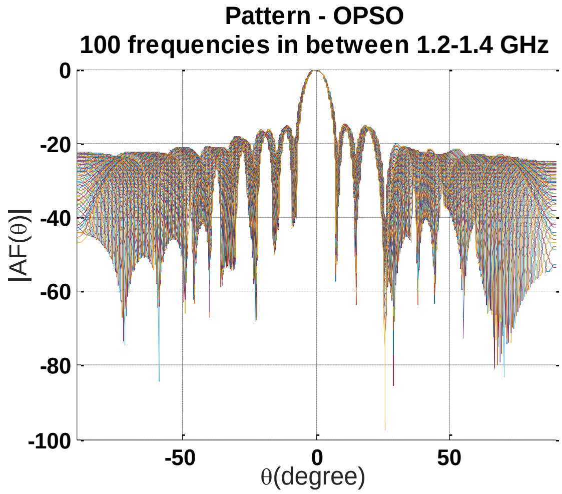

Fig. 10. Array pattern obtained from OPSO for 100 frequecies.

It is found that Frost as well as both the algorithms forms the main beam towards the desired direction and sharp nulls towards the interference direction for all the chosen 100 frequencies.

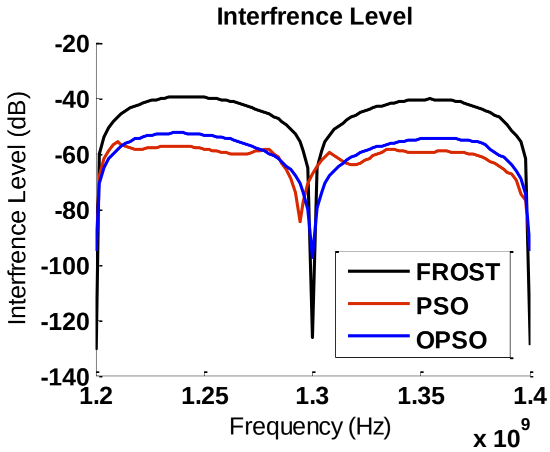

Fig. 11. Comparison of interference level.

Fig.11 depicts the depth of null obtained from Frost, PSO and OPSO for 100 frequencies in the desired frequency range i.e. 1.2GHZ1.4GHz. The PSO and OPSO algorithms are trained for only three different frequencies that are 1.2, 1.3 and 1.4GHz but tested for all the frequencies in the range 1.2GHz-1.4GHz. The null depth for the tested frequencies is acceptable i.e. approximately -40dB which can suppress the interference.

The comparison of SLL is depicted in Fig. 12 and it is found out that OPSO shows comparably low SLL than PSO. Moreover the SLL obtained form OPSO is better than classical Frost method.

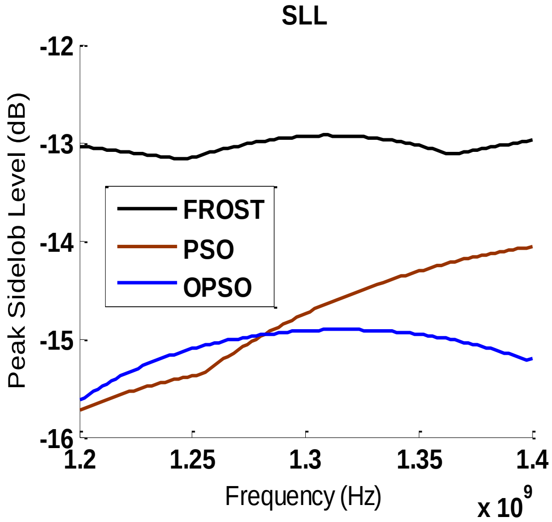

Fig. 12. Comparison of SLL

B. Scenario 2: Two interferences

Wideband beamforming is achieved with two nulls which are located at -23.5782° and 30°. The convergence curves for evolutionary algorithms are shown in Fig. 13 and it is found that OPSO provides low MSE as compared to PSO.

