Characterization of 4 Element Compact Microstrip Patch Antenna Array for Efficient Null Steering

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Abstract **─** Null steering in radiation pattern of linear antenna array is essential for minimizing degradation in signal-to-noise ratio performance due to undesired interference. High directivity and miniaturization are other key factors for proficient design of antenna arrays. Thus, the development of small sized antenna elements with high directivity is strategic point of interest. Consequently, the four element bowtie patch antenna array has been designed and simulated using IE3D software, and compared with conventional rectangular patch antenna array. Null steering is performed by varying element excitations in isotropic antenna array, rectangular patch antenna array and bowtie patch antenna array with main emphasis on position and depth of nulls to analyze the radiation characteristics of the designed models. The mutual coupling effects at different inter-element spacings are also presented for both the designed arrays. It has been observed that using bowtie patches as the element in the array brings about comparatively more effective null steering, and enhances the performance of the array as compared to the conventional rectangular patches.

Index Terms **─** Antenna array, isotropic elements, mutual coupling, non-isotropic elements, null steering, Schelkunoff polynomial method.

I. INTRODUCTION

The demand for extended functionalities provided by wireless communications has risen beyond all expectations over the last decade. With the growing demand for wireless communications, the need for better coverage, improved capacity and higher transmission has risen. In wireless communication systems, null steering is of great significance for rejecting unwanted interference while receiving the desired signal. Null steering in antenna radiation pattern finds its applications in radar, sonar and many communication systems for minimizing degradation in signal-to-noise ratio performance due to undesired interference [1]. Further, the electromagnetic interferences between radiating elements in an antenna array, is expressed by the modification of the surface currents distribution. This phenomenon, called mutual coupling, depends on the antenna type and the distance between its elements. The coupling between the elements of antenna array has a great importance in the design of antenna arrays, because it may cause a change in the radiation pattern.

Methods of null steering in antenna arrays including controlling the amplitude-only, phase only, position only and complex amplitude, i.e., amplitude and phase both have been extensively used for isotropic antenna arrays. Null steering by controlling the complex weights involves larger degree of freedom, which makes it the most effective but also most costly method because of the controllers used for phase shifters and variable attenuators for each array element [2]. Moreover, the computational time to find the values of element amplitudes and phases also increases with the increase in number of elements in the array [3]. The phase-only and position-only nulling methods are inherently non-linear and, thus cannot be solved by analytical methods without any approximation. The nulling equations for phase only control can be linearized by assuming that the phase perturbations are small, but it cannot be used to place nulls at symmetric location with respect to the main beam. Methods based on non-linear optimization techniques [4] have been proposed for steering the nulls symmetrically with respect to the main beam, but the resultant patterns of these methods have significant pattern distortion because of large phase perturbations used. Moreover, null steering with small phase perturbations results in increased side lobe level (SLL) in the direction symmetric to nulling direction with respect to the main beam [5]. The nulls can be steered in symmetrical directions with respect to the main beam by element position control method using a mechanical driving system such as servomotors [6]. Null steering with amplitude-only control, make use of a set of variable attenuators to adjust the element amplitudes. The number of attenuators and the computational time are halved, if the element amplitudes have even symmetry about the centre of the array [7].

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There has been a lot of research work being carried out on null steering of antenna array of isotropic elements using various optimization techniques such as Genetic Algorithm (GA), Simulated Annealing (SA), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), Tabu Search Optimization, Bacterial Foraging Algorithm, Backtracking Search Optimization Algorithm [2, 8-12] and many more. All these methods have their own advantages and drawbacks, but have been less explored for null steering of arrays of non-isotropic elements. Choudhari et al. have used Schelkunoff polynomial method (SPM) for phase controlled null steering of microstrip patch antenna array and found it to be an effective analytic approach to synthesize the null controlled patterns [13]. Dwivedi and Banerjee have applied SPM in combination with PSO for null steering of array of isotropic elements [14]. Much of the work on null steering has been implemented for isotropic antenna arrays. However, there has been relatively little effort in analyzing the use of non-isotropic antenna elements in the array design. An antenna element to be used in array environments should have small size and broad patterns. The scanning performance of an array is generally determined by the element spacing which, in turn, is limited by the element size, hence, the physical size of the element is an important consideration in the design of an array. The better approach to address these issues is to explore the design and analysis of antenna array of non-isotropic antenna elements.

