Effects of Inter-Element Spacing and Number of Elements on Planar Array Antenna Characteristics

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ABSTRACT

Planar array antenna is seen as one of the innovative solutions of massive MIMO and 5G networks since they provide directive beams. In this paper, planar array antenna with square and rectangular arrangements based on 2 x 2 antenna elements as one subarray was proposed. Then, array factor for the the planar array antenna with up to 64 antenna elements was calculated to analyze the effects of inter-element spacing and number of elements on the antenna characteristics. Higher values of inter-element spacing contributed to higher number of side lobes, narrower main lobe, higher directivity and lower half power beamwidth (HPBW). Inter-element spacing equals to 0.5λ was found to be the most suitable value for planar array antenna design based on the analysis. Meanwhile, higher number of antenna elements increased the value of directivity of the planar array with narrower HPBW. Therefore, there is a tradeoff between directivity and HPBW in designing planar array antenna for massive MIMO application.

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1. INTRODUCTION

Antenna array is seen as one of the innovative solutions of massive MIMO and 5G networks for their performance enhancement capability in multipath environment [1]. The performance of massive MIMO technology strongly depends on properties and configurations of the antenna arrays being deployed [2]. Often, the array configurations are required to be compact and produce high gain without neglecting the antenna performance such as radiation pattern, efficiency and mutual coupling. It can be noted that 2D and 3D configuration of antenna elements (planar arrays) have become suitable for massive MIMO instead of 1D configuration (or linear arrays) due to the constraint in array aperture.

Antenna array refers to the assembly of single radiating antenna elements in an electrical and geometrical configuration as considered in the classical textbook by [3]. The design of antenna arrays involves mainly first the selection of single antenna element followed by array geometry, and then the determination of the element excitations required for achieving a particular performance. The total field of the array is equal to field of a single element at a selected reference point multiplied by a factor of that array known as array factor (AF). Planar array configuration refers to the placing of single antenna element along a rectangular grid to form a square or rectangular array as shown in Figure 1. Often, high directivity of planar array can be accomplished by inserting more antenna elements within a fixed size. The total size of the antenna array includes number of elements and distance of inter-element spacing.

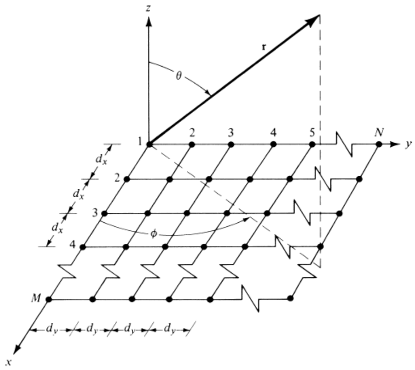

Figure 1. Planar array configuration

Several simulations work have been done to analyze the antenna array characteristics based on the theory of array factor. [4] have studied the impact of number of elements on AF for uniform linear antenna arrays. In another work, [5] have also investigated the impacts of inter-element spacing on AF for uniform linear antenna arrays. Meanwhile, in the work presented by [6] the pattern of AF is calculated for square planar arrays. The study in [7] have analyzed the effects of inter-element spacing and phase shift excitation on radiation pattern of microstrip antenna arranged in linear, planar and circular array configurations. Therefore, this paper intends to study the effects of inter-element spacing and number of antenna elements on planar array antenna characteristics by applying the theory of array factor. The paper is organized as follows. In Section 2, array factor for planar array configuration is presented. The effects of inter-element spacing on planar array characteristics are calculated in Section 3. Then, the effects of number of elements on the planar array characteristics are analyzed in Section 4. Finally, Section 5 concludes this paper.

2. ARRAY FACTOR (AF) FOR PLANAR ARRAY ANTENNA

2.1. Theory of Array Factor (AF)

Theory of AF is often used to calculate the overall pattern of antenna array by considering the array geometry, element spacing, orientation and the antenna type. AF depends on the number of elements, geometrical configuration, elements spacing, relative amplitudes and phases of the applied signal to each antenna element. The array factor (AF) for the entire planar array with N and M number of elements depicted in Figure 1 can be expressed by:

$$AF = \sum_{n=1}^{N} I_{n1}\left[\sum_{m=1}^{M} I_{m1} e^{j(m-1)(kd_x \sin\theta\cos\phi+\beta_x)}\right] e^{j(n-1)(kd_y \sin\theta\sin\phi+\beta_y)} \quad (1)$$

where

N : number of antenna elements along y-axis
M : number of antenna elements along x-axis
I_{n1} and I_{m1} : excitation coefficient of each element along y-axis and x-axis
d : spacing between elements in wavelength (λ)
β : progressive phase shift between elements

k: propagation constant = $\frac{2\pi}{\lambda}$

2.2. Planar Array Configurations

In this paper, planar array configurations are going to be analyzed from 2 x 2 elements to 8 x 8 elements (where N and M are even numbers). The proposed planar array configurations are divided into square (N = M) and rectangular (N ≠ M) arrangements where 2 x 2 antenna elements serve as the basic subarray, SA (1-unit array) as depicted in Figure 2. Square array arrangement starting from SA_{1-1} up to SA_{4-4} and rectangular array arrangement from SA_{1-2} to SA_{1-15} and SA_{2-3} to SA_{2-7} are shown in Figure 3.