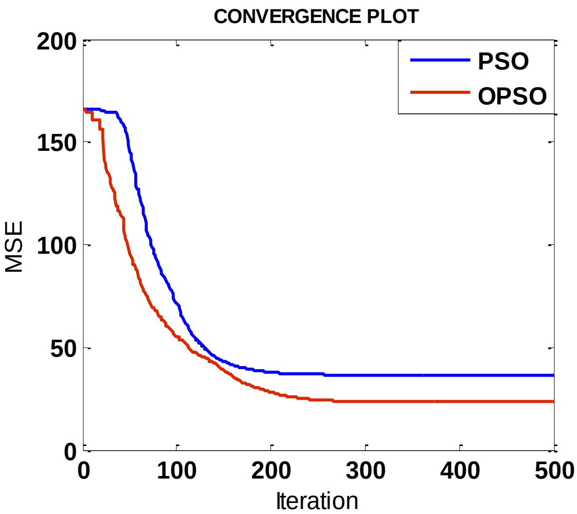

Fig. 13. Comparison of convergence curve of MSE with number of iterations.

The radiation patterns of Frost, PSO and OPSO for three different frequencies are depicted in the Fig. 14, 15 and 16 respectively.

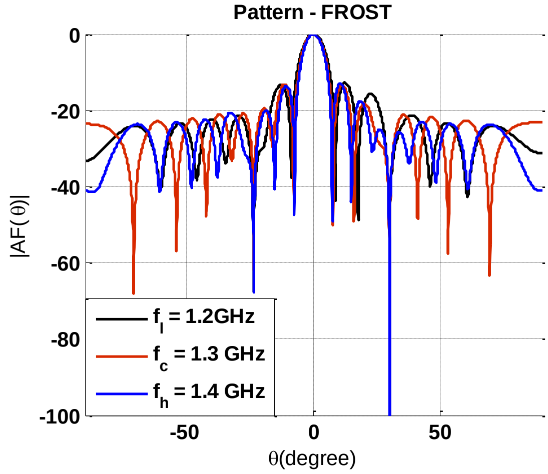

Fig. 14. Array pattern obtained from Frost

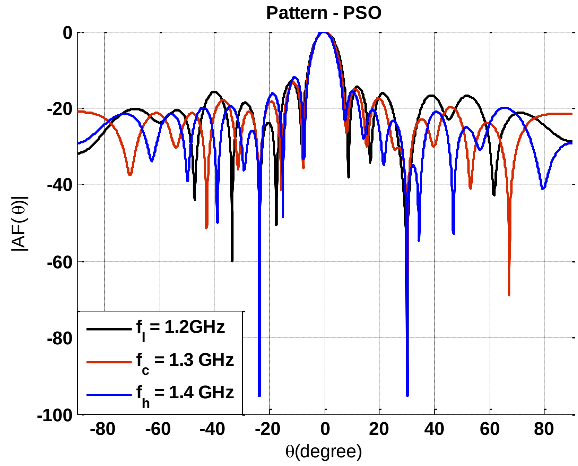

Fig. 15. Array pattern obtained from PSO.

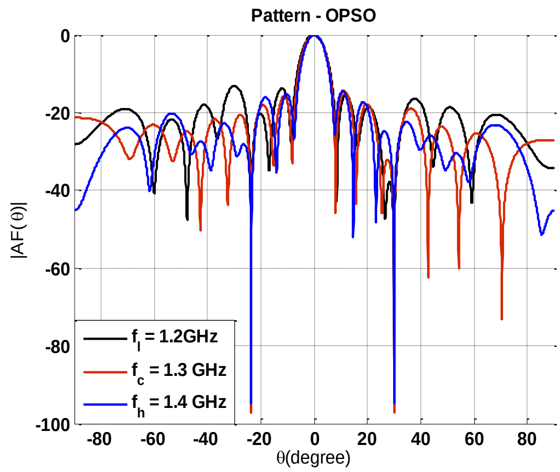

Fig. 16. Array pattern obtained from OPSO.