In this paper, a performance comparison of null steering of isotropic antenna array and non-isotropic linear antenna arrays consisting of rectangular and bowtie patches is presented. The nulls are imposed in the direction of interference by using Schelkunoff polynomial method for controlling the excitation amplitudes of array elements instead of phase and position control due to their limitations as discussed above. Hence, a Matlab code has been generated to derive the excitation amplitudes for isotropic and non-isotropic elements and the data is then utilized in the design of 4-element isotropic and non-isotropic microstrip patch antenna array for demonstrating the null steering of the designed antenna arrays.

II. DESIGN SPECIFICATIONS OF ARRAY AND COPLANAR WAVEGUIDE FEED SECTION

Antenna array size reduction has attracted increasing interest in wireless communication so as to reduce the total size of devices. One way to reduce the total size of an array antenna is to place elements of an antenna array close to each other. But the factor called mutual coupling that effects the radiation pattern, depends on inter element spacing and causes undesirable effects on antenna characteristics [15]. Therefore, the selection of appropriate design parameters is prerequisite for performance evaluation of the designed models. The process of antenna array design involves the selection of elements and geometry of array, and the determination of the excitations of array elements required for achieving desired radiation characteristics with prescribed location of the major lobe and nulls, SLL, and beamwidth [16].

As reported in literature the antenna pattern synthesis can be classified into several categories. One of these groups requires antenna patterns with narrow beams and low side lobes. This guarantees the radiating or receiving energy to be more focused in specific directions. Various techniques such as the binomial method, Dolph–Chebyshev method, and Taylor line-source are proposed to serve this purpose.

Another group requires that the antenna patterns exhibit a desired distribution in the entire visible region, which is also referred to as beam shaping. A typical example is the design of a sector beam pattern, which allows the antenna array to have a wider angular coverage. This is usually accomplished by using the Fourier transform technique and the Woodward–Lawson method.

A third group usually requires that the antenna patterns possess nulls in desired directions. This property is widely used in smart antenna systems to eliminate the interference from specific noise directions. The Schelkunoff polynomial method is an effective approach to synthesize the null controlled patterns.

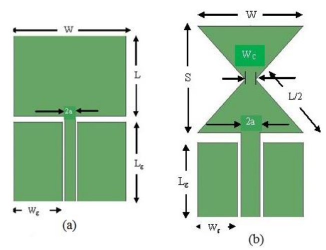
Although existing designs offer excellent performance, many other considerations such as miniaturization of antennas and increased directivity have become important due to the increasing demand for small antennas as a result of the rapid development in wireless communications. The bowtie antenna originally proposed by Lodge demonstrates these benefits [17].

Considering the performed investigation in wideband antenna categories, two antenna geometry types: rectangular and bowtie patch antennas have been selected for present study. Both the rectangular patch antenna and bowtie patch antenna shown in Fig. 1 (i) have been designed to operate at resonant frequency of 4.9 GHz. The substrate material that is used is FR4 with dielectric constant 4.4, thickness of 1.6 mm and loss tangent 0.02. The essential parameters for the design of the two antennas, calculated using analytical equations given in [18] and [19] are presented in Table 1.

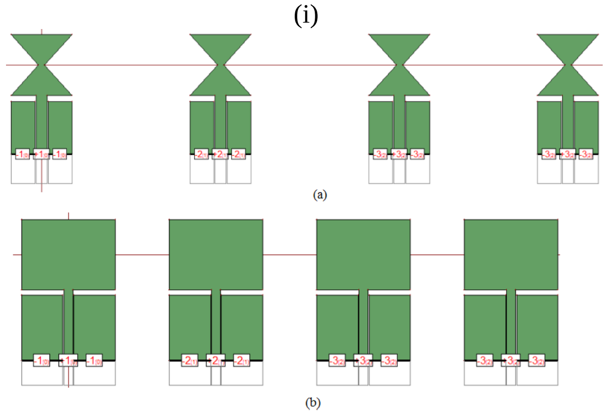
The coplanar waveguide antenna feeding operates well in wideband frequency to field matching and impedance transforming and they can also be printed on single side of the substrate. For the antenna arrays being studied, the 50 ohm CPW transmission line has been designed with metal strip width $2a = 1.8$ mm and gap dimension of 0.22 mm, calculated using equations given in [20]. The width of CPW feeding structure is similar to the width of the patch. For rectangular patch antenna L_g = 12.9 mm and W_g = 8.18 mm. For bowtie patch antenna L_g = 8 mm and W_g = 3.88 mm.

