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IMPACT OF ELEMENT LENGTHS AND SPACINGS ON THE PERFORMANCE CHARACTERISTICS OF YAGI-UDA ANTENNA

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ABSTRACT

This work examines the impact of element lengths and spacing on the performance behaviours of Yagi-Uda antenna. Four Yagi-Uda antenna types are used as candidates for numerical investigation including Yagi-Uda antenna of uniform lengths of directors with uniform spacings (YUDUS), Yagi-Uda array of uniform lengths of directors with non-uniform spacings (YUDNS), Yagi-Uda array of varying lengths of directors and uniform spacings between directors (YVDUS), and Yagi-Uda antenna varying length of directors with non-uniform director spacings (YVDNS). Upon utilizing method of moments procedure, far-zone radiation field, directivity, front-to-back ratio, and side lobe radiation emerge and are therefore utilized as performance metrics for analyzing the behaviour of those Yagi-Uda antenna types. It is observed that YVDNS exhibits better directive main lobe radiation and lower side lobe radiation than others. It is observed also that YVDNS has maximum front-to-back ratio which suggests better electromagnetic energy radiation than others. These characteristics properties of YVDNS design commend the antenna for a number of practical applications more than any other type of Yagi-Uda antenna.

Keywords: Far zone patterns, front-to-back ratio, unequal spacing, uniform spacing.

INTRODUCTION

Yagi-Uda antenna produces and maintains directive end-fire beam over a wide frequency spectrum which is advantageous in radar, television reception and point to point communication. These remarkable features have invigorated humongous investigative interests in the antenna over the years. Prominent works which have provided insightful approaches to Yagi antenna design include experimental measurements of Cheong et al (2014)Yao et al (2011); Dejean and Tentzaris (2007); Lim (2007); Ehphenspech and Poehler (1959), Method of Moment formulations of Balanis (1997), Thiele (1969); Raji and Adekola (2017); Adekola and Raji (2017), and Raji et al (2018), to mention a few. While Cheng (1991) and Cheng and Chen (1973) demonstrated by using perturbation technique that Yagi-Uda antenna may record a marginal increase in gain or directivity when the lengths and spacing between the elements are varied. These works as remarkable as their findings are, do not show how inter element spacings and variations in element lengths affect front- to- back ratio as well as other important design parameters of the antenna. It is in this regard that we give considerable attention on the quantitative investigation of the impact of elements' lengths and separation between elements on the radiated fields, front to back ratio, directivity as well as side lobe radiation of Yagi-Uda antenna operating within wide band frequency spectrum of $500MHz \le f \le 650MHz$ with a view to ascertaining Yagi-Uda design that would exhibit the best radiation properties. Four Yagi-uda antenna designs are considered for numerical investigation. One is Yagi-Uda antenna of uniform lengths of directors with uniform spacings (YUDUS), the second configuration is Yagi-Uda array consisting of equal lengths of directors with non-uniform spacings (YUDNS). Another entity is Yagi-Uda array with varying lengths of directors and equally spaced directors (YVDUS) while the last is Yagi-Uda antenna design consisting of varying directors' lengths and non-equal director spacings (YVDNS). A powerful analytical tool known as Method of moments is employed for transforming electric field integral equation which connects the electric field impressed on the antenna with the induced current, into Ohm's circuit parameters which facilitates the determination of current distribution on all the configurations of Yagi-Uda antenna. Calculation of performance indices of interest to this paper and which forms basic formalism through the performance of those Yagi-Uda antenna types are assessed, is subjected to the numerical solution of current distribution.

SYSTEM MODEL

Figure 1 is the depiction of Yagi-Uda array of uniform and varying lengths of directors of concern here. Figure 1(a) portrays Yagi antenna of uniform lengths of directors while Fig. 1(b) displays Yagi-Uda of varying lengths of directors.

