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On the Radiation Characteristics of End-Fire Arrays of Equally Spaced Elements

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Abstract: *This paper investigated impact of inter- element spacings on the radiation behaviours of end fire arrays of linear elements. By using pattern multiplication concept to evaluate the electric field radiated by the antenna when excited with sinusoidal current distribution, it was found that, the beam-widths of the main lobe radiations in all the arrays employed as candidates for investigation, reduced as the number of element in the array increased which suggested better directivity. However, improvement in the directivity was accompanied by appearance of undesirable small minor lobe radiation. In addition, It was observed that, the radiation patterns exhibited remarkable unidirectional main lobe radiation when the spacing between array was* 0.25λ*, while at the spacing of* 0.5λ*, the antenna produced main or primary lobe radiations in opposite direction. At higher spacings however, the beam pattern further degenerates into three main lobes with one along the array axis while other lobes are normal to the array axis. Furthermore, it was discovered that the array factor patterns and radiated electric field patterns of the antenna displayed characteristics that were largely similar. It was also revealed through the study that, the antenna exhibited varying behaviour at different spacings and the choice of the antenna's spacing plays greater role in the performance behaviour exhibited by the antenna.*

Keywords: fifth generation, multiple input multiple output, directivity, linear array, transmitting antenna.

1. INTRODUCTION

Fifth generation (5G) broadband technology has been proposed as viable solution to meeting increasing broadband spectrum demand, high data rates as well as supporting data intensive applications like virtual reality, augmented reality, internet of things (IOT) [1]. Multiple input and multiple output (MIMO) technology which employs a number of antenna arrays at both the transmitting and receiving station will play great role in 5G mobile communication for increasing transmission link, overcoming multipath fading, and providing directive beam for tracking a number of mobile phones. These arrays may be constructed or designed in linear form, circular form or phased array form. Over the years, researchers have carried out a number of works on the design of antenna arrays for communication purposes. These include [2] and [3] which focussed on design of broadside arrays of uniformly spaced elements for Radar. The former revealed among other things that broadside arrays produced excellent beam radiations when the inter element spacing was below one wavelength while at greater wavelength spacing, undesirable grating lobes appeared. [4] investigated the effects of mutual coupling on the field radiated by four-element linear array. Biogeography based optimization tool was employed elsewhere [5] to optimize position, amplitude and phase excitations of linear arrays with a view to producing radiation beams of minimum side lobe levels. Genetic Algorithm has also been adopted to synthesize radiation patterns of linear antenna arrays suitable for adaptive signal processing technique [6] as well as for optimizing thinned linear array of uniformly excited isotropic elements in order to achieve reduction in the side lobe level [7]. Using particle swarm optimization (PSO), the excitation amplitude, phase, position and length of linear arrays were optimized [8]. The cited paper under reference here posits that, the design of antenna arrays using PSO has considerable benefits over other optimization techniques.

Developing antenna arrays that will perform satisfactorily in Millimeter wave communication for 5G mobile standard is an ongoing research and hence this work focuses on quantitative investigation of the impacts of spacings and number of elements on the radiation characteristics of linear arrays whose main lobe radiation is directed in the same direction as the axis of the antenna. We employ pattern multiplication concept for calculating electric fields radiated by the antenna and whose computations using Matlab 2016a on Intel Pentium (R) CPU B960 @ 2.20GHz and 64-bit operating system produce field patterns of the antenna at large distance from the antenna.

The paper is structured such that section 1 focuses on the introduction while section 2 is the methodology. Section 3 bothers on the numerical results while section 4 is the concluding remark.

2. METHODOLOGY

Figure 1 shows a dipole antenna positioned at the origin of Cartesian coordinate system with a differential element lying symmetrically along the z-axis, distance z' from the origin. The observation point or field point $P(x,y,z)$ is situated at a distance $\overline{r}$ from the origin, while $\overline{R}$ is the distance from the source point to the field point. The derivation of the $\hat{\theta}$ -component of the electric field radiated in free space by the dipole when excited with sinusoidal current distribution of the form $I_0 \cos(k_0) z'$ has been explicitly provided in [2]. To avoid unnecessary repetition, the electric field derived shall be quoted in this paper and admits an expression of the form

$$\overline{E} = \hat{\theta}\, \frac{j\eta_0 I_0 \cos(\pi/2\cos\theta) e^{-jk_0 r}}{2\pi r \sin\theta} \tag{1}$$

in which $(j, \eta_{0,} I_0)$, denote imaginary number, free space intrinsic impedance, current amplitude respectively. $\overline{E}$ is the $\hat{\theta}$ -component of the electric field radiated by a dipole antenna when excited with sinusoidal current source.