Table 1: Dimensions of antenna elements

Antenna Element	Dimensions	
Rectangular Patch	Length of rectangular patch (L)	14.06 mm
	Width of rectangular patch (W)	18.6 mm
	Area	261.52 mm^2
Bowtie Patch	L/2	7.07 mm
	W	10 mm
	W_C	1.0 mm
	S	10 mm
	Area	55 mm^2



(i)



(ii)

Fig. 1. (i) Geometries of CPW fed: (a) rectangular patch antenna, and (b) bowtie patch antenna. (ii) Geometry of 4-element: (a) bowtie patch antenna array, and (b) rectangular patch antenna array.

The theoretical calculations are verified by simulating the antenna in IE3D software and thereafter arrays of 4-elements with inter element spacing of 29.18 mm (λ/2) are designed and simulated.

III. ARRAY SYNTHESIS USING SCHELKUNOFF POLYNOMIAL METHOD

The null controlled patterns can be generated using Schelkunoff polynomial method [16]. The method is used to calculate the elements excitations from the required number of nulls and their positions taken as input. The array factor for an N-element array with equal spacing, non-uniform amplitude, and progressive phase excitation, is given by:

$$AF = \sum_{n=1}^{N} a_n e^{j(n-1)(kd\cos\theta+\beta)} = \sum_{n=1}^{N} a_n e^{j(n-1)\psi}, \quad (1)$$

where,
N = number of elements;
a_n = amplitude weight at element n;
$\Psi = kd\cos\theta + \beta$;
$k = 2\pi/\lambda$ = wave number;
λ = signal wavelength;
d = spacing between the elements;
θ = an incidence angle of signal from the array normal;
β = progressive phase.

The array factor of an N-element array is a polynomial of degree N−1 and therefore it has N − 1 zeros. By proper placement of the zeros on the z-plane, a desired array factor can be designed.

Let $Z = e^{j\psi} = e^{j(kd\cos\theta+\beta)}$,

$$AF = \sum_{n=1}^{N} a_n Z^{(n-1)} = a_1 + a_2 Z + a_3 Z^2 + \dots + a_N Z^{(N-1)}, \quad (2)$$

The above equation is simply a polynomial in the complex variable z. Recall that a polynomial of order N has N zeros which may be complex. The polynomial for the AF above is of order N-1 zeros. If the zeros are numbered starting from one, the zeros will be 1, 2, ..., N-1. The AF is then rewritten as:

$$AF = a_n(Z-Z_1)(Z-Z_2)(Z-Z_3)\dots(Z-Z_{(N-1)}), \quad (3)$$

where Z_1, Z_2, Z_3 … Z_{n-1} are roots of the polynomial. The roots Z_n of the polynomial can be positioned on, inside or outside the unit circle. The roots Z_n that lie on the unit circle contribute to the nulls in the radiation pattern in the fixed directions θ_1, θ_2, θ_3 … θ_{N-1}, and a_1, a_2 … a_n are the corresponding element excitations which can be obtained by equating (2) and (3).

Hence, we can choose the zeros Z_n to be whatever we want corresponding to the nulls θ_n as:

$$Z_n = e^{j(kd\cos\theta_n+\beta)},$$

and then figure out what the weights a_n should be to give us the same pattern.

IV. RESULTS AND DISCUSSION

For investigating the null placement in non isotropic antenna array, the proposed array geometries (Fig. 1 (ii)) of bowtie microstrip patch and rectangular microstrip patch elements shown in Fig. 1 (i) have been designed and simulated using IE3D on a personal computer with Intel Core i7 processor running at 3.40 GHz with 4 GB RAM, and the performance of the two has been evaluated for different amplitude ratios.

Based on Schellkunoff polynomial method, in 4 element array 3 nulls can be oriented along direction of interference. In this work it is intended to impose two nulls at the peaks of the two side lobes ($\theta_1 = 45°$ and $\theta_2 = -45°$) and the third null at 155° by changing the amplitude ratio to 0.395:1:1:0.395 as calculated by Schelkunoff polynomial method.

