Null Placement in Uniform Linear Array by Phase Control of Edge Elements

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Abstract.

This paper presents a novel method of null placement by controlling only the excitation phase of the edge elements of a uniformly excited linear antenna array. Antenna parameters such as directivity, First Null Beam Width (FNBW) and Half Power Beam Width (HPBW) are obtained analytically through array synthesis. Then the pattern gets degraded due to the required null placement. Subsequently to enhance the pattern, antenna parameters and to find out the optimum value of the excitation phase, suitable evolutionary algorithm has been employed. The whole simulation is carried out using a 10-element uniform, linear antenna array by two different approaches to comparatively study the effects.

Keywords. Null placement, Phase control, Edge element, Array symmetric method, Classical DE algorithm

INTRODUCTION

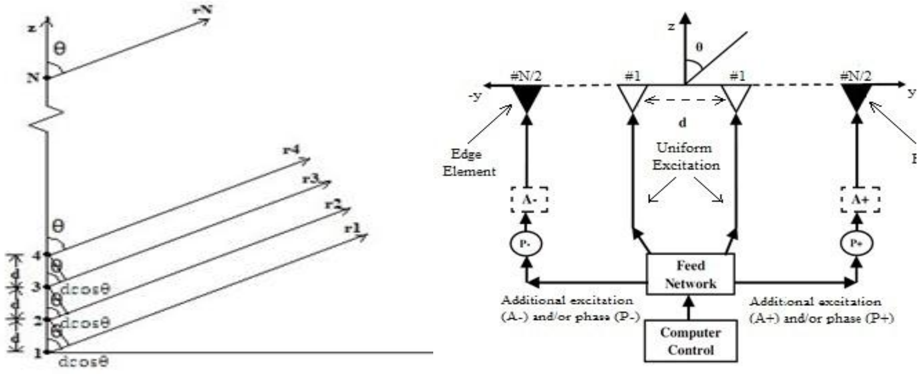
In the modern era of communication system, a major role is played by antenna. Starting from Wi-Fi, Bluetooth, GPS, etc. to RADAR, SONAR, UAVs to Satellite Communications, every single wireless gadget requires an antenna and more specifically an antenna array [1]. But the objective of an antenna is not restricted to just transmitting and receiving signals, it should also be able to optimize radiated energy in some particular required direction and should be able to suppress it in other directions. Although the antenna directivity can be increased by increasing the number of array elements or by reducing the inter element spacing [2] but still suppression of unwanted signals is very essential for further increase in directivity. Generally, this suppression of unwanted signals is done by masking the interference signal from a particular direction. This method of masking is known as null placement and in earlier times researchers used to place nulls analytically [3-6], but later researchers found out that due to this analytical placement of null, various antenna parameters are deteriorating and moreover multiple null and wide null cannot be placed analytically. This gave rise to the use of evolutionary algorithms to overcome the limitations.

Researchers started applying evolutionary algorithms to overcome limitation in the form of pattern degradation of antenna array with null placements. Accordingly, Goudos et.al. [7] in his research work has compared different evolutionary algorithms by applying them to antenna design related problems. Then he concluded from the results that he found out, that Genetic Algorithms (GA), Particle Swarm Optimization (PSO) and Differential Evolution (DE) algorithms are some of the most popularly used algorithms in antenna design. His results also suggest that classical DE is one of the simplest and efficient among the three. Using this result, later Mathur et.al. [8] proposed a null placing method using PSO algorithm in uniform linear array and they obtained desirable results. This supports the results obtained by Goudos et.al. Another method of null placement has been discussed by researchers Hamza et.al. [9] in their work. It uses Genetic Algorithm along with the method suggested by Schelkunoff in order to increase the speed of beam steering and they also observed an improvement in the radiation pattern of the array and an increased accuracy in null placement. But they had done it for circular array. In the recent years' researchers Jamunaa et.al. [10] had worked on this null placement method with uniform linear array. They had approached with phase only control method where they had kept the amplitude of all the elements uniform and used evolutionary algorithm to optimize the phase of all the elements in order to place accurate null. From the results it was concluded that they could successfully place nulls. But they had done this method only for single null placement and they concluded that their work can be further studied and extended for multiple null. Chatterjee et.al. [11] in their work also, proposed a novel least perturbation based method of constrained null placement for a non-uniformly excited linear antenna array. They have carried out their work by controlling the excitation amplitude and phase of the edge elements which makes the antenna design less complex. But antenna array synthesis can also be done only by controlling the phase and keeping amplitude constant which reduces the runtime as well as cost.