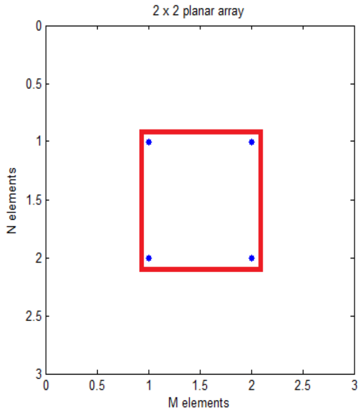

Figure 2. 2 x 2 subarray (SA_{1-1})

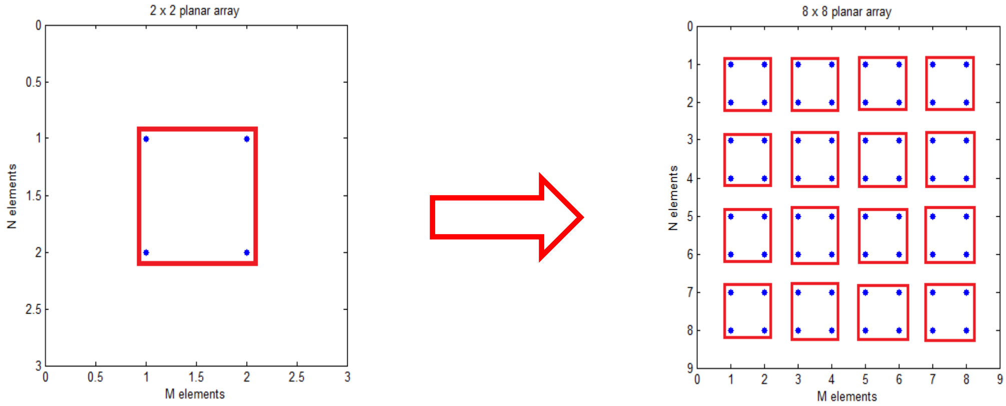

Figure 3 (a). Square array from SA_{1-1} to SA_{4-4}

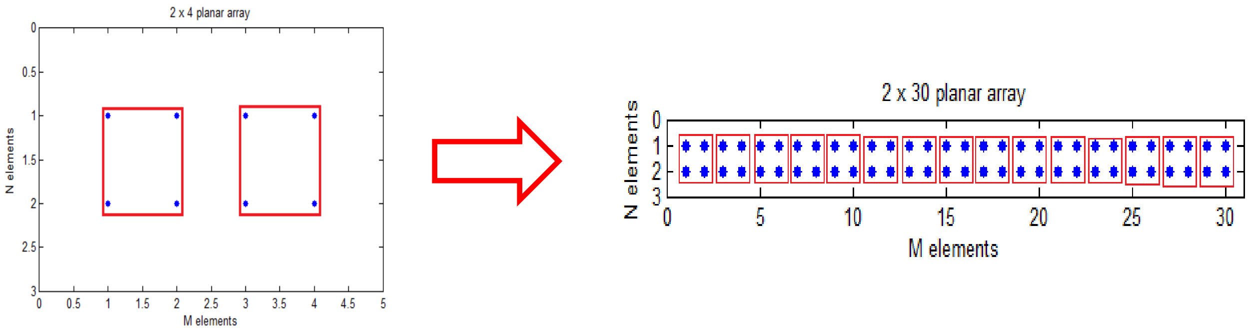

Figure 3 (b). Rectangular array from SA_{1-2} to SA_{1-15}

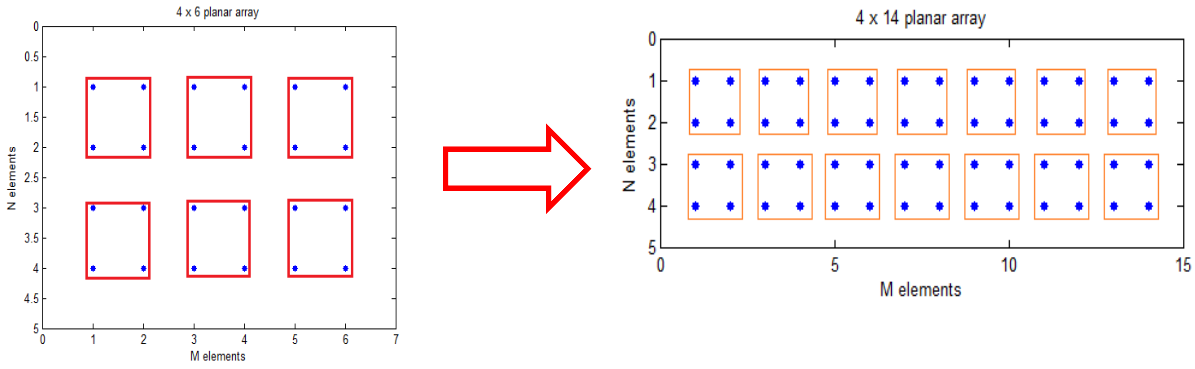

Figure 3 (c). Rectangular array from $SA_{2\text{-}3}$ to $SA_{2\text{-}7}$

3. EFFECTS OF INTER-ELEMENT SPACING ON PLANAR ARRAY CHARACTERISTICS

The AF for isotropic antennas with uniform amplitude and phase are calculated by using Matlab 2013 software for the square and rectangular array arrangements proposed in 2.2 by using equation (1). Different values of inter-element spacing (d = 0.25λ, 0.5λ, 0.6λ, 0.65λ, 0.7λ and 0.75λ) are used to calculate the AF of the proposed planar array configurations. From these calculations, the planar array antenna characteristics such as array factor patterns, directivity and half power beamwidth (HPBW) are evaluated [8].

3.1. Array Factor Patterns

The AF patterns of the planar array configurations with different inter-element spacing are plotted in rectangular form and some are shown in Figure 4.