From the Fig.14, 15 and 16, it can be said that null are located at exact position as desired for all the three different frequencies. The tabular representation of performance parameters is shown in Table-II. It is found out that SLL is reduced by applying OPSO with no deviation in the angle of nulls.

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Table- II: Comparison of performance parameters

Frequency↓	Method ↓	Parameter	
		SLL(dB)	Deviation in null angle (Degree)
1.2GHz	Frost	-12.75	0
	PSO	-12.99	0
	OPSO	-13.1	0
1.3GHz	Frost	-13.17	0
	PSO	-13.23	0
	OPSO	-14.51	0
1.4GHz	Frost	-13.06	0
	PSO	-11.93	0
	OPSO	-14.43	0

In order to test the algorithms for all frequencies between 1.2GHz-1.4GHz, the array patterns are plotted for 100 frequencies between the desired frequency range. The simulation results obtained from Frost, PSO and OPSO are shown in Fig. 17, 18 and 19respectively. It is found that all the three algorithms can form sharp nulls towards the interference direction for all the 100 frequencies between 1.2GHz-1.4GHz.

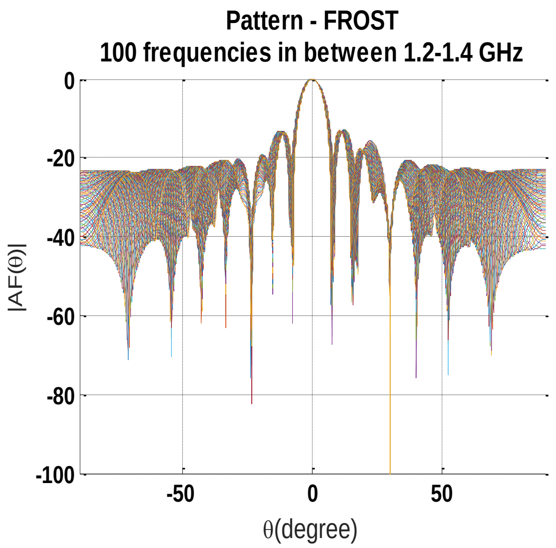

Fig. 17. Array pattern obtained from Frost for 100 frequencies.

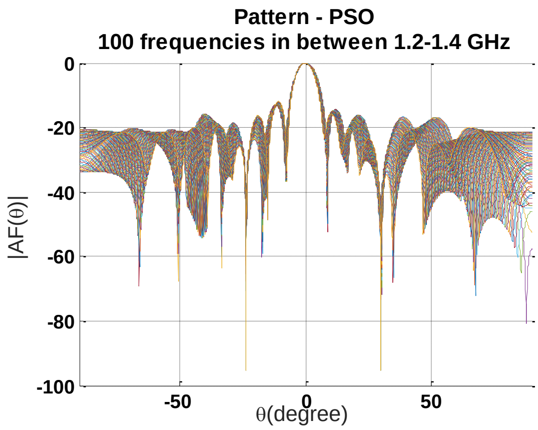

Fig. 18. Array pattern obtained from PSO for 100 frequencies.

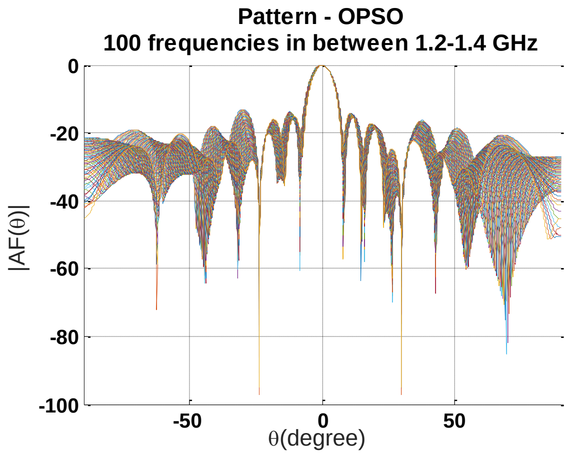

Fig. 19. Array pattern obtained from OPSO for 100 frequencies.