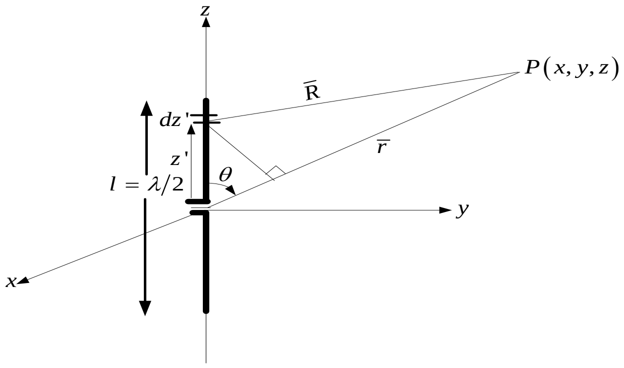


Figure 1: Geometry of a dipole antenna

Antenna arrays can be designed in such a way that radiations are directed along the axis of the array. That form of the array is referred to as end fire array, and is illustrated in Figure 2.

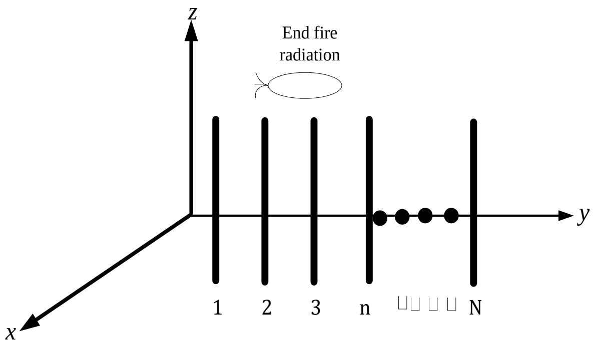


Figure 2: Geometry of linear array and illustration of end fire radiation

The total field of an array may be obtained by multiplying the field of a single element at the origin by the array factor, otherwise referred to as pattern multiplication theorem. This is described by expression of the form.

$$E_t = radiated\ field\ of\ a\ \ dipole\ at\ origin \times Array\ factor \tag{2}$$

where E_t denotes the total field of an array.

The array factor, symbolized here by AF_1 and AF_2 of uniformly spaced end fire arrays whose maximums are directed along $\theta = 0^0$ and $\theta = 180^0$ admit expressions in the forms represented by

$$AF_1 = \frac{\sin\left(Nk_0 d/2(\cos\theta - 1)\right)}{N\sin\left(k_0 d/2(\cos\theta - 1)\right)}\ \ for\ \theta == 0^0 \tag{3}$$

$$AF_1 = \frac{\sin\left(Nk_0 d/2(\cos\theta + 1)\right)}{N\sin\left(k_0 d/2(\cos\theta + 1)\right)}\ \ for\ \theta = 180^0 \tag{4}$$

in which (N, k_0, d) in equations (3) and (4), respectively represent, total number of elements in the array, propagation constant and inter-element spacings between the elements.

When equations (3) and (4) are substituted in equation (2), the electric fields radiated by the arrays admits expressions of the form:

$$E_{t1} = \frac{j\eta_0 I_0 \cos(\pi/2\cos\theta)e^{-jk_0 r}}{2\pi r\sin\theta} \cdot \frac{\sin\left(Nk_0 d/2(\cos\theta-1)\right)}{N\sin\left(k_0 d/2(\cos\theta-1)\right)} \quad for\ \theta = 0^0 \tag{5}$$

$$E_{t2} = \frac{j\eta_0 I_0 \cos(\pi/2\cos\theta)e^{-jk_0 r}}{2\pi r\sin\theta} \cdot \frac{\sin\left(Nk_0 d/2(\cos\theta+1)\right)}{N\sin\left(k_0 d/2(\cos\theta+1)\right)} \quad for\ \theta = 180^0 \tag{6}$$

where E_{t1} and E_{t2} , respectively denote total field of the end fire arrays oriented along $\theta = 0^0$, and $\theta = 180^0$.
Having derived expressions for the total electric fields of the end fire arrays oriented in the directions of interest, use is then made of those expressions to generate results for the electric field patterns of various models of the antenna. This is discussed in what follows.