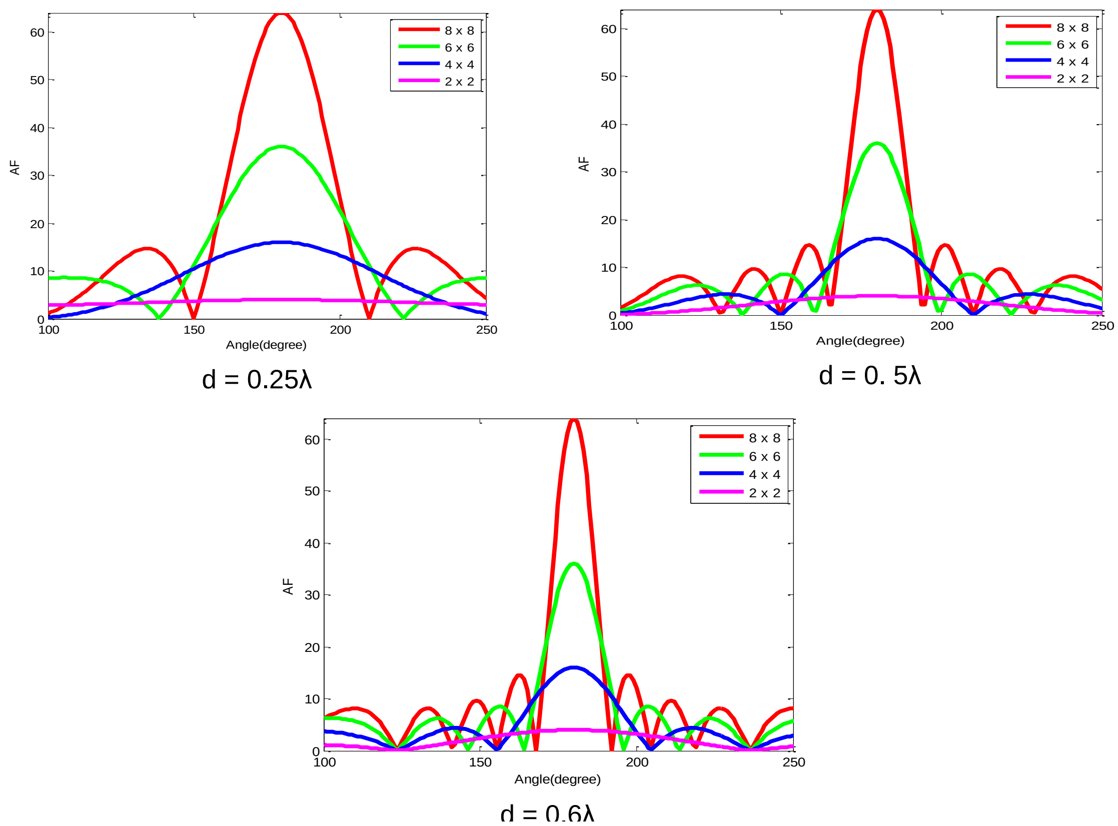

Figure 4 (a). Array factor patterns for square array arrangements

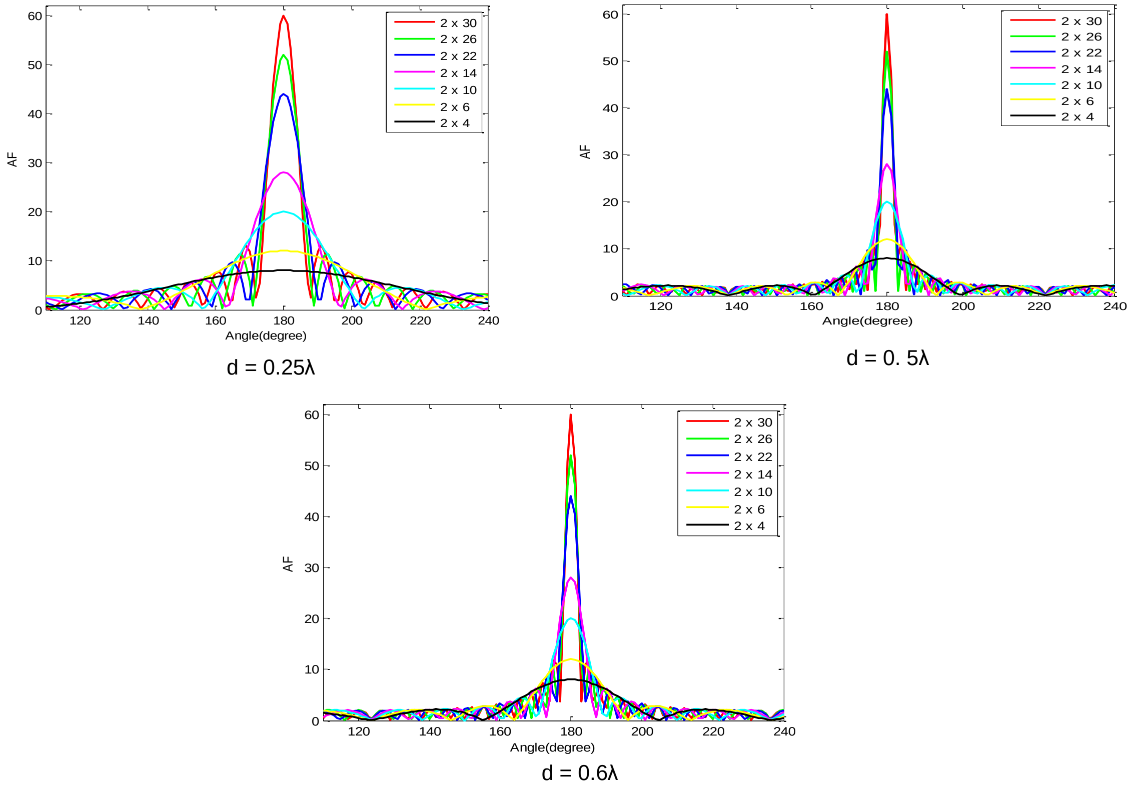

Figure 4 (b). Array factor for rectangular array arrangements (SA_{1-2} to SA_{1-15})

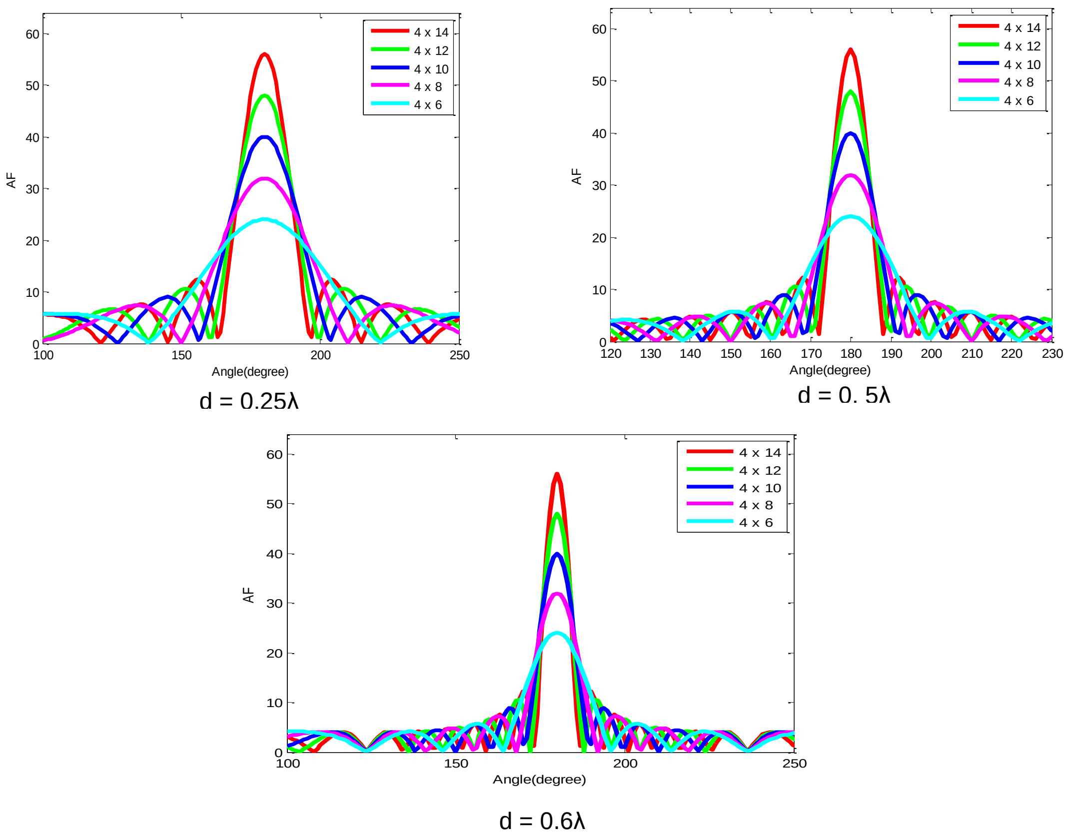

Figure 4 (c). Array factor for rectangular array arrangements (SA_{2-3} to SA_{2-7})

From the AF patterns plotted in Figure 4, it can be noted that different values of inter-element spacing will affect the number of side lobes created as well as the width of the main lobe. For all of the planar array configurations, the number of side lobes created increased when the value of d is increasing. Meanwhile, the width of the main lobe becomes narrower when the value of d is increasing.

