



New method for pattern synthesis of an unequally spaced array with dynamic range ratio improvement

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Abstract

The amplitude-phase synthesis of an unequally spaced array is discussed in this study along with a new method that improves the Amplitude Dynamic Range (ADR) ratio with fewer elements. In this method, the Hankel matrix is established using the sampling points of a prescribed array factor. The array elements' locations are estimated using the eigenvalues of the Hankel matrix. The magnitude of the array currents is then calculated using the Least Squares Method (LSM). By defining the reduction parameter, the ADR can be significantly reduced. Some theoretical and practical arrays are given to verify the performance of the proposed method. The obtained results are compared to those obtained by other methods and simulation data.

1. Introduction

Nowadays, antenna arrays have been widely employed for different targets, including electronic tracking, satellite communication systems, interference suppression, 5G cellular networks, directivity increase, and spatial multiplexing [1-4]. Typically, the assessment of the excitations that better satisfy the pattern synthesis requirements is an important challenge in array design problems [5-8]. To this end, several approaches have been introduced, considering the shape of the array, the character of the desired pattern, and the degrees of freedom that characterize the array excitations [9-11].

Synthesis of the radiation pattern of an array is done by changing both the amplitude and phase of the array elements. In array engineering, this problem is called amplitude-phase synthesis [12]. Nevertheless, in some applications like reflect-array antennas having either pencil or contoured beams, only the phase of the unit cells is the controllable parameter in the design procedure [13,14]. The magnitude of unit cells is predetermined by the other parameter in these applications. Additionally, changing the phase of the array elements is more practical and useful than changing their

magnitudes. This procedure for pattern synthesis of an array is called phase-only synthesis.

Most of the introduced methods for radiation pattern synthesis cannot control the Amplitude Dynamic Range (ADR). In [15], a null steering approach was introduced by changing only the excitation phases of a part of the array of elements. In this work, the required phase excitations are employed in the objective function. Then, by using the quasi-Newton method, the Mean Square Error (MSE) between the desired and synthesized pattern is minimized. In [16], it is tried to obtain the required array patterns with controlled nulls.

In [17], a new technique is introduced to determine the array weights with minimum ADR ratio. The array designed using this method can generate a pencil beam pattern with zero phases. Also, using it, the phases of the excitation coefficients can be continuously controlled. In [18], the autocorrelation matching technique is introduced to synthesize the power pattern of an equally-spaced array. In [19], a teaching-learning-based method is proposed for the synthesis of reconfigurable uniformly excited linear arrays.

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In this work, the modified quantum particle swarm optimization and symbiotic organisms search algorithms are employed in the synthesis procedure.

This article presents a new method for determining the amplitude and phase of the excitation coefficients of an unequally spaced array. In this work, it is tried to design a non-uniform array with a minimum ADR ratio. By establishing the Hankel matrix and calculating its eigenvalues, the location of the array elements is determined. The amplitude of excitation currents is calculated using the Least Squares Method (LSM). Then, by defining the reduction parameter, the ADR is reduced. Several practical arrays, including the sum and difference pattern, are investigated to confirm the effectiveness of the presented method.

2. Mathematical formulation

Consider a linear, unequally-spaced array oriented along the z -axis direction composed of N elements. Let I_n , d_n , and k be the weight and location of the n th element and the wavenumber defined by $2\pi/\lambda$ (λ is wavelength), respectively. By defining $u=\cos\theta$, where θ is the elevation angle, the array factor $F(u)$ can be described as follows:

$$F = \sum_{n=1}^N I_n \exp(jkd_n u). \quad (1)$$

Assuming L is the array length, the prescribed array factor can be reconstructed using $2M+1$ samples with the uniform sampling step $\Delta \approx 1/(2L)$ over the interval $-1 \leq u \leq 1$ [20].