So, these research works lead to the motivation of our method of null placement which has been discussed in this paper. So in the proposed method, only the phase of the edge elements is controlled. This has two advantages. Firstly, there is no requirement of attenuator which makes the appliance using the antenna array lighter and cheaper. And secondly, the design becomes simpler. Moreover, a uniformly excited linear antenna is taken so that the design time and complexity also reduces. The design of this antenna array has been approached by two methods. At first, the conventional method which gave rise to some drawbacks which leads to the second method of array symmetry. The analytical results are then optimized using classical DE algorithm which in turn improves the value of radiation parameters and optimizes the value of phase.

PROPOSED METHOD

First Approach: Conventional Method



(b)

(a)

Figure 2.1 Conventional Uniform Linear Array (a) Geometry, (b) Schematic diagram of edge element control

When a uniform linear array of N number of isotropic elements placed along the z-axis then the far field observation obtained is shown in Figure 2.1(a). So, the array factor of uniform linear array is given by equation (2.1),

$$\mathrm{AF}(\theta) = \left[e^{+j0(kd\cos\theta+\beta)} + e^{+j1(kd\cos\theta+\beta)} + e^{+j2(kd\cos\theta+\beta)} + \cdots + e^{+j(N-1)(kd\cos\theta+\beta)}\right] \tag{2.1}$$

$$\mathrm{AF}(\theta) = \left[\sum_{n=1}^{N} e^{j(n-1)(kd\cos\theta+\beta)}\right] \tag{2.2}$$

Now, let us assume $\psi = kd\cos\theta + \beta$, then the equation (2.2) will become,

$$\mathrm{AF}(\theta) = \left[\sum_{n=1}^{N} e^{j(n-1)\psi}\right] \tag{2.3}$$

In order to make the array factor more compact, both sides of the equation (2.3) is multiplied by $e^{j\psi}$, and the modified array factor is given by equation (2.4).

$$\mathrm{AF}(\theta)e^{j\psi} = \left[e^{j\psi} + e^{j2\psi} + \cdots + e^{j(N-1)\psi} + e^{jN\psi}\right] \tag{2.4}$$

Equation (2.3) is then subtracted from equation (2.4), and the expression becomes,

$$\mathrm{AF}(\theta)\left(e^{j\psi} - 1\right) = \left(-1 + e^{jN\psi}\right) \tag{2.5}$$

$$\mathrm{AF}(\theta) = e^{j\left[\frac{(N-1)}{2}\right]\psi}\left[\frac{\sin\left(\frac{N}{2}\psi\right)}{\sin\left(\frac{\psi}{2}\right)}\right] \tag{2.6}$$

Now, by taking the physical center of the array as the reference point, then the array factor in equation (2.6) will be reduced to,

$$\mathrm{AF}(\theta) = \left[\frac{\sin\left(\frac{N}{2}\psi\right)}{\sin\left(\frac{\psi}{2}\right)}\right] \tag{2.7}$$

The schematic diagram of edge element control in uniform linear array is shown in Figure 2.1(b). Array factor of N numbered linear array with uniform excitation is given by the equation (2.7) in which wave number $k = \frac{2\pi}{\lambda}$, where λ is incident wave length, inter element spacing $d = \frac{\lambda}{2}$, and θ is the elevation angle. Array factor can be considered as the summation of array factor due to rest of the elements $AF_R(\theta)$ as represented by equation (2.9) and array factor due to edge elements $AF_E(\theta)$ which is represented by equation (2.10), and here $\psi = kd(\sin\theta - \sin\theta s)$.

$$AF(\theta) = AF_R(\theta) + AF_E(\theta) \tag{2.8}$$

$$AF_R(\theta) = \left[\frac{\sin\left(\frac{(N-2)}{2}\psi\right)}{\sin\left(\frac{\psi}{2}\right)}\right] \tag{2.9}$$

$$AF_E(\theta) = e^{j\left(\frac{N-1}{2}\right)\psi} + e^{-j\left(\frac{N-1}{2}\right)\psi} = 2\cos\left[\left(\frac{N-1}{2}\right)\psi\right] \tag{2.10}$$