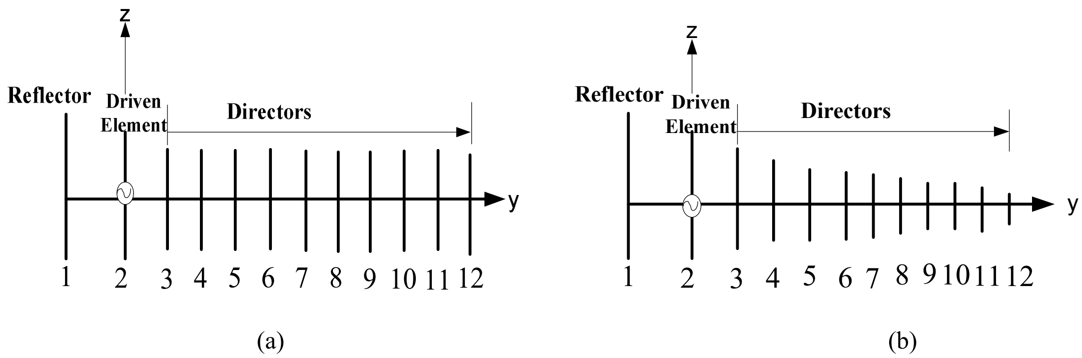


Figure 1: Yagi-Uda Antenna Configurations: (a) Yagi-Uda array of uniform lengths of directors, (b) Yagi-Uda array of varying lengths of directors.

When thin wire approximation critical to Harrington's method of moment procedure (Harrington, 1993) is used, and assuming that radius of the wire is much less than the operating wavelength and length, the scattered electric field developed at the surface by applying excitation voltage at the feed point of the Yagi antenna shown in figure (1) is expressible in a form:

$$E^{s} = \frac{\eta_0}{jk_0}\int_{-h_n}^{h_n} I_n\left(z_n'\right)\left[\left(1+jk_0R\right)\left(2R^2-3a^2\right)+k_0^2R^2a^2\right]\frac{e^{-jk_0R}}{4\pi R^5}dz_n' \tag{1}$$

where j is an imaginary number, η_0 is the free space intrinsic impedance, k_0 is the propagation constant. $I_n\left(z_n'\right)$ is the unknown current induced on the surface of the wires, a is the radius of the wire while R symbolizes the distance from the source point to an observation point.

It is assumed here that the Yagi-Uda antenna conductors are perfectly conducting such that the boundary condition appropriate to the net electric field is enforced at the surface of the antenna. In that regard the electric field impressed on the antenna is expressed as the negative of scattered electric field and assumes form given (Raji and Adekola, 2018)

$$E^{i} = \frac{j\eta_0}{k_0}\int_{-h_n}^{h_n} I_n\left(z_n'\right)\left[\left(1+jk_0R\right)\left(2R^2-3a^2\right)+k_0^2R^2a^2\right]\frac{e^{-jk_0R}}{4\pi R^5}dz_n' \tag{2}$$

Equation (2) is the electric field integral equation whose unknown is the current represented by $I_n\left(z_n'\right)$, and is expressed in terms of integral operator L as

$$E^{i} = L\left[I_n\left(z_n'\right)\right] \tag{3}$$

where

$$L\left[I_n\left(z_n'\right)\right] = \int_{-h_n}^{h_n} I_n\left(z_n'\right)\left[\left(1+jk_0R\right)\left(2R^2-3a^2\right)+k_0^2R^2a^2\right]\frac{e^{-jk_0R}}{4\pi R^5}dz_n' \tag{4}$$

Matrix representation of equation (3) is facilitated by method of moments in which the unknown current is expressed as finite series expansion of current basis function and unknown coefficients in a form given as

$$I_n\left(z_n'\right) = \sum_n\sum_k I_{nk}\, f_{nk} \tag{5}$$

in which I_{nk} is the unknown current coefficient of the basis function while f_{nk} is the known basis function. In this work, Fourier series expansion function of the form $cos\left[\frac{(2k-1)\pi z_n'}{2h_n}\right]$ is utilized. (n,k) represent respectively, the number of elements in the array and expansion modes that are used to cover the length of each wire.