3.2. Directivity (D)

The calculated directivity of the planar array configurations is presented in Table 1. Figure 5 illustrate the variations of directivity with respect to different values of inter-element spacing based on the values tabulated in Table 1.

Table 1. Directivity of Planar Array

Sub-arrays	D (dB) d = 0.25λ	D (dB) d = 0.5λ	D (dB) d = 0.6λ	D (dB) d = 0.65λ	D (dB) d = 0.7λ	D (dB) d = 0.75λ
SA_{1-1}	-1.2152	4.0515	5.6987	5.8226	5.5118	4.964
SA_{2-2}	4.866	10.4672	11.5952	11.769	12.2843	13.1518
SA_{3-3}	8.2031	14.1182	15.2183	15.9788	16.6871	16.5332
SA_{4-4}	10.9259	16.6993	17.9868	18.7952	18.9593	19.71
SA_{1-2}	1.471	7.2791	8.652	8.7412	8.7183	8.6941
SA_{1-3}	3.1631	9.136	10.4217	10.6865	10.7573	10.4251
SA_{1-5}	5.2837	11.4402	12.7409	12.9651	12.6668	12.6668
SA_{1-7}	6.6809	12.9409	14.1992	14.4196	14.3262	14.0755
SA_{1-11}	8.5424	14.942	16.1009	16.2936	16.1847	15.8826
SA_{1-13}	9.2225	15.6785	16.7811	16.9616	16.8437	16.5229
SA_{1-15}	9.8005	16.3085	17.364	17.5323	17.3922	17.0581
SA_{2-3}	6.601	12.3024	13.3822	13.8107	14.4301	14.8653
SA_{2-4}	7.8853	13.594	14.7209	15.1704	15.5691	16.3951
SA_{2-5}	8.8463	14.5921	15.7657	16.0759	16.6752	17.3214
SA_{2-6}	9.6426	15.4053	16.5761	16.8701	17.4619	18.2177
SA_{2-7}	10.3042	16.0914	17.2215	17.5825	18.1053	18.86

Based on the directivity variations plotted in Figure 5, inter-element spacing does affect the values of directivity for planar array antenna. Lower value of directivity is observed for lower value of inter-element spacing and vice versa. Significant variations of directivity can be seen for d = 0.25λ and d = 0.5λ, however very slight changes are observed for directivity with d > 0.5λ. Therefore, inter-element spacing equal to 0.5λ or λ/2 is favored to achieve higher directivity in planar array antenna [7].

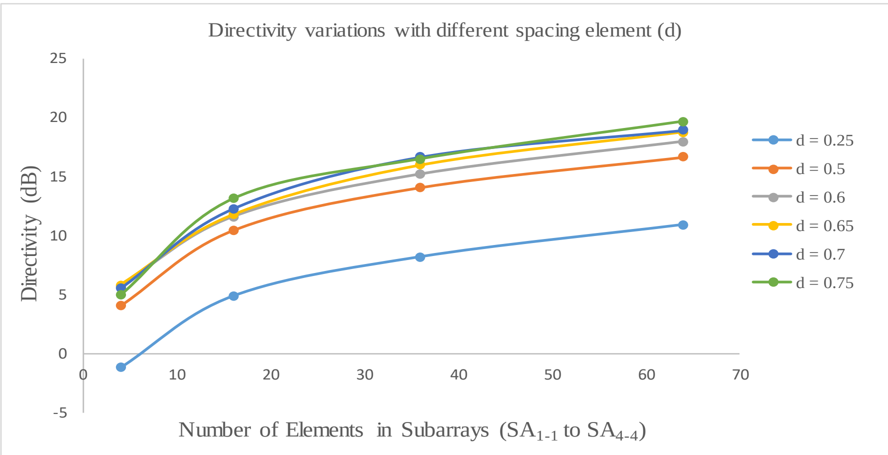

Figure 5 (a). Directivity variations in square array arrangements

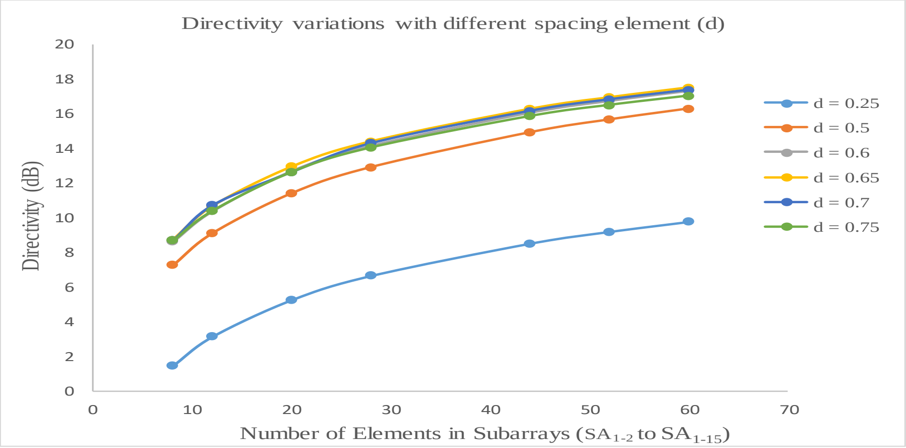

Figure 5 (b). Directivity variations in rectangular array arrangements (SA_{1-2} to SA_{1-15})