The elevation pattern gain plots shown in Fig. 2 (i) and Fig. 3 depict the symmetric patterns with respect to the main beam because of the element-amplitude's symmetry around the center element of the array. Hence, null placement at one side of the main beam results in occurrence of an image null at the other side of the main beam.

In all the three cases, three nulls have been steered to 45°, −45° and 155° by controlling only the element amplitudes as calculated using Equations (2) and (3). With the change in amplitude, the side lobe level decreases from −12.29 dB to −25.34 dB for rectangular antenna array and from −13.31 dB to −25.5 dB for bowtie antenna array. For rectangular antenna array the NDL decreases from −16.57 dB to −27.14 dB at 45°. Null steering is achieved better in bowtie antenna array with considerable decrease in NDL from −22.59 dB to −31.75 dB.

The 2D radiation patterns of the two arrays obtained for different amplitudes are shown in Fig. 2 (ii) and Fig. 4. It can be clearly observed from the 2D radiation patterns that nulls have been successfully steered to desired location by changing the amplitude as obtained by Schelkunoff polynomial method. Further the maximum gain of the major lobe decreases from 6.76 dBi to 6.3 dBi for bowtie antenna array, whereas for rectangular antenna array it decreases from 7.92 dBi to 7.3 dBi.

It can be observed that null steering has been successfully achieved for both the isotropic and non-isotropic patch arrays. The comparative analysis on the basis of position and depth of nulls is presented in Table 2. It can be clearly depicted from the Fig. 2 (i) and Fig. 3 that the pattern symmetry is retained in all the three cases. For isotropic antenna array, the nulls have been steered to 45°, −45° and 155° with significant decrease in the depth of nulls. For the rectangular and bowtie patch antenna arrays, the two nulls have been successfully steered towards the peaks of the two side lobes (45° and −45°) except for the third nulling location steered towards the peak of the side lobe at 135° instead of 155°.

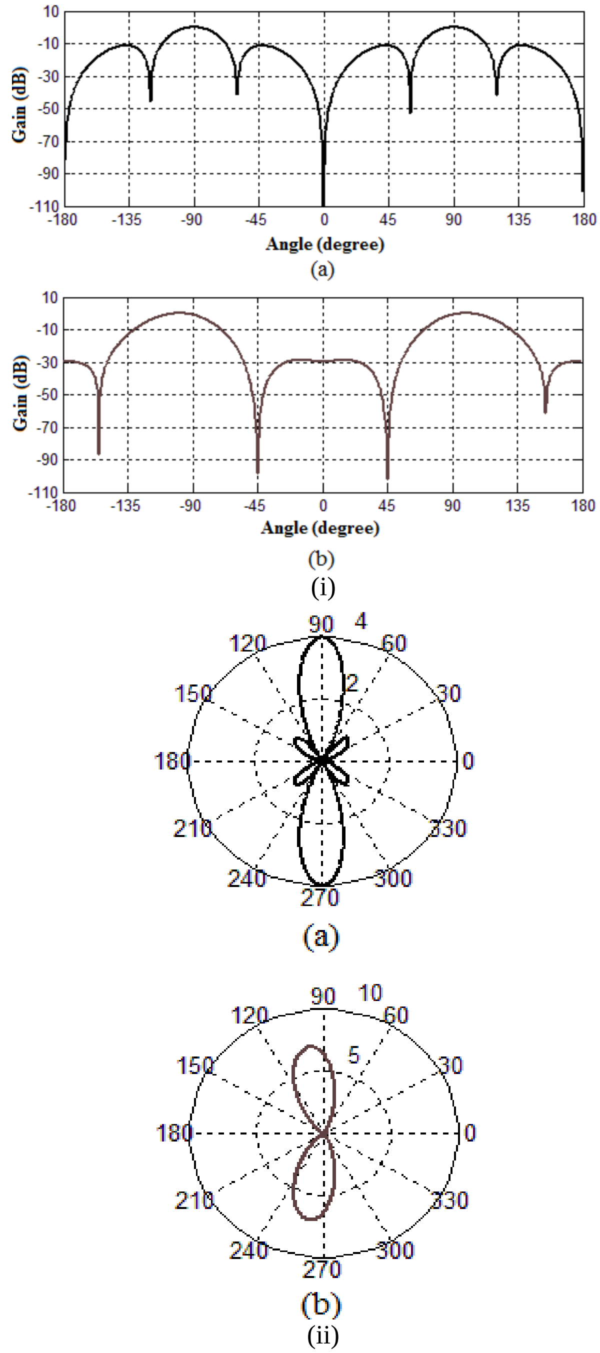


Fig. 2. (i) Gain versus angle plots of 4-element isotropic antenna array with: (a) amplitude 1:1:1:1 and (b) amplitude 0.395:1:1:0.395. (ii) 2D radiation patterns of 4-element isotropic antenna array with: (a) amplitude 1:1:1:1 and (b) amplitude 0.395:1:1:0.395.