Additional control for null placement are only the phases -P and +P that are being fed directly to the edge elements because amplitude is constant, so, A=1. So, the modified array factor contribution due to edge elements ($AF_E(\theta)|_m$) is given by equation (2.11).

$$AF_E(\theta)|_m = e^{-j(-P)}e^{-j\left(\frac{N-1}{2}\right)\psi} + e^{-jP}e^{j\left(\frac{N-1}{2}\right)\psi} \tag{2.11}$$

As the array is assumed to be symmetric, so –P = +P = P. So on adding the terms the equation (2.11) becomes equation (2.12).

$$AF_E(\theta)|_m = 2\cos\left[\left(\frac{N-1}{2}\right)\psi - P\right] \tag{2.12}$$

Consequently, modified array factor along is given by equation (2.13).

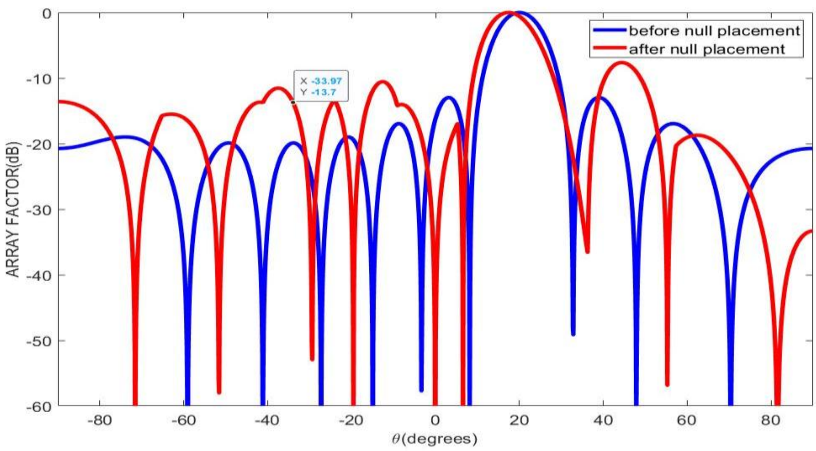
$$AF(\theta)|_m = AF_R(\theta) + AF_E(\theta)|_m \tag{2.13}$$

Now θ_n be the desired single null position in which total array factor $AF(\theta)|_m$ is considered as zero to achieve the desired result, which provides the final expression for array factor in equation (2.14). Then by substituting $\theta = \theta_n$ in equation (2.14) and solving, the required value of P is obtained in equation (2.15) where $\psi_n = kd\,(\sin\theta_n - \sin\theta_s)$.

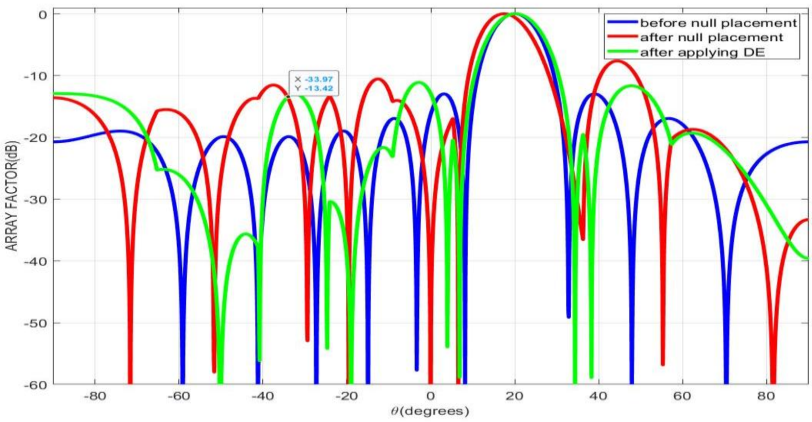
$$AF(\theta)|_m = \left[\frac{\sin\left(\frac{(N-2)}{2}\psi\right)}{\sin\left(\frac{\psi}{2}\right)}\right] + 2\cos\left[\left(\frac{N-1}{2}\right)\psi - P\right] \tag{2.14}$$

$$P = -\frac{\pi}{2} + \frac{(N-1)\psi_n}{2} + \sin^{-1}\left(-\frac{\sin\left(\frac{(N-2)}{2}\psi_n\right)}{2\sin\left(\frac{\psi_n}{2}\right)}\right) \tag{2.15}$$

But this method has a drawback which is illustrated with an example in Figure 2.2 (a), (b). All the array factor plots have been simulated for 10 elements array, with 0.5λ inter element spacing beam steered at 20° and the null has to be placed at -34°. It must be noted that as isotropic elements are considered in the present investigation, the array factor plot itself represents the radiation pattern of the array.