3. NUMERICAL RESULTS

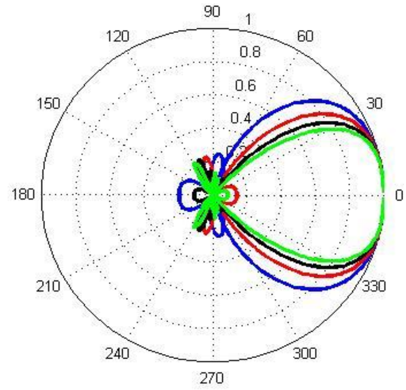
It was reported elsewhere [2, 9& 10] that undesirable grating lobe occurs when the inter-element spacings d between the array elements are of multiple of wavelength (λ), that is $d = s\lambda$, wherein $s = 1, 2, 3, ...$ In that regard, numerical results are obtained in this work for the array factor patterns and far zone electric field patterns when inter element spacings are within the range of $0.25\lambda \le d \le 0.9\lambda$. Results obtained when the exercise is carried out are represented in graphical formats and are discussed in sections (3.1) and (3.2).

3.1 Radiation Fields

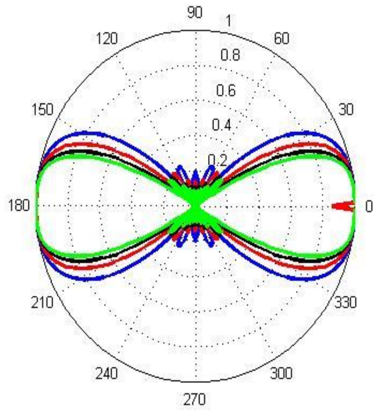
Figures (3) and (4) describe the far zone electric fields radiated by linear arrays of various elements in which blue solid line, red solid line, black solid line, and green solid line, respectively represent results for 5-element, 7-element, 9 element and 11-element arrays, respectively, and which are obtained by computing equations (5) and (6) in Matlab environment. Those figures describe the summation of contribution of each element to the far electric field, when excited by sinusoidal current source. It is observed that, the beam-width of the main lobe reduces as the number of elements increases, one characteristic behaviour that is common to most antennas and as such this antenna is not an exception. It is also seen that most electromagnetic energy is directed at the main lobe of the antennas with accommodating side lobes. In addition, it is found that when quarter wavelength spacing is employed between antenna arrays in all the cases considered, the radiated fields exhibit unidirectional property with main lobe beam along the axis of the antenna, described by $\theta = 0^0$ or $\theta = 180^0$, as portrayed in Figures 3(a) and 4(a). On the other hand, when half-wavelength spacing is utilized, the far-zone fields degenerate into two lobes in opposite direction (bidirectional), described by $\theta = 0^0$, and $\theta = 180^0$ as seen in Figures 3(b) and 4(b), respectively. At higher spacings, the antennas further degenerate into three lobes producing radiation fields not only along the main axis but also in the direction perpendicular to the main axis, as evident in Figure 3-4 (c & d). It is clear that the antenna spacing contributes significantly in pattern exhibited and is a factor to be considered in the design of the antenna.

3.2 Array Factor Patterns

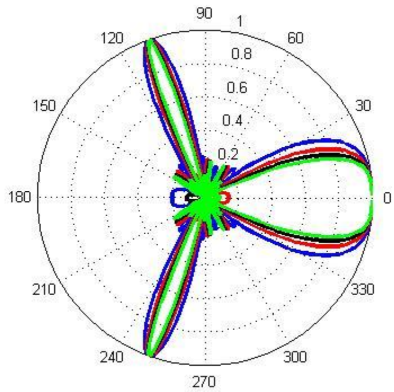
In the same manner, computations of equations (3) and (4) lead to array factor patterns, illustrated in Figures. (5) and (6), respectively which describe radiation behaviours of array of isotropic elements at spacings within the range $0.25\lambda \le d \le 0.9\lambda$. These figures are produced without putting into consideration omnidirectional nature of dipole antenna. Without mincing words, these characteristic profiles are largely similar to those of Figs. (3) and (4) which have been discussed in detail in section(3.1).