$$u_m = m\Delta = m/2L, \quad m = -M, \dots, 0, \dots, M. \quad (2)$$

The samples of the prescribed pattern can be expressed in vector form $\mathbf{V} = [F(m/2L)]_{1 \times (2M+1)}$; $m = -M, \dots, 0, \dots, M$. Two sample matrices $\mathbf{G}$ and $\mathbf{L}$ can be established using vector $\mathbf{V}$ as follows [20]:

$$\mathbf{G} = \begin{bmatrix} V_2 & V_3 & \cdots & V_{M+1} \\ V_3 & V_4 & \cdots & V_{M+2} \\ \vdots & \vdots & \ddots & \vdots \\ V_{M+2} & V_{M+3} & \cdots & V_{2M+1} \end{bmatrix}_{(M+1) \times M} \quad (3)$$

$$\mathbf{L} = \begin{bmatrix} V_1 & V_2 & \cdots & V_M \\ V_2 & V_3 & \cdots & V_{M+1} \\ \vdots & \vdots & \ddots & \vdots \\ V_{M+1} & V_{M+2} & \cdots & V_{2M} \end{bmatrix}_{(M+1) \times M} \quad (4)$$

Combining these matrices gives the Hankel matrix $\mathbf{H}$ using the following equation [9]:

$$\mathbf{H} = (\mathbf{G}^T \mathbf{L})^{-1} \mathbf{L}^T \mathbf{G}. \quad (5)$$

To save the number of elements, the Singular Value Decomposition (SVD) of the Hankel matrix $\mathbf{H}$ can be carried out as follows:

$$\mathbf{H} = \mathbf{U} \mathbf{S} \mathbf{W}^T, \quad (6)$$

in which $\mathbf{U}$ and $\mathbf{W}$ are the unitary matrices, and $\mathbf{S}$ is a diagonal matrix, including the singular values of $\mathbf{H}$. The number of principal singular values of $\mathbf{H}$ equals the number of array elements. For many practical arrays, the number of non-zero singular values is less than the number of array elements. So, by regarding the Q principal singular values,

which correspond to a new array with fewer elements, a low-rank approximation of $\mathbf{H}$ is achieved as follows [20]:

$$\mathbf{H}_Q = \mathbf{U}_Q \mathbf{S}_Q \mathbf{W}^T, \quad (7)$$

where $\mathbf{H}_Q$ is the low-rank version of $\mathbf{H}$. It is worthy to note that there is not a clear relationship between the primary number of array elements N and the reduced number of array elements Q . For each case study, after specifying the singular values of matrix $\mathbf{H}$, only non-principal or non-zero singular values remain, and the other ones are withdrawn. In [21], the fractional Fourier series of the prescribed pattern (F_r) can be expressed using the distinct eigenvalues ζ_n of the low-rank matrix $\mathbf{H}_Q$, in which c_n s are constant coefficients.

$$F_r = \sum_{n=1}^Q c_n \exp(\zeta_n u). \quad (8)$$

By comparing Eqs. (1) and (8), it is found that the locations of the elements of the new array (d_n) can be calculated using the phase of normalized eigenvalues ζ_n as follows:

$$\begin{cases} d_n = L\alpha_n/\pi \\ \alpha_n = \angle(\zeta_n/|\zeta_n|) \end{cases} \quad -\pi \leq \alpha_n \leq \pi \quad (9)$$

where L and α_n are the array length and the phase of normalized eigenvalues (in radians), respectively. After determining the array element's locations d_n , the weight of the elements I_n can be determined using the LSM. To this end, the following system of equations is established:

$$\mathbf{A}\mathbf{X} = \mathbf{B} \rightarrow \mathbf{X} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{B}, \quad (10)$$

$$\mathbf{A} = \begin{bmatrix} e^{jkd_1 u_1} & e^{jkd_2 u_1} & \cdots & e^{jkd_Q u_1} \\ e^{jkd_1 u_2} & e^{jkd_2 u_2} & \cdots & e^{jkd_Q u_2} \\ \vdots & \vdots & \ddots & \vdots \\ e^{jkd_1 u_P} & e^{jkd_2 u_P} & \cdots & e^{jkd_Q u_P} \end{bmatrix}, \quad (11)$$

$$\mathbf{X} = [I_1 \quad I_2 \quad \cdots \quad I_Q]^T, \quad (12)$$

$$\mathbf{B} = [F(u_1) \quad F(u_2) \quad \cdots \quad F(u_P)]^T, \quad (13)$$

in which $P \approx 5L/\lambda$ is the total number of samples and is determined using the Nyquist theorem [5]. The second purpose of this paper is to reduce the ADR defined by:

$$ADR = \frac{\max(|I_n|)}{\min(|I_n|)}, \quad n = 1, \dots, Q. \quad (14)$$

To this end, the absolute values of weights I_n s are modified to the new real weights w_n s so that the ADR of the new array is less than that of the primary array. The value of the weights is determined using the following equation:

$$w_n = \eta [|I_n| - \min(|I_n|)], \quad n = 1, \dots, Q, \quad (15)$$

in which $0 < \eta < 1$ is the parameter that is used to reduce the ADR. In this case, the array factor is rewritten as follows:

$$F = \sum_{n=1}^Q w_n \exp(j\varphi_n) \exp(jkd_n u), \quad (16)$$

in which φ_n is the phase of the n th excitation coefficient. By defining $k d_n u = \psi_n$, $\cos(\varphi_n - \psi_n) = C_n$ and $\sin(\varphi_n - \psi_n) = S_n$ the array factor is rewritten as:

$$F = \sum_{n=1}^Q (w_n C_n + j w_n S_n). \quad (17)$$

The radiated power of the array can be calculated as follows:

$$|F|^2 = \left| \sum_{n=1}^Q (w_n C_n + j w_n S_n) \right|^2 = (w_1 C_1 + \dots + w_N C_N)^2 + (w_1 S_1 + \dots + w_N S_N)^2. \quad (18)$$

After some algebraic manipulations, the array factor is reduced as:

$$|F|^2 = \sum_{n=1}^Q w_n^2 [C_n^2 + S_n^2] + 2 \sum_{n=1}^{Q-1} w_n \sum_{m=n+1}^Q w_m [C_n C_m + S_n S_m]. \quad (19)$$

Since $S_n^2 + C_n^2 = 1$, Eq. (19) is simplified to the following equation:

$$|F|^2 = \sum_{n=1}^Q w_n^2 + 2 \sum_{n=1}^{Q-1} w_n \sum_{m=n+1}^Q w_m [C_n C_m + S_n S_m]. \quad (20)$$

Substituting Eq. (21) into Eq. (20) leads to Eq. (22) as follows:

$$\begin{aligned} C_n C_m + S_n S_m &= \cos(\varphi_n - \psi_n) \cos(\varphi_m - \psi_m) \\ &+ \sin(\varphi_n - \psi_n) \sin(\varphi_m - \psi_m) = \\ &\cos[\varphi_n - \varphi_m + (\psi_n - \psi_m)], \end{aligned} \quad (21)$$

$$|F|^2 = \sum_{n=1}^Q w_n^2 + 2 \sum_{n=1}^{Q-1} \sum_{m=n+1}^Q w_n w_m \cos[\varphi_n - \varphi_m + (\psi_n - \psi_m)]. \quad (22)$$

It should be noted that in the above equations, φ_n s are the only unknowns. The target is to minimize the following expression:

$$\min_{\varphi_n} \|\mathbf{F} - \mathbf{F}_d\|_2, \quad (23)$$

in which $\mathbf{F}_d$ is the vector that includes the samples of the desired pattern and $\|\cdot\|_2$ is the norm-2 operator. The problem's solution is not easily determined. To this end, the introduced technique in [19] is employed. In each iteration, Eq. (23) is used to compute the MSE.

3. Results and discussion

In this section, several arrays are studied, and the results are compared to validate the performance of the proposed method.

3.1. Sum pattern

In the first example, amplitude-phase synthesis of an equiripple pattern with $SLL = -25$ dB and array length $L = 10\lambda$ is considered. Figure 1 shows the obtained results using the proposed and the conventional Dolph-Tschebyscheff method [22]. Although a small deviation of about 2.5 dB is seen in the first two side lobes, the accuracy of the obtained results in other regions is good. Also, the magnitude and phase of the obtained currents for both methods are plotted in Figure 2. The proposed method not only reduces the number of elements in the designed array when compared to the conventional method, but it also reduces the ADR of the designed array about 21% when compared to the Dolph-Tschebyscheff technique. It is worthy of mentioning that the phases of I_n s in the Dolph-Tschebyscheff method are zero.