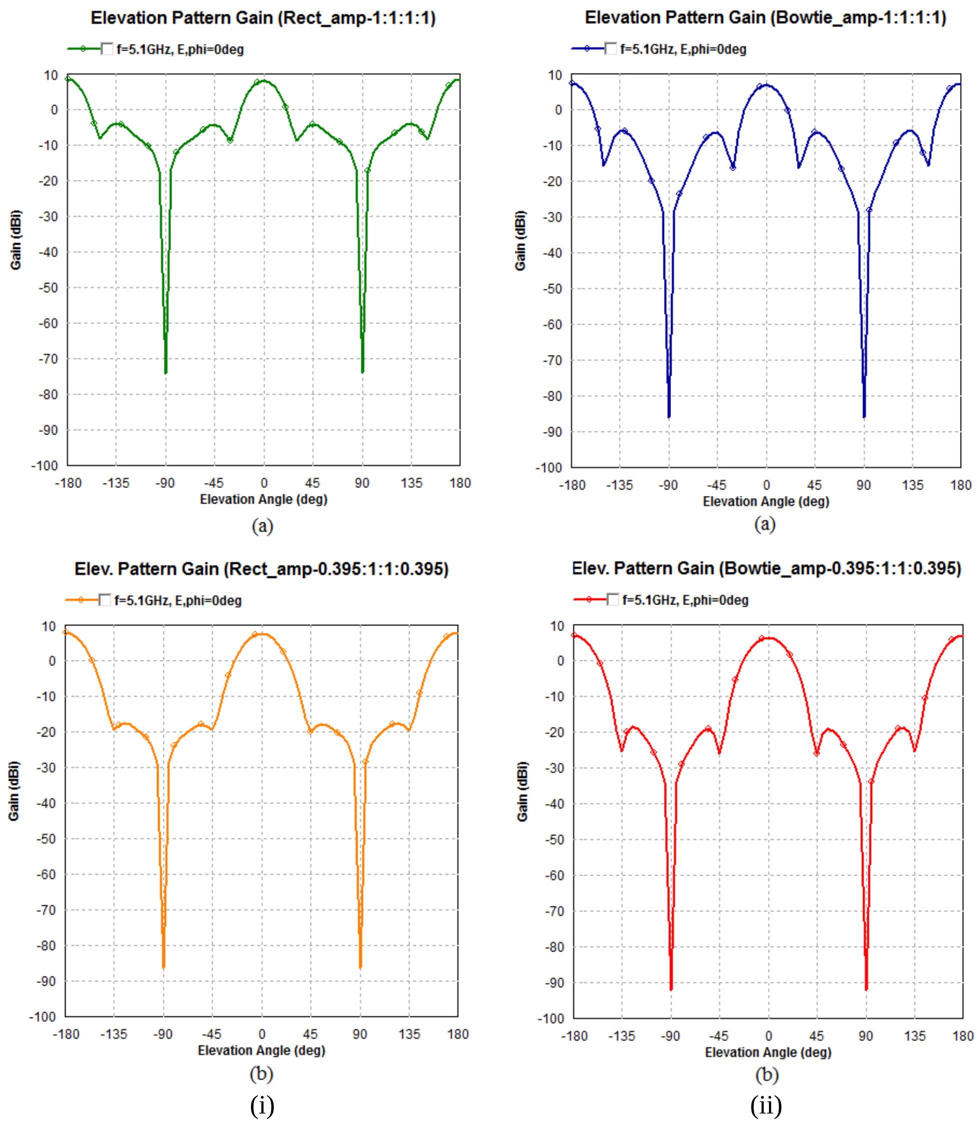


Fig. 3. Gain versus angle plots of (i) 4-element rectangular patch antenna array with: (a) amplitude 1:1:1:1 and (b) amplitude 0.395:1:1:0.395; (ii) 4-element bowtie patch antenna array: (a) amplitude 1:1:1:1 and (b) amplitude 0.395:1:1:0.395.