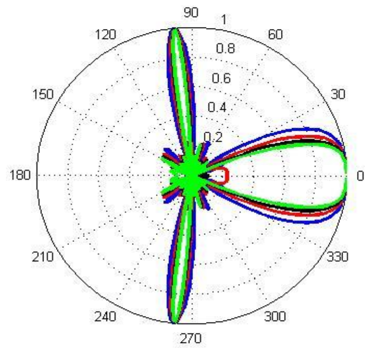
(a) $d = \lambda/4$



(b) $d = \lambda/2$

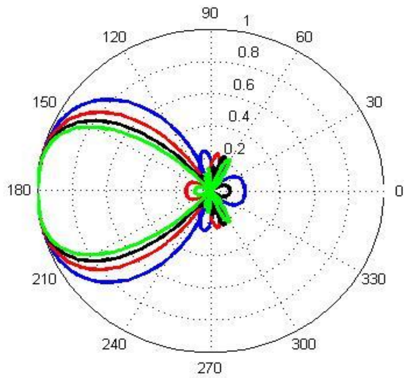


(c) $d = 3\lambda/4$

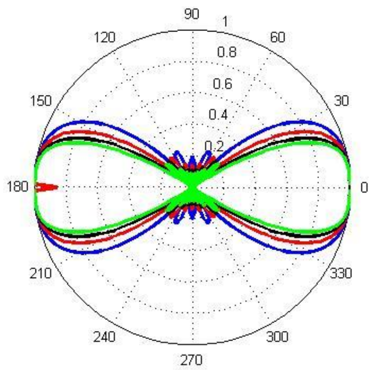


(d) $d = 9\lambda/10$

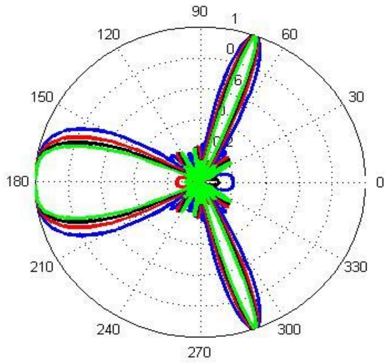
Figure 3: Far zone patterns of end fire arrays of uniformly spaced elements along the main axis described by $\theta = 0^0$, blue line: 5-element, red line : 7 element, black line: 9-element, green line: 11-element with inter-element spacings within the range: $0.25\lambda \le d \le 0.9\lambda$



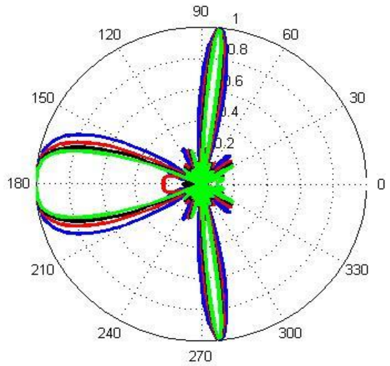
(a) $d = \lambda/4$



(b) $d = \lambda/2$

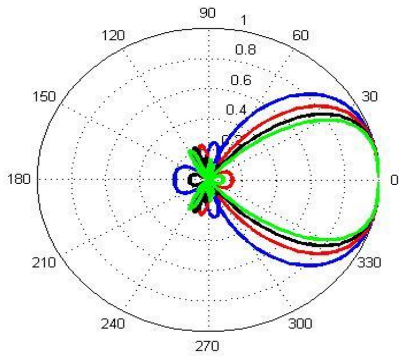


(c) $d = 3\lambda/4$

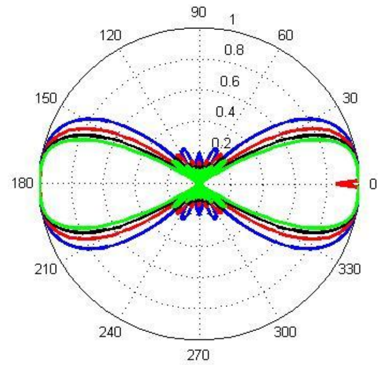


(d) $d = 9\lambda/10$

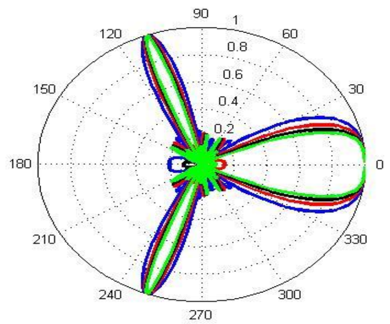
Figure 4: Far zone patterns of end fire arrays of uniformly spaced elements along the main axis described by $\theta = 180^0$, blue line: 5-element, red line : 7 element, black line: 9-element, green line: 11-element with inter-element spacings within the range: $0.25\lambda \le d \le 0.9\lambda$