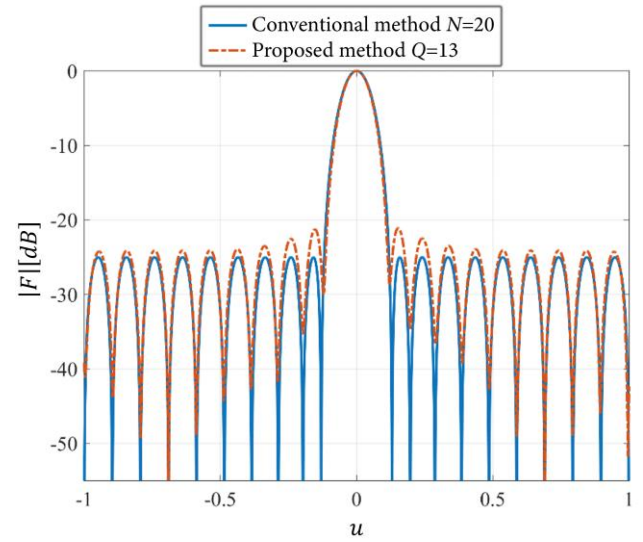


Figure 1. The synthesis results of the sum pattern with $SLL=25$ dB and $ADR=2.12$.

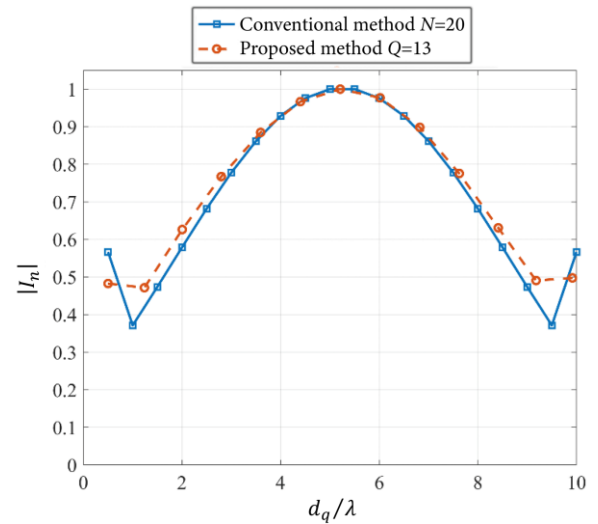


Figure 2. Magnitude of the sum pattern with $SLL=25$ dB and $ADR=2.12$.

3.2. Difference pattern

In the second example, amplitude-phase synthesis of a difference pattern with the first side lobe about -25 dB, and array length $L = 12\lambda$ is considered. Figures 3 and 4 show the obtained results and the amplitude and phase of the array currents using the proposed and the conventional Bayliss method [22]. It is seen that the designed array using the proposed method has eight fewer elements than the Bayliss array, and the desired and synthesized pattern are matched very well. The ADR of the proposed array is about 55% lower than that of the Bayliss array.

3.3. Flat-top pattern

In the third example, amplitude-phase synthesis of a flat-top pattern with non-zero values over the interval $|u| \leq 0.35$ and array length $L = 13\lambda$ is considered. The desired pattern and synthesized pattern using the proposed and Fourier methods [22] are plotted in Figure 5. It is seen that the accuracy of the proposed method with $Q=19$ is better than the Fourier method with $N=26$. The amplitude and phase of the obtained currents for both methods are depicted in Figures 6 and 7,