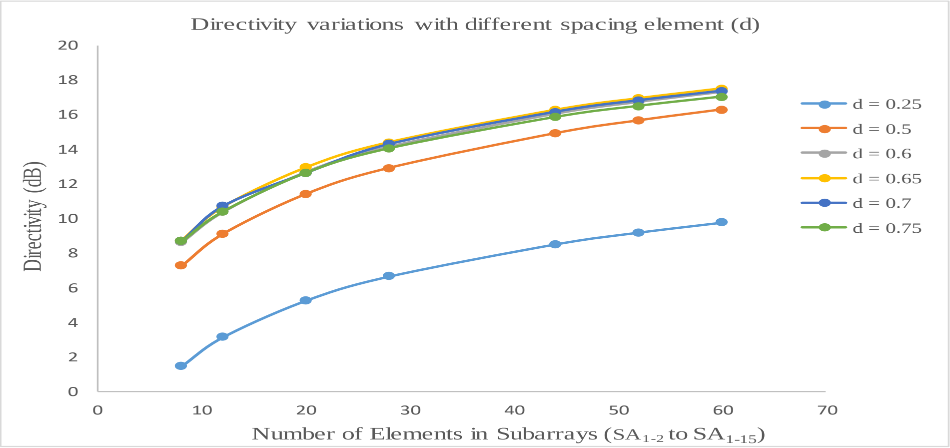

Figure 5 (c). Directivity variations in rectangular array arrangements (SA_{2-3} to SA_{2-7})

3.3. Half Power Beamwidth (HPBW)

The calculated HPBW of the planar array configurations is presented in Table 2. Figure 6 illustrate the variations of HPBW with respect to different values of inter-element spacing based on the values tabulated in Table 2.

Table 2. HPBW of Planar Array

Sub-arrays	HPBW (°) d = 0.25λ	HPBW (°) d = 0.5λ	HPBW (°) d = 0.6λ	HPBW (°) d = 0.65λ	HPBW (°) d = 0.7λ	HPBW (°) d = 0.75λ
SA_{1-1}	0	62.32	51.1	46.92	43.39	40.37
SA_{2-2}	55.69	27.02	22.45	20.71	19.21	17.92
SA_{3-3}	35.67	17.62	14.67	13.53	12.56	11.72
SA_{4-4}	26.41	13.12	10.92	10.08	8.73	8.73
SA_{1-2}	73.31	34.75	28.83	26.57	24.64	22.97
SA_{1-3}	48.4	23.66	19.67	18.15	16.84	15.71
SA_{1-5}	28.93	14.35	11.95	11.03	10.24	9.55
SA_{1-7}	20.64	10.28	8.56	7.9	7.34	6.85
SA_{1-11}	13.13	6.55	5.46	5.04	4.37	4.37
SA_{1-13}	11.11	5.55	4.62	4.27	3.96	3.7
SA_{1-15}	9.63	4.81	4	3.7	3.21	3.21
SA_{2-3}	42.34	20.81	17.31	15.97	14.82	13.83
SA_{2-4}	33.49	16.65	13.79	12.73	11.81	11.02
SA_{2-5}	27.5	13.65	11.37	10.49	9.09	9.09
SA_{2-6}	23.26	11.57	9.64	8.89	8.26	7.71
SA_{2-7}	20.11	10.02	8.34	7.7	6.67	6.67