Table 2: Position and depth of nulls in radiation pattern of 4x1 isotropic and non-isotropic antenna array for different amplitudes

Antenna Element	Amplitude Ratio	Null 1		Null 2		Null 3	
		Position	Depth (dB)	Position	Depth (dB)	Position	Depth (dB)
Isotropic	1:1:1:1	60°	-55	-60°	-40	120°	-40
	0.395:1:1:0.395	45°	-105	-45°	-100	155°	-60
Rectangular	1:1:1:1	30°	-16.57	-30°	-16.49	150°	-16.14
	0.395:1:1:0.395	45°	-27.14	-45°	-26.81	135°	-26.59
Bowtie	1:1:1:1	30°	-22.59	-30°	-22.16	150°	-22.16
	0.395:1:1:0.395	45°	-31.75	-45°	-31.74	135°	-31.39

As can be seen from the plots shown in Figs. 4 and 5 for both the designed antenna arrays, i.e., rectangular as well as bowtie, when we change amplitude ratio to 0.395:1:1:0.395, the gain at 155 º and -155º undergo a slight variation; i.e., from -5.6 dB to -1.08 dB for bowtie antenna array and shows a variation from -4.2 dB to -0.15 dB for rectangular antenna array. However, for both the arrays the gain changes significantly at 135º and -135º as the nulls present at 149º and -149º have got steered towards 135º and -135º, i.e., the direction of maxima of minor lobes (direction of interference).

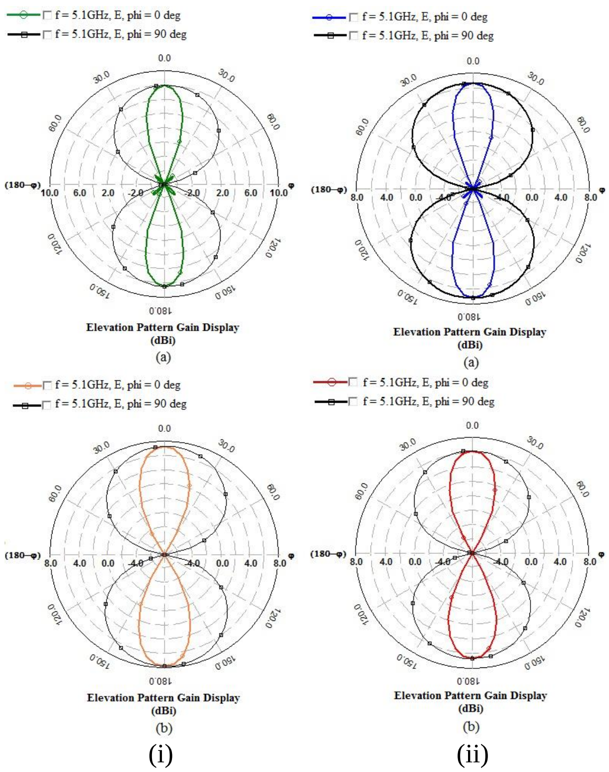


Fig. 4. 2D radiation patterns of (i) 4-element rectangular patch antenna array with: (a) amplitude 1:1:1:1 and (b) amplitude 0.395:1:1:0.395; (ii) 4-element bowtie patch antenna array with: (a) amplitude 1:1:1:1 and (b) amplitude 0.395:1:1:0.395.

Effect of mutual coupling have to be introduced while designing antenna array because in practical arrays this effect changes radiation pattern significantly. Coupling effect produced due to elements interaction while all the elements in array are excited causes elements pattern alter from isolated pattern [21]. Hence, it is important to investigate mutual coupling effect to calculate optimum inter-element spacing and IE3D is a good platform to analyze this effect [22]. To explore the mutual coupling effect, an analysis of the variation of S_{12} with respect to inter-element spacing has been presented in Table 3 and the plots are shown in Fig. 5.