(a)

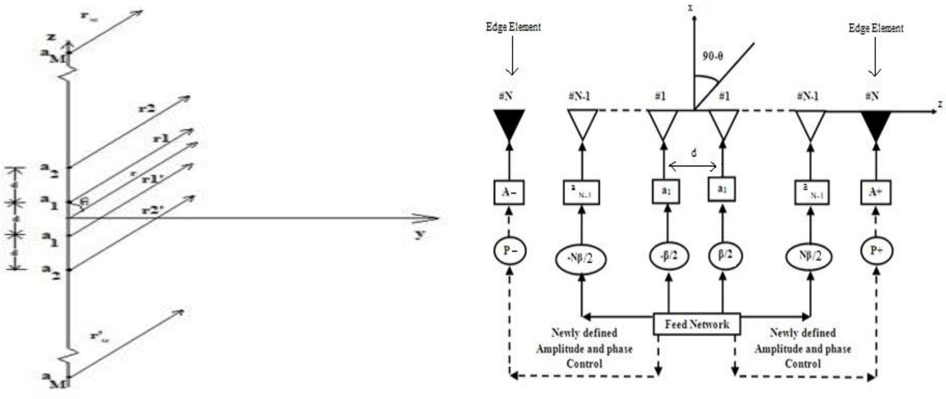


(b)

Figure 2.2 Conventional Uniform Linear Array Factor Null Placement at -34° (a) Analytical, (b) Using DE

It is observed from Figure 2.2 that no null is placed exactly at -34° and it has shifted towards -30°. Neither it could be placed analytically nor it could be rectified by applying DE. The reason behind this observation is that there are too many assumptions taken in this method such as the actual antenna array center is not at the origin, but during the mathematical calculations the physical center of the array is taken as the reference point for which the phasor part of the equation gets cancelled. So the algorithm cannot find the value of phase at certain points and hence it could not place the null properly resulting in the shift. This led the proposed method towards the second approach.

Second Approach: Array Symmetric Method



(a) **(b)**

Figure 2.3 Non-Uniform Symmetric Linear Array (a) Geometry, (b) Schematic diagram of edge element control

Generally, all the array elements in a non-uniform linear array have different excitation amplitudes. But in this proposed approach, all the excitation amplitude (a_n) values are set as 1, which makes the non-uniform linear array work as a uniform linear array. Since in this method already the antenna array is placed symmetrically along the z-axis so the actual center of the array already lies at the origin. So no assumption is required in this approach. Figure 2.3(a) shows the geometry of linear symmetric array. The array factor of linear array of 2N isotropic element is given by equation (2.16), where $k = 2\pi/\lambda$ is the wave number, a_n is the excitation amplitude of nth element, d is the inter-element spacing.

$$\mathrm{AF}(\theta) = 2\sum_{n=1}^{N} \cos\left[\left(\frac{2n-1}{2}\right) kd(\cos\theta)\right] \tag{2.16}$$

Figure 2.3(b) shows the schematic diagram of edge element control in non-uniform linear array. So, the array factor expression for 2N numbered beam steered uniformly excited linear array is given by equation (2.17).

$$\mathrm{AF}(\theta) = 2\sum_{n=1}^{N} \cos\left[\left(\frac{2n-1}{2}\right) \psi\right] \tag{2.17}$$

Here, $\psi = kd(\sin\theta - \sin\theta_s)$, where θ_s represents the steered main beam position. Further, d is the uniform inter element spacing, $k=2\pi/\lambda$ is the wave number and θ is the elevation angle whose value lies within $-\pi/2$ to $+\pi/2$. Moreover, edge element contribution can be generalized as given in equation (2.18).