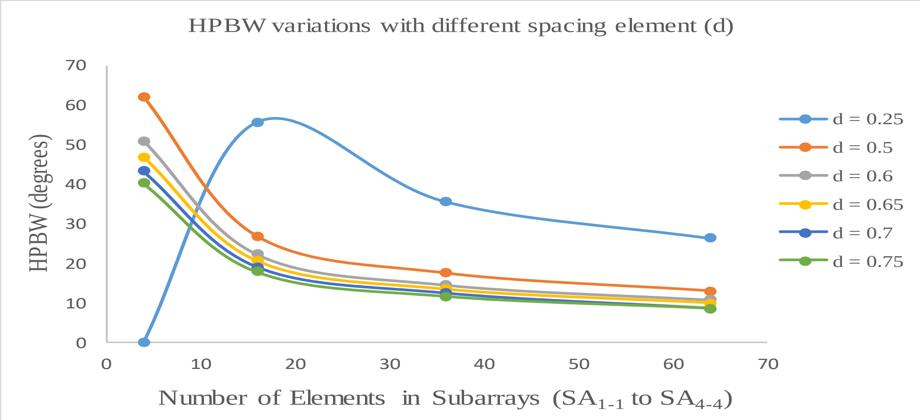

Figure 6 (a). HPBW variations in square array arrangements

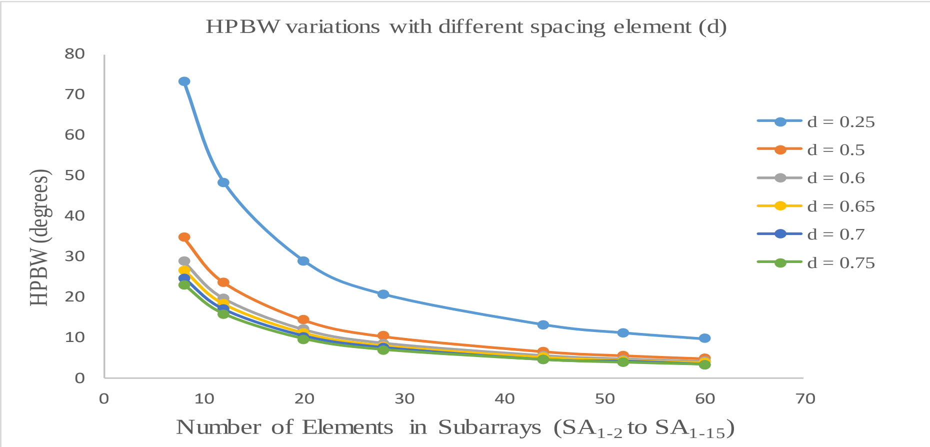

Figure 6 (b). Half power beamwidth variations in rectangular array arrangements (SA_{1-2} to SA_{1-15})

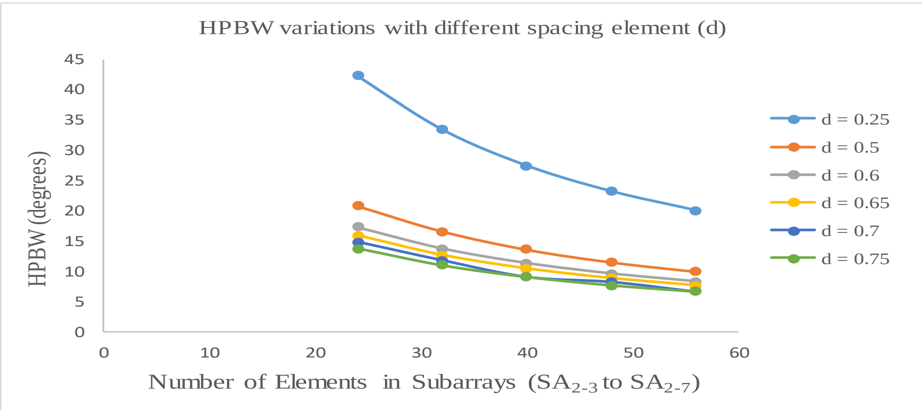

Figure 6 (c). Half power beamwidth variations in rectangular array arrangements (SA_{2-3} to SA_{2-7})

Based on the HPBW variations plotted in Figure 6, inter-element spacing does affect the values of HPBW for planar array antenna. Higher value of directivity is observed for lower value of inter-element spacing and vice versa. Significant variations of HPBW can be seen for d = 0.25λ and d = 0.5λ, however very slight changes are observed for HPBW with d > 0.5λ. This holds true since higher directivity accomplished in planar array antenna is at the expense of narrow HPBW [8].

4. EFFECTS OF NUMBER OF ELEMENTS ON PLANAR ARRAY CHARACTERISTICS

Concerning the effects of inter-element spacing analyzed before, value of d = 0.5λ is suitable to use in order to observe the effects of number of elements on planar array characteristics such as directivity and HPBW. Table 3 and Figure 7 displays the values of directivity with respect to number of antenna elements.

Table 3. Directivity of Array Factor for Planar Array

Number of elements	Directivity (dB)
4	4.0515
8	7.2791
12	9.136
16	10.4672
20	11.4402
24	12.3024
28	12.9409
32	13.594
36	14.1182
40	14.5921
44	14.942
48	15.4053
52	15.6785
56	16.0914
60	16.3085
64	16.6993

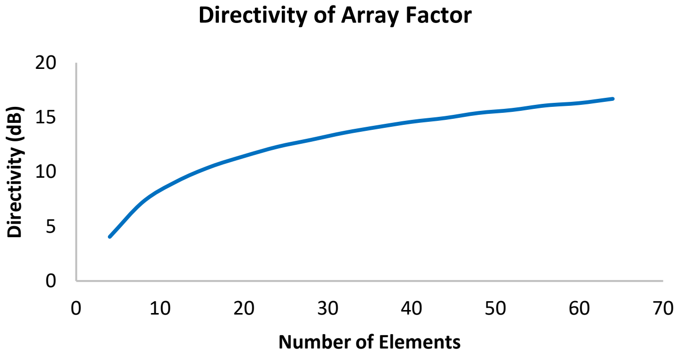

Figure 7. Directivity of array factor for planar array

It can be noted that, the directivity of planar array antenna increases with the number of antenna elements. This indicates that, higher directivity of antenna array can be achieved by placing large number of antenna elements in the array aperture. The values of HPBW of planar array antenna with respect to the number of antenna alements are depicted in Table 4 and Figure 8.