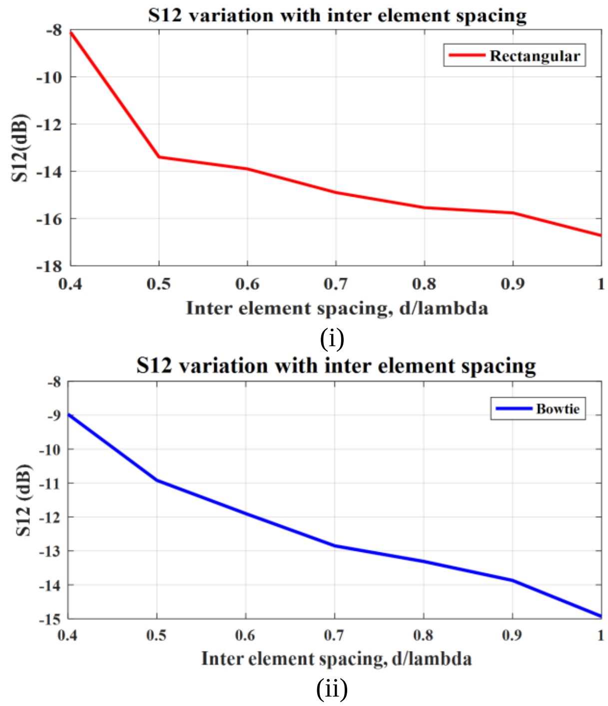


Fig. 5. Mutual coupling of: (i) 4-element rectangular patch antenna array, and (ii) 4-element bowtie patch antenna array.

It is observed from the variation of S_{12} as a function of inter element spacing, that the mutual coupling gets reduced with increase in the element spacing. Furthermore, both the curves plotted in Fig. 5 shows a significant variation in S_{12} for the change in spacing from 0.4λ to 0.5λ. Whereas the variation gets reduced beyond 0.5λ as depicted by the gradual slope of the two curves, thus indicating half wavelength distance to be the optimum one.

The comparative analysis performed for non-isotropic antenna arrays of rectangular and bowtie patches indicates better performance exhibited by the bowtie antenna array not only in terms of occupied area but also improved radiation characteristics. The dimensions of the two elements given in Table 1 show that the area of bowtie patch is 55 mm^2 which is approximately 80% less than that of rectangular patch which leads to much reduced computational time of 31 min 58 sec for bowtie array, whereas the execution takes 10 hr 2 min 29 sec for rectangular array performed on Intel Core™ i7, 3.40 GHz processor. Further, from the performance comparison detailed in Table 3, it can be seen that the value of S_{11} at the optimum spacing (λ/2) for bowtie antenna array is −20.57 dB, whereas for rectangular antenna array it is −13.72 dB.

Table 3: S_{11} and S_{12} for different inter element spacing

Element Excitation (Amplitude Ratio) = 0.395:1:1:0.395						
Inter Element Spacing	4 Element Bowtie Array			4 Element Rectangular Array		
	Resonant Frequency (GHz)	At Resonant Frequency		Resonant Frequency (GHz)	At Resonant Frequency	
		S_{11} (dB)	S_{12} (dB)		S_{11} (dB)	S_{12} (dB)
0.4λ	5.15	-17.97	-8.97	4.43	-21	-8.12
0.5 λ	5.12	-20.57	-10.92	4.93	-13.72	-13.4
0.6 λ	5.02	-22.13	-11.9	4.61	-12.19	-13.9
0.7 λ	4.93	-19.67	-12.85	5.53	-16.2	-14.9
0.8 λ	5.07	-17.24	-13.31	5.17	-16.10	-15.54
0.9 λ	5.12	-18.66	-13.87	4.98	-15.74	-15.76
1 λ	5.08	-20.36	-14.93	4.83	-13.73	-16.72

V. CONCLUSION

Null steering in antenna array of isotropic and non-isotropic elements has been presented in this paper. The algorithm for amplitude controlled null steering of linear antenna array using Schelkunoff polynomial method has been developed in MATLAB. The simulation results demonstrate that by using Schelkunoff method the null steering has been effectively attained in 4-element rectangular antenna array and bowtie antenna array to obtain the desired radiation pattern with nulls imposed at the direction of interferences. The single element bowtie antenna offers the advantage of reduced area but it also achieves high directivity. Further, the results show that using bowtie patches as the element in the array brings about comparatively more effective null steering, and enhances the performance of the array as compared to the conventional rectangular patches, with a decrease in SLL and NDL to −25.47 dB and −31.75 dB respectively, with a significant reduction of the area of the array, which is desirable for application where small antennas are required. It has been observed that the mutual coupling between elements decreases substantially with significant variation at half wavelength spacing.

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