Equation (5) is substituted in eqn. (3) to obtain the following expression for the impressed electric field

$$E^i = \sum_n \sum_k I_{nk} \, L\left[f_{nk}\right] \tag{6}$$

An inner product of eqn. (6) with each Dirac delta weighting function w_{nm} results in expression of the form

$$\langle E^i, w_{nm} \rangle = \sum_n \sum_k I_{nk} \, \langle w_{nm} \, L\left[f_{nk}\right] \rangle \tag{7}$$

Equation (7) is transformed into matrix form of familiar Ohm's law circuit parameters represented by

$$\left[V\right] = \left[I\right]\left[Z\right] \tag{8}$$

where $\left[V\right] = \langle E^i, w_{nm} \rangle$ is the voltage vector, which contains terms that describe the mode of exciting the antenna, $\left[Z\right] = \langle w_{nm} \, L\left[f_{nk}\right] \rangle$ is the impedance matrix whose values are functions of geometry of the antenna while $\left[I\right] = \left[I_{nk}\right]$ is the current vector which contains terms that represent the unknown complex amplitude of the current.

The unknown complex current coefficient emerges when matrix inversion of impedance matrix and multiplication by voltage vector is carried out as denoted by

$$\left[I\right] = \left[Z\right]^{-1}\left[V\right] \tag{9}$$

RADIATION ELECTRIC FIELDS

The radiated electric field associated with induced current distribution on Yagi-Uda admits representation of the form

$$E_\theta = -j\,\omega\,A_\theta \tag{10}$$

in which E_θ is the radiated electric field, ω is the angular frequency in rad/s, j remains as defined earlier, and A_θ is the $\theta-$ component of magnetic vector potential which is deducible from integral of current distribution, and Green's function and admits representation in the form given by Raji and Adekola (2017) as

$$A_\theta = -\frac{\mu_0 e^{-jk_0 r} \sin\theta}{4\pi r} \sum_n \left\{ exp\left[jk_0\left(x_n \sin\theta \cos\varphi + y_n \sin\theta \sin\varphi\right)\right] \sum_k I_{nk} \left[\frac{sin\left(\frac{(2k-1)\pi}{2h_n} + k_0 \cos\theta\right)h_n}{\left(\frac{(2k-1)\pi}{2h_n} + k_0 \cos\theta\right)h_n} + \frac{sin\left(\frac{(2k-1)\pi}{2h_n} - k_0 \cos\theta\right)h_n}{\left(\frac{(2k-1)\pi}{2h_n} - k_0 \cos\theta\right)h_n} \right] \right\} h_n \tag{11}$$

where $exp(-jk_0 r)/r$ is the free space green's function, h_n is the half of lengths of the wires.

The radiation electric field obtained by substituting eqn. (11) in (10) is expressed by

$$E_\theta = \frac{j\omega\mu_0 e^{-jk_0 r}\sin\theta}{4\pi r}\sum_{n=1}\left\{ exp\left[jk_0\left(x_n \sin\theta\cos\varphi + y_n\sin\theta\sin\varphi\right)\right]\sum_k I_{nk}\left[\frac{sin\left(\left(\frac{(2k-1)\pi}{2h_n}+k_0\cos\theta\right)h_n\right)}{\left(\frac{(2k-1)\pi}{2h_n}+k_0\cos\theta\right)h_n} + \frac{sin\left(\left(\frac{(2k-1)\pi}{2h_n}-k_0\cos\theta\right)h_n\right)}{\left(\frac{(2k-1)\pi}{2h_n}-k_0\cos\theta\right)h_n}\right]\right\}h_n \tag{12}$$

DIRECTIVITY OF YAGI-UDA ANTENNA

The power per unit area symbolized by P_{av} that radiates outwardly to a large distance r from Yagi-Uda antenna admits representation of the form of eqn. (13a).