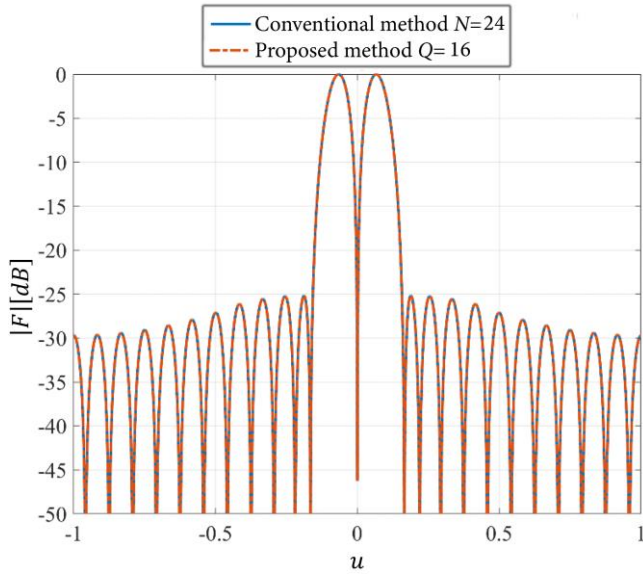


Figure 3. The synthesis results of the difference pattern with $ADR=3.13$.

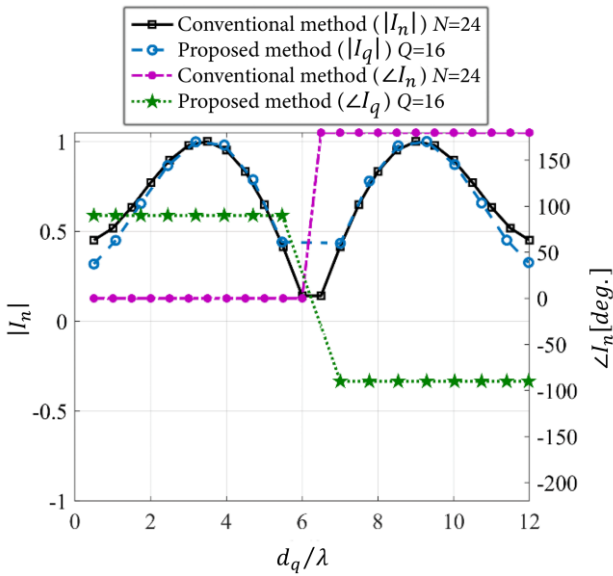


Figure 4. Magnitude and phase of the currents of the difference pattern with $ADR=3.13$.

respectively. The results show that the ADR of the designed array is about 78% less than that of the Fourier method.

Table 1 shows some of the main parameters of the obtained results, such as the total number of array elements Q , ADR , reduction percent of dynamic range η_0 , MSE , and the required running time (t). The proposed method is implemented in MATLAB, and it is run using a computer with CPU core i7 & 16G RAM. It can be seen that the proposed method can be used to design an unequally-spaced array with the minimum number of elements, minimum dynamic range, and lower MSE .

4. Practical array example

To assess the performance of the proposed method in real applications, the previously designed array with an equiripple array factor is simulated using the full-wave simulator, HFSS software. The simulated array is made of a half-wavelength dipole antenna, arranged along the x -axis.

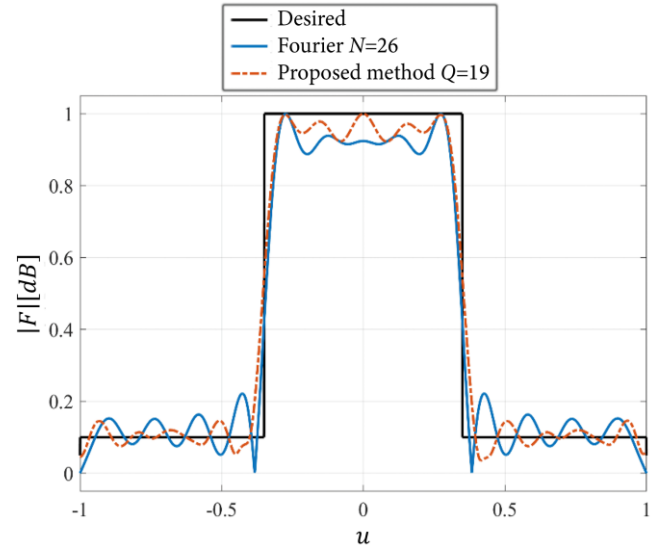


Figure 5. The synthesis results of the flat-top pattern with $ADR=41.16$.