The comparison of performance parameters such as null depth for both interferences, deviation in angle of interference and peak SLL are depicted in Fig. 20, 21 and 22 respectively. The comparison in done for 100 frequencies between 1.2GHz-1.4GHz and it is found that the OPSO can improve the performance over PSO and Frost.

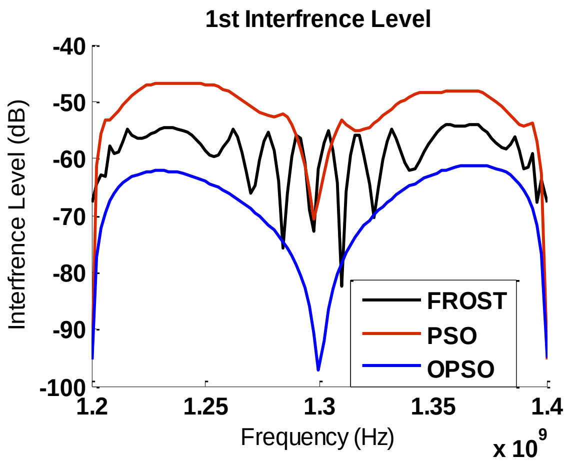

Fig. 20. Comparison of 1st interference level.

From the Fig. 19 and 20, it can be said that OPSO not only reduce the null depth for the trained frequencies but also for the other frequencies in the given range. There is an improvement of approximately 30dB and 35dB for the first interference and second interference respectively. This improvement is achieved for center frequency as well as for all the frequencies in the range.

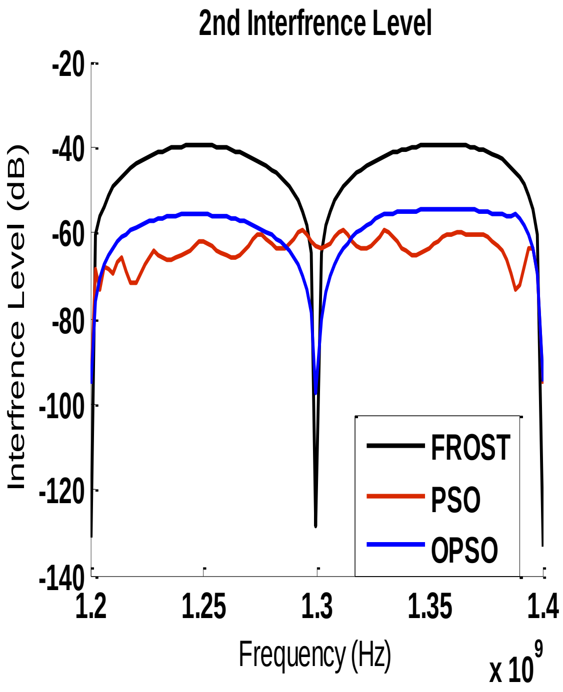

Fig. 21. Comparison of 2nd interference level.