$$P_{av} = \frac{\left|E_\theta(\theta,\varphi)\right|^2 + \left|E_\varphi(\theta,\varphi)\right|^2}{2\eta_0} \tag{13a}$$

where E_θ, E_φ, respectively are the $\theta-$, and $\varphi-$ components of radiated electric field. There exists only the $\theta-$ component of the field radiated by Yagi-Uda antenna as obtained in eqn. (12). Hence, power per unit area that radiates, symbolized here by, S_r is expressed by

$$S_r = \frac{\left|E_\theta(\theta,\varphi)\right|^2}{2\eta_0} \tag{13b}$$

The directivity of Yagi-Uda antenna as a function of distance r is the ratio of maximum power per unit area to power density averaged all over directions Adekola and Okereke (1989), and can be expressed as

$$\text{Directivity} = \frac{S_r(max)}{S_r(ave)} \tag{14}$$

in which $S_r(max)$ is the maximum power density. If the total power radiated symbolized symbolized by P_{rad} is expressed by

$$P_{rad} = r^2\int_0^{2\pi}\int_0^{\pi} S_r \; \sin\theta\, d\theta\, d\varphi \tag{15}$$

Then, the average power density $S_r(ave)$ assumes a form given as

$$S_r(ave) = \frac{P_{rad}}{4\pi r^2} \tag{16}$$

When eqn. (16) is substituted in eqn. (14), directivity in decibel (dB) is expressed by:

$$\text{Directivity (dB)} = 10\ log_{10} \frac{4\pi r^2 S_r(max)}{P_{rad}} \tag{17}$$

SIDE LOBE RADIATION

Side lobe radiation is usually undesirable in communication system. It constitutes for example in radar system false target within the visible range of frequency of interest. Span of electromagnetic signal covered by an antenna is also dependent on the level of side lobe radiation exhibited. It is well known that the lower the side lobe level, the better the coverage area of electromagnetic signal transmission. Side lobe in decibel of Yagi-Uda antenna, denoted by S can be determined by using the expression of the form

$$S = 20\ log_{10} \frac{D_{max}}{D} \tag{18}$$

in which D_{max} is the magnitude of the peak of side lobe radiation while D is the highest magnitude of main lobe radiation which in most cases is unity.

FRONT-TO-BACK-RATIO

By definition, a measure of electromagnetic energy concentrated in the major lobe relative to that of the back lobe is the front-to-back ratio of a directional antenna like Yagi-Uda antenna. It can be determined using the expression of the form given elsewhere Balanis, (1997)

$$F(dB) = 20\ \log_{10}\left[\frac{E_\theta\left(\theta = 90^0, \varphi = 90^0\right)}{E_\theta\left(\theta = 90^0, \varphi = 270^0\right)}\right] \tag{19}$$

where $F(dB)$ is the front –to-back ratio in decibel, and E_θ is the far-zone electric field, expressed by eqn. (12).

NUMERICAL RESULTS

We describe systematically in this section of the work the numerical results obtained for the far zone patterns, directivity, side-lobe radiation, and front-to-back ratio using various analytical expressions obtained in the foregoing.

Far Zone Radiation Patterns

With the help of equation (12), Figure 2(a) shows the far zone patterns of Yagi-Uda array of uniform lengths directors with uniform spacings between directors (YUDUS) whose design parameters are given as: *Length of reflector* $= 0.495\lambda$, *length of driven element* $= 0.47\lambda$, *length of directors* = 0.41λ, *spacing between reflector and driven element* $= 0.25\lambda$, *spacing between driven element and first director* $= 0.325\lambda$, *spacing between directors* $= 0.325\lambda$, *radius of wires* $= 0.033\lambda$. Figure 2(b) is the radiation patterns computed for Yagi Uda array of varying lengths of directors with uniform spacings between directors (YVDUS) by employing the design specifications given as: *Length of reflector* $= 0.495\lambda$, *length of driven element* $= 0.47\lambda$, *length of director 1 and 2* $= 0.41\lambda$, *length of director3* = 0.406λ, *length of director4* = 0.405λ, *length of director5* $= 0.403\lambda$, *length of director6* $= 0.402\lambda$, *length of director7 and 8* $= 0.401\lambda$, *length of director 9 and 10* $= 0.40\lambda$, *spacing between reflector and driven element* $= 0.25\lambda$, *spacing between driven element and director1* $= 0.325\lambda$, *spacing between directors* $= 0.325\lambda$, *and radius of wires* $= 0.033\lambda$.