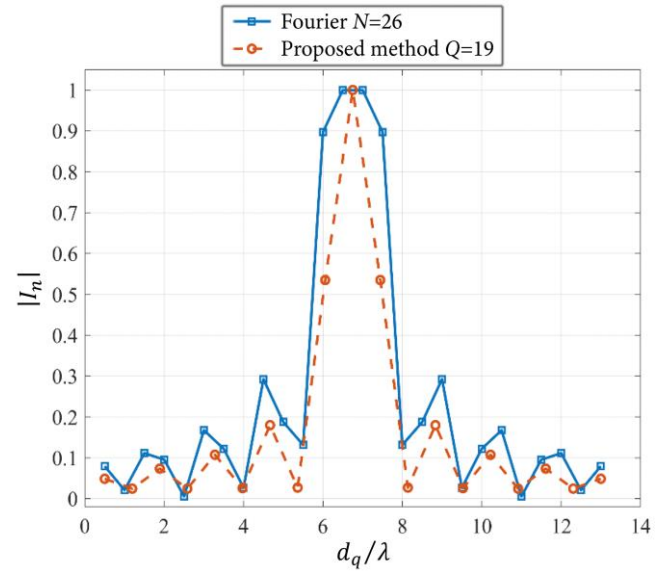


Figure 6. Magnitude of the currents of the flat-top pattern with $ADR=41.16$.

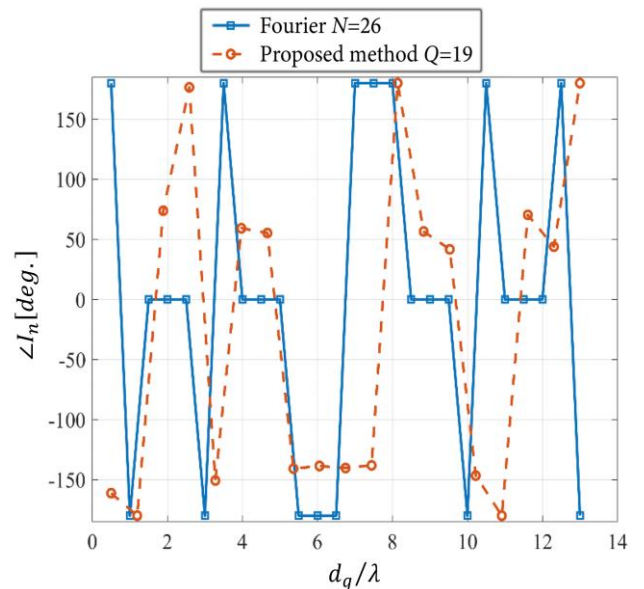


Figure 7. Phase of the currents of flat-top pattern with $ADR=41.16$.

Table 1. Comparison of the obtained results.

			<i>ADR</i>	η_0 (%)	<i>MSE</i>	<i>t</i> (s)
Example I	Proposed method	$Q=13$	2.12	21	1.8e-4	10.27
	Dolph-Tschebyscheff	$N=20$	2.69			
Example II	Proposed method	$Q=16$	3.13	55	≈ 0	10.24
	Bayliss method	$N=24$	7.04			
Example III	Proposed method	$Q=19$	41.16	78	6.9e-3	10.62
	Fourier method	$N=26$	187.6			