Table 4. HPBW for Planar Array

Number of elements	HPBW
4	62.32
8	34.75
12	23.66
16	27.02
20	14.35
24	20.81
28	10.28
32	16.65
36	17.62
40	13.65
44	6.55
48	11.57
52	5.55
56	10.02
60	4.81
64	13.12

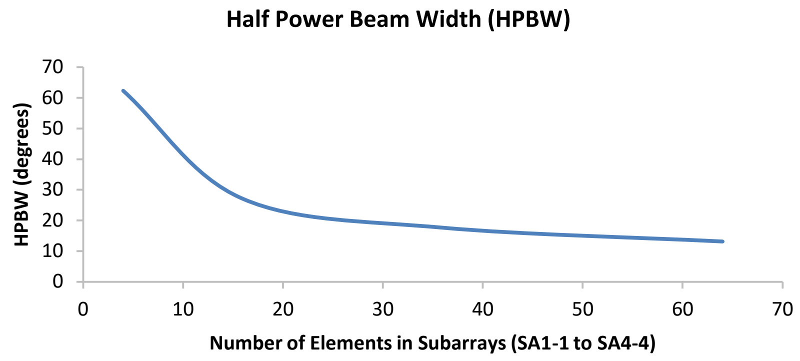

Figure 8 (a). HPBW for planar array

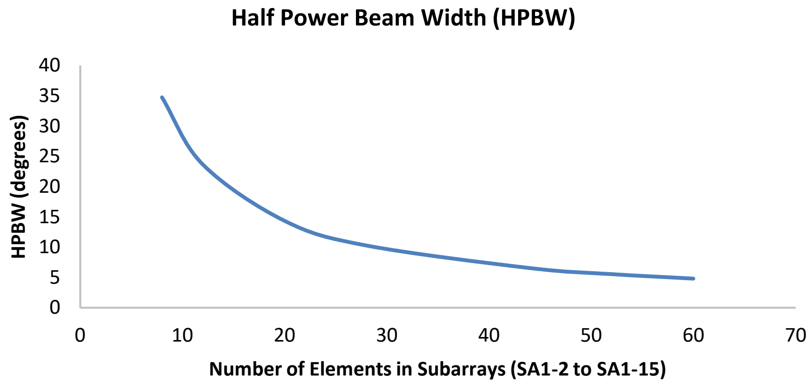

Figure 8 (b). HPBW for planar array

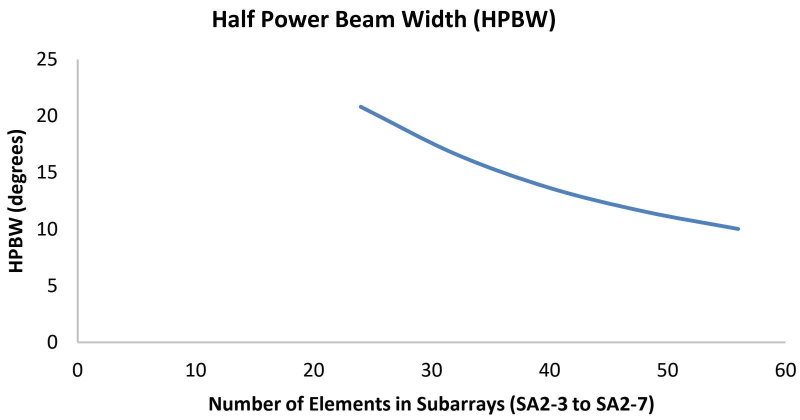

Figure 8 (c). HPBW for planar array

However, HPBW of planar array antenna decreases as the number of antenna elements increases as compared to its directivity. This shows that HPBW will become narrower when large number of antenna antenna elements are installed in the array aperture.

5. CONCLUSION

As a conclusion, effects of inter-element spacing and number of antenna elements on planar array characteristics can be analyzed by applying the theory of array factor. Planar array configurations of square and rectangular arrangements with 2 x 2 antenna elements serve as the basic subarray are analyzed. Array factor patterns, directivity and half power beamwidth are the characteristics evaluated in the calculation of array factor. Increasing number of side lobes and narrower main lobe width are created when the value of inter-element spacing increases. However, the directivity of planar array antenna increases with higher number of antenna elements at the expense of narrower HPBW. Based on the effects of inter-element spacing, 0.5λ is found to be the most suitable spacing to be used in the design of planar array antenna. It can also be seen that increasing number of antenna elements can increase the directivity of the planar array and decrease its half power beamwidth. This indicates that there is a tradeoff between directivity and half power beamwidth in the design of planar array antenna. Therefore, it is possible to design planar array antenna for massive MIMO application by inserting high number of antenna elements with inter-element spacing equal to 0.5λ or λ/2 without compromising the overall array size.

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