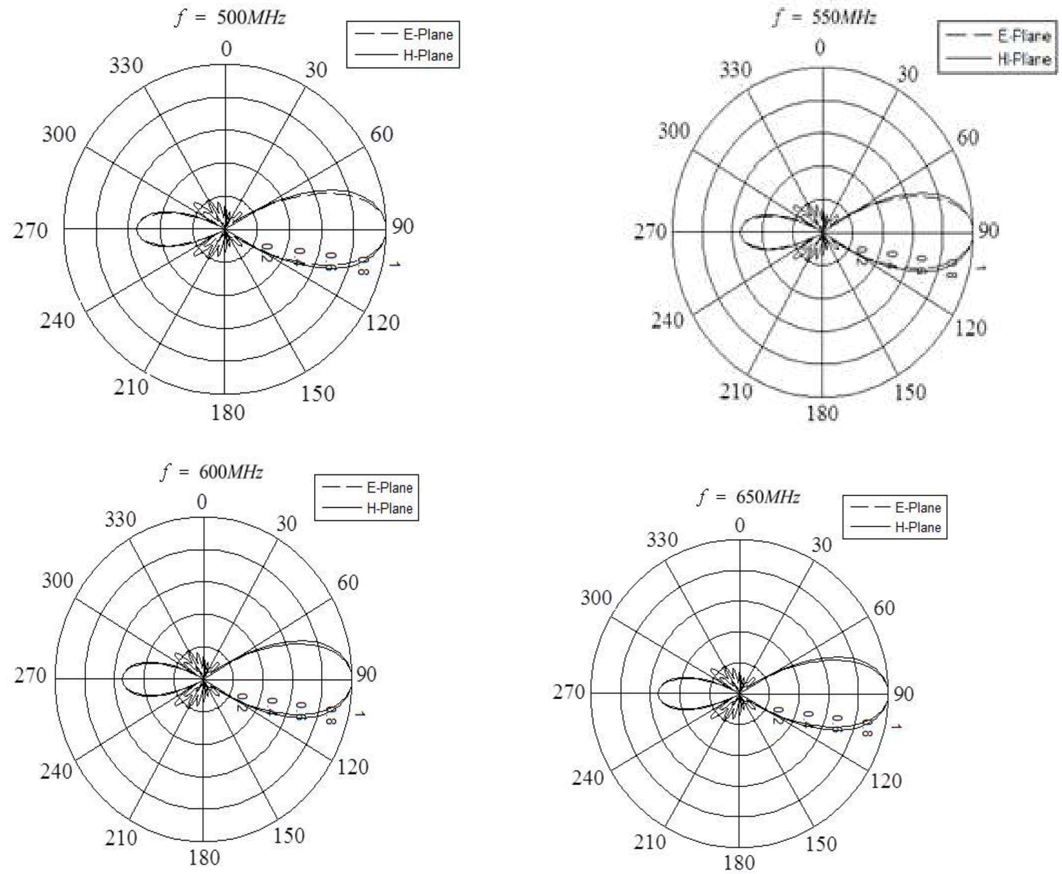
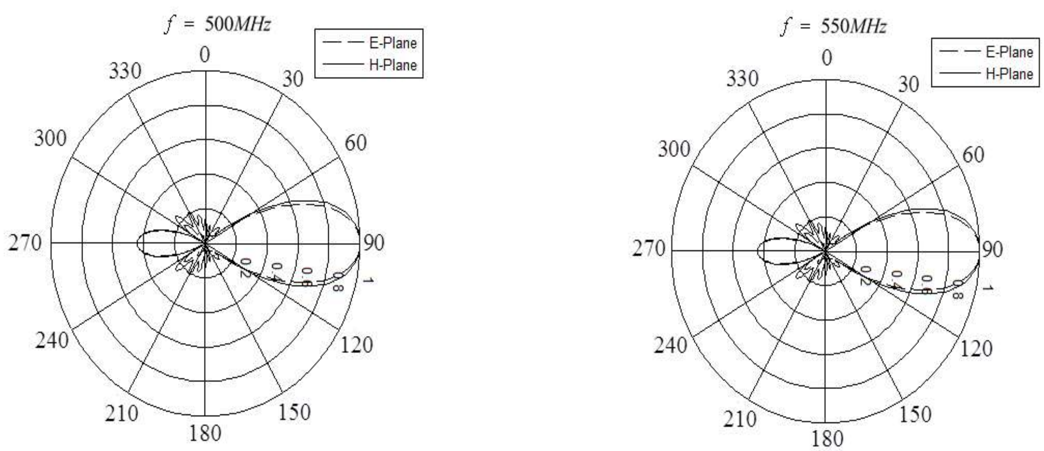