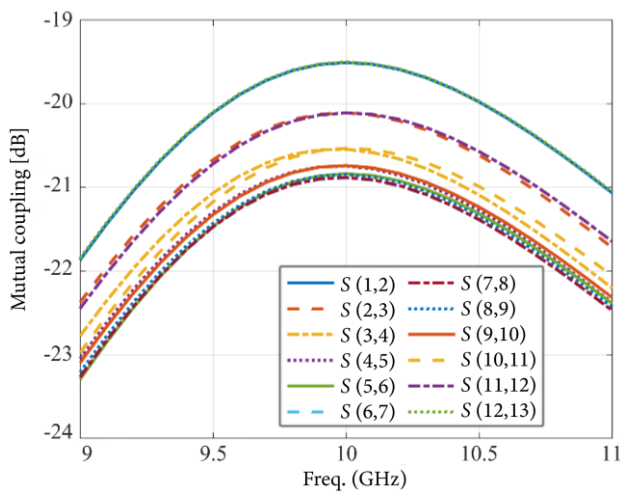
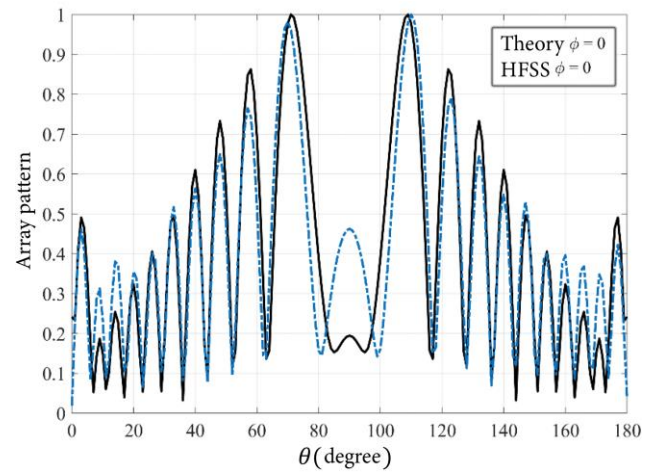
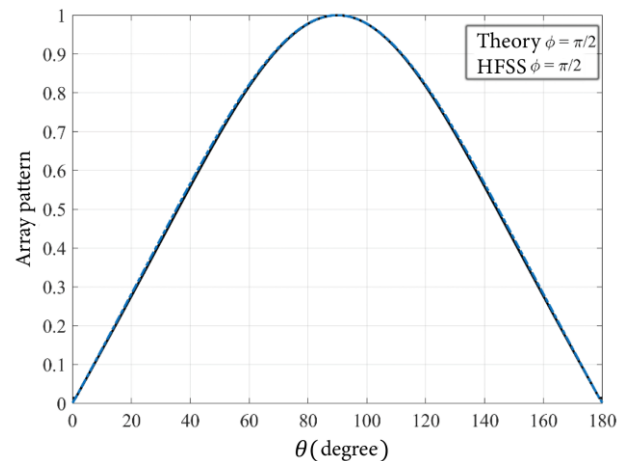
**Figure 8.** The simulation results of the mutual coupling in the implemented dipole array in HFSS.

Figure 8 shows the simulation results of the mutual coupling between two adjacent elements. It is seen that the minimum and maximum coupling between the elements are about -20.9 dB and -19.4 dB, respectively.

The total radiation pattern of the implemented dipole array with $Q=13$ elements at standard planes of $\phi=0$ and $\phi=\pi/2$ is depicted in Figures 9 and 10, respectively. The total radiation pattern includes both element and array factors. For an array oriented along the x -axis, the value of the array factor at $\phi=\pi/2$ is constant. So, the total radiation pattern in this plane is approximately the same as the element pattern.

In Figure 9, a deviation is seen in the broadside direction and over a small range of elevation angles. This is because we only focused on optimizing the array factor in the theory section. Thus, the proposed array model has not considered mutual coupling between elements that causes a significant difference in the element radiation patterns. Hence, in real radiation problems, the mutual coupling reduces the accuracy of the proposed method. However, the proposed method can be used for the primary design of a practical array with acceptable accuracy. It is clear that for the real array, an optimization process should be applied using the full-wave simulator.

**Figure 9.** The total radiation pattern of the implemented dipole array in HFSS at $\phi=0$.**Figure 10.** The total radiation pattern of the implemented dipole array in HFSS at $\phi=\pi/2$.

5. Conclusion

A new approach was proposed for amplitude and phase synthesis of the radiation pattern of an unequally-spaced antenna array. The main purpose of this work is to improve the Amplitude Dynamic Range (ADR) ratio with a reduced

number of elements. In this paper, using the sample points of the desired pattern and establishing the Hankel matrix, first, the location of the array elements is evaluated, and then, by the Least Squares Method (LSM), the excitation currents are determined. By defining the reduction parameter, the ADR is reduced, and the phase of the array weights is calculated. Some practical arrays are studied to verify the performance of the proposed method.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

First author: Data curation; Formal analysis; Software; Conceptualization; Investigation; Methodology; Validation; Visualization; Writing - original draft.

Second author: Conceptualization; Formal analysis; Writing - review and editing.

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Biographies

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