$$\mathrm{AF}(\theta) = \mathrm{AF}(\theta)|_{\mathrm{Rest}} + \mathrm{AF}(\theta)|_{\mathrm{Edge}} \tag{2.18}$$

In equation (2.18), $\mathrm{AF}(\theta)|_{\mathrm{Rest}}$ and $\mathrm{AF}(\theta)|_{\mathrm{Edge}}$ has been given in equation (2.19) and (2.20) respectively.

$$\mathrm{AF}(\theta)|_{\mathrm{Rest}} = 2\sum_{n=1}^{N-1} \cos\left[\left(\frac{2n-1}{2}\right) \psi\right] \tag{2.19}$$

$$AF(\theta)|_{Edge} = 2\cos\left[\left(\frac{2N-1}{2}\right)\psi\right] \tag{2.20}$$

So, the edge elements for the linear array are directly fed with additional excitation phase -P and +P to the left and right edge element respectively. Consequently, modified array factor ($AF(\theta)|_{Edge\_m}$) for 2N numbered linear array is given by equation (2.21).

$$AF(\theta)|_{Edge\_m} = e^{-j(-P)}e^{-j\left(\frac{2N-1}{2}\right)\psi} + e^{-jP}e^{j\left(\frac{2N-1}{2}\right)\psi} \tag{2.21}$$

As the array is symmetric so by substituting P+ = P- = P in equation (2.21) the modified array factor is given by equation (2.22).

$$AF(\theta)|_{Edge\_m} = 2\cos\left[\left(\frac{2N-1}{2}\right)\psi - P\right] \tag{2.22}$$

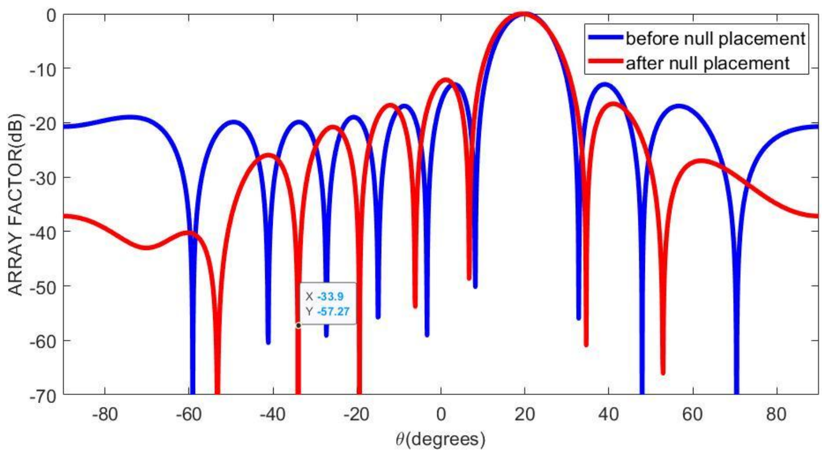
Accordingly, the modified array factor of the complete array is given by equation (2.23).

$$AF(\theta)|_{modified} = 2\sum_{n=1}^{N-1}\cos\left[\left(\frac{2n-1}{2}\right)\psi\right] + 2\cos\left[\left(\frac{2N-1}{2}\right)\psi - P\right] \tag{2.23}$$

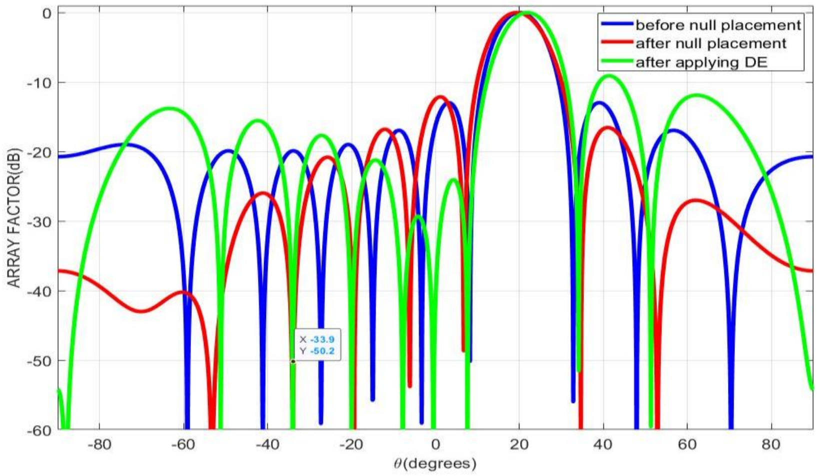
Now θ_n be the desired single null position in which total array factor $AF(\theta)|_{modified}$ is considered as zero to achieve the desired result. So, by substituting $\theta = \theta_n$ in equation (2.23) and solving, the required value of P is obtained in equation (2.24) where $\psi_n = kd(\sin\theta_n - \sin\theta_s)$.