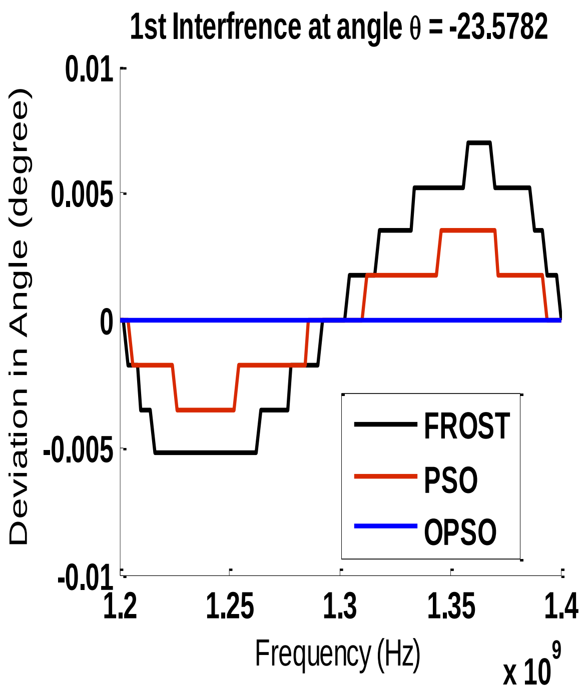

Fig. 22. Comparison of deviation in angle of 1st interference

There is small deviation in angle of nulls for PSO and Frost . The deviation in angle of nulls should be minimum in order to cancel out the interfering signals. OPSO achieved very small deviation in comparison to PSO and Frost which is clearly visible from the Fig. 22 and 23.

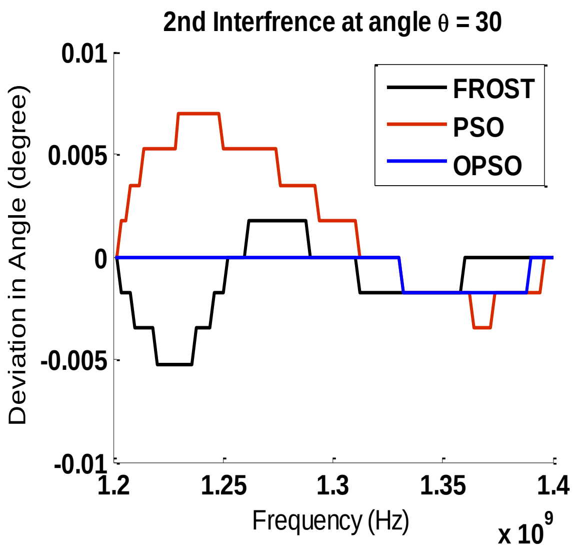

Fig. 23. Comparison of deviation in angle of 1st interference

For OPSO, SLL is reduced for all frequencies as compared to PSO and Frost which is more clear from the Fig. 24. The maximum improvement of 2.97dB and 2.15dB is achieved form OPSO as compared to PSO and frost respectively.

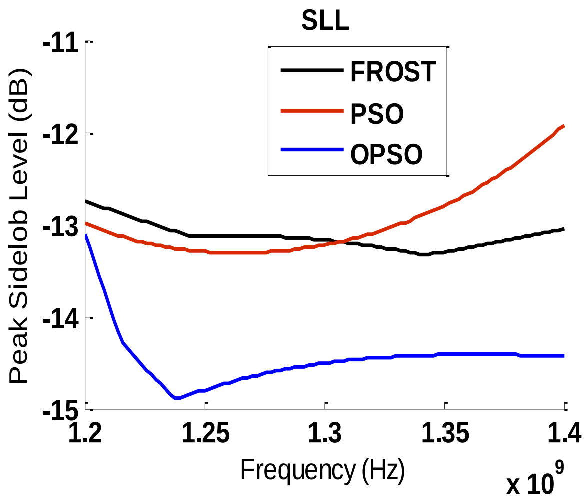

Fig. 24. Comparison of SLL

VI. CONCLUSION

A new approach is presented to form main beam towards the desired direction and nulls towards the interference direction at the same time over a specified frequency range. The evolutionary algorithm such as OPSO with novel objective function is used to design wideband beamforming. Firstly PSO and then OPSO are applied successfully to achieve wideband beamforming and it is proved by two different scenarios. By comparing the results obtained from both the evolutionary algorithms and classical method Frost algorithm it is shown that OPSO improves peak SLL and there is almost no angle deviation in the position of nulls for every frequency. So, PSO and OPSO can be used for beamforming in RADAR, SONAR, satellite TVs etc.

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