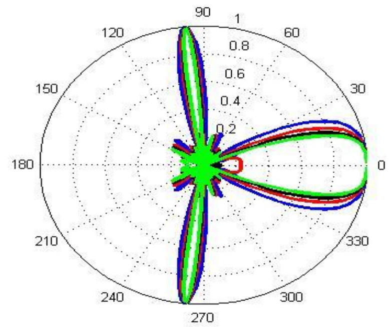
(a) $d = \lambda/4$



(b) $d = \lambda/2$

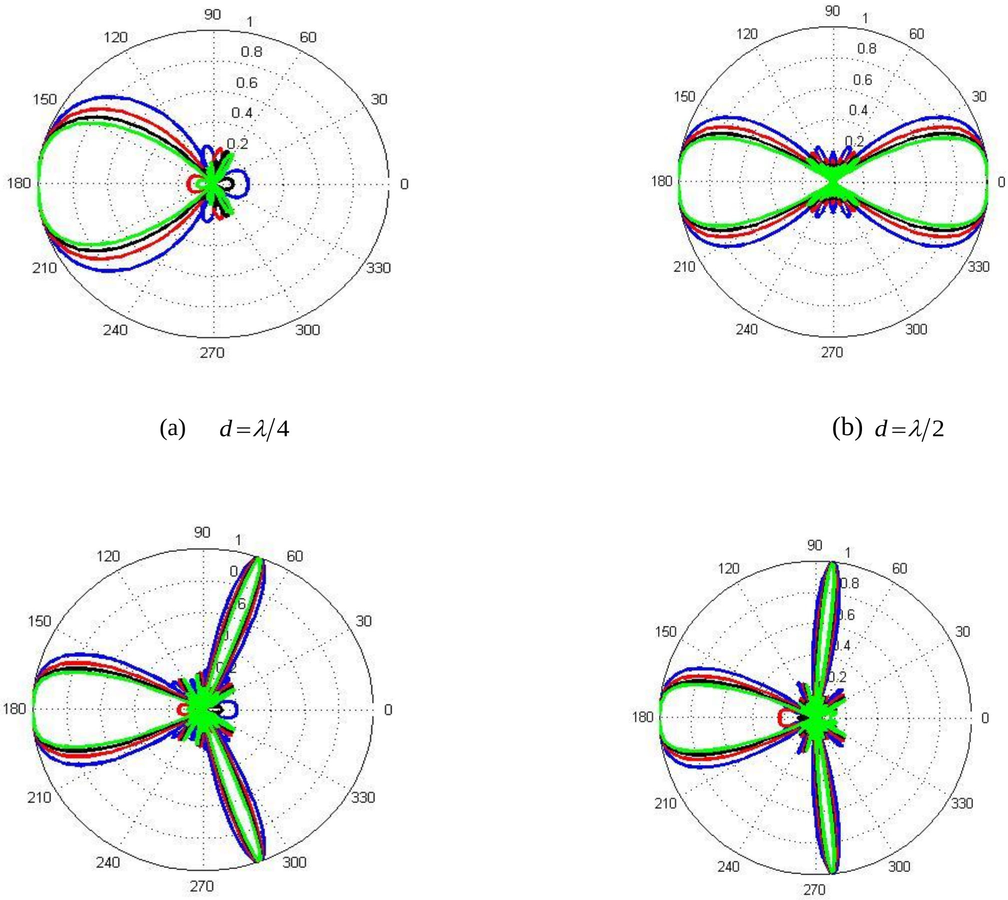


(c) $d = 3\lambda/4$



(d) $d = 9\lambda/10$

Figure 5: Array factor patterns of end fire arrays of uniformly spaced elements along the main axis described by $\theta = 0^0$, blue line: 5-element, red line: 7 element, black line: 9-element, green line: 11-element, with inter-element spacings within the range: $0.25\lambda \le d \le 0.9\lambda$



(a) $d = \lambda/4$ (b) $d = \lambda/2$

(c) $d = 3\lambda/4$ (d) $d = 9\lambda/10$

Figure 6: Array factor patterns of end fire arrays of uniformly spaced elements along the main axis described by $\theta = 180^0$, blue line: 5-element, red line : 7 element, black line: 9-element, green line: 11-element, with inter-element spacings within the range: $0.25\lambda \leq d \leq 0.9\lambda$

4. CONCLUDING REMARKS

The impact of spacings and number of elements on the radiation characteristics of end fire arrays of equally spaced elements is investigated in this paper. By employing pattern multiplication theorem, the electric field radiated by the antenna is determined. Numerical data are compiled for the array factor and radiation field exhibited by various models of the antenna which are illustrated in graphical formats, using values of spacings lower than wavelength (λ). It is found that, the antenna produces single main lobe when the spacing between array is 0.25λ, while at the spacing of 0.5λ, main or primary lobe radiations exist in both directions of the array axis. At greater spacings of 0.75λ and 0.9λ, multiple main lobes are produced with two lobes in the direction perpendicular to the array axis while the other is in the same direction as the array axis . It is also observed that, the main lobe beam widths of the radiated field patterns and array factor patterns become narrower as the spacing and number of elements increase. This observation clearly suggests that, directivity of the end fire arrays increases with spacing and number of elements. It is also found that antenna spacing contributes in no small measure to the radiation features of the antenna and is an important factor to be considered when designing antenna of this type.

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