$$P = -\frac{\pi}{2} + \frac{(2N-1)\psi_n}{2} - \sin^{-1}\left(\sum_{n=1}^{N-1}\cos\left[\left(\frac{2n-1}{2}\right)\psi_n\right]\right) \tag{2.24}$$

Hence, the effectiveness of the proposed method has been illustrated in Figure 2.4 (a), (b) through design instances of a 10 elements linear array with main beam position at 20°. Single null placement at -34° has been considered. The inter element spacing has been kept at 0.5λ.



(a)



(b)

Figure 2.4 Uniform Symmetric Linear Array Factor Null Placement at -34° (a) Analytical, (b) Using DE

From Figure 2.4 it is observed that null can be exactly placed where it is required which in this case is -34°, both analytically and by applying DE. The convergence curve in Figure 2.5 also shows that this is the best fit value.

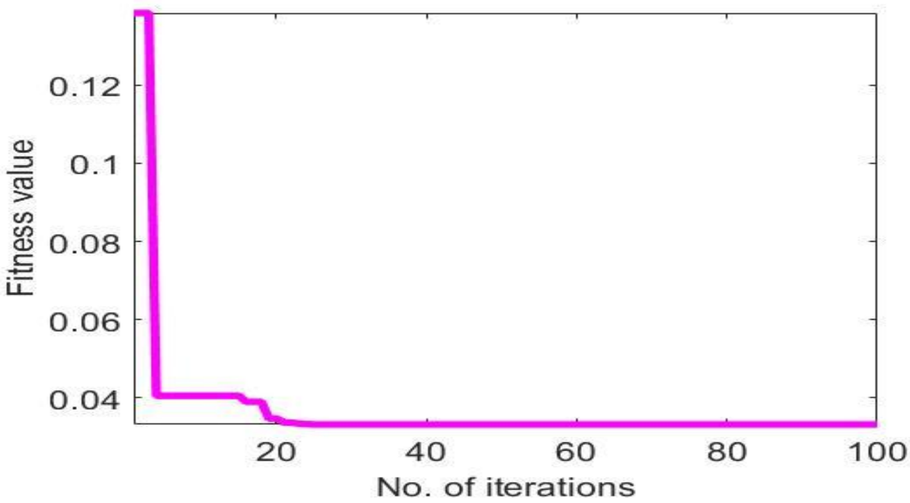


Figure 2.5 Convergence curve of Uniform Symmetric Linear Array Factor with Null at -34°

Multiple null placement can also be achieved by this proposed method of symmetric array. Such an example has been illustrated in Figure 2.6 through design instances of a 10 elements linear array with main beam position at 20°. One null placed at -34° while the other at -9°. The inter element spacing has been kept at 0.5λ.

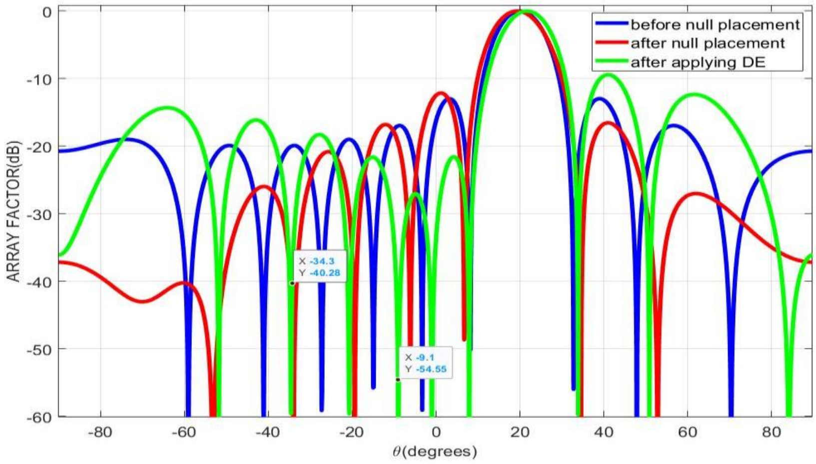


Figure 2.6 Uniform Symmetric Linear Array Factor with Null placed at -34° and -9°

The convergence curve in Figure 2.7 also shows that this is the best fit value. While Table 2.1 shows the comparative study of parametric effect, before and after the application of DE and for both single as well as multiple null.

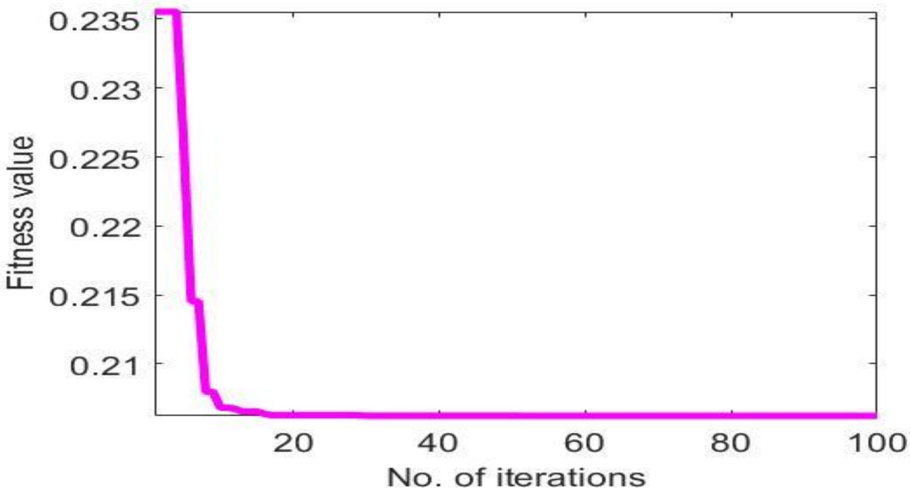


Figure 2.7 Convergence curve of Uniform Symmetric Linear Array Factor with Null at -34° and -9°

Table 2.1 Parametric effect on radiation characteristics before and after applying DE

	HPBW (in degrees)	**FNBW (in degrees)**	**Directivity (in dB)**	**Optimized phase (in terms of wavelength)**
Before Null Placement	**10.8**	**24.5**	**10**	**-**
After Analytical Null Placement	**11.9**	**27.6**	**9.7199**	**13.0323**
After applying DE for Single Null	**11.1**	**26.2**	**9.7212**	**0.8971**
After applying DE for Multiple Null	**11.1**	**25.7**	**9.7198**	**0.7935**

CONCLUSION

This article demonstrates the method of phase control of edge elements through array symmetric approach for null placement analytically. The effectiveness of the design has been illustrated using an example of 10 elements array. Further performance improvement of the method has been carried out using classical DE algorithm. Thus from the results obtained it can be observed that the proposed method can perfectly place null, both single as well as multiple as well as it can improve the radiation parameters values which deteriorated due to analytical null placement. And last but not the least, this proposed method can perfectly optimize the value of excitation phase. Hence, it can be concluded that the proposed method is fit for single and multiple null placement and has the ability to handle multiple objectives. So, it can be used to design linear antenna arrays for any number of array elements.

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Biographies

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Sayan Chatterjee was born in Kolkata, India, in 1980. He received BE degree (gold medal) in 2003 and received ME degree in 2005. He has completed his Ph.D. degree in 2015 from Jadavpur University. He has worked in SAMEER, India, as a Scientist and was involved in the design of various strategic microwave subsystem and systems from 2005 to 2009. He was deputed to California Institute of Technology, Northridge in 2007 as visiting scholar. Presently he is an Associate Professor in the Department of ETCE at Jadavpur University, Kolkata. He has received AICTE Carrier award for young teacher in 2015. He is a senior member of IEEE since 2008 and was served as treasurer and secretary of the IEEE Kolkata section from 2014 to 2017. His research interest includes microwave and millimeter wave antennas, passive devices, SIW based subsystem and the design of wide band slotted array antennas, device modeling.