Figure 2a: Far field patterns radiated by Yagi-Uda array of uniform lengths of directors with uniform spacings (YUDUS) within the frequency band $500\,MHz \leq f \leq 650\,MHz$



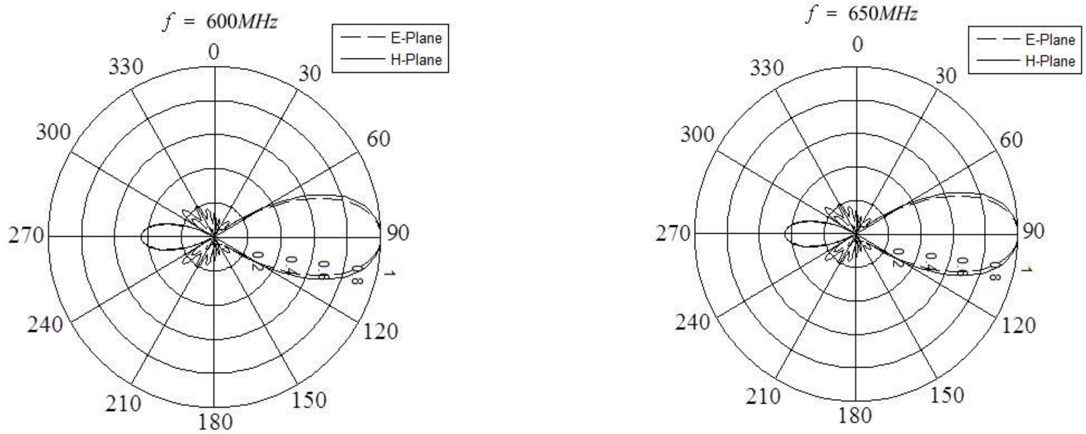


Figure 2b: Far field (E-and H-planes) patterns radiated by Yagi-Uda array of varying lengths of directors with uniform spacings (YVDUS) within the frequency band.

Similarly, Figure 3(a), on the other hand describes the patterns of far zone electric and magnetic fields produced by Yagi-Uda array of uniform lengths of directors with unequal spacings between directors (YUDNS), wherein the design parameters become thus: *Length of reflector* $=0.495\lambda$, *length of driven element* $=0.47\lambda$, *length of directors* = 0.41λ, *spacing between reflector and driven element* $=0.25\lambda$, *spacing between driven element and first director* $=0.325\lambda$, *radius of wires* $=0.033\lambda$, *spacing between director 1 and 2* $=0.3\lambda$, *spacing between director 2 and 3* $=0.31\lambda$, *spacing between director 3 and 4* $=0.315\lambda$, *spacing between director 4 and 5* = 0.315λ, *spacing between director 5 and 6* $=0.32\lambda$, *spacing between director 6 and 7* $=0.32\lambda$, *spacing between director 7 and 8* $=0.321\lambda$, *spacing between director 8 and 9* $=0.325\lambda$, *spacing between director 9 and 10*= 0.325λ.

Figure 3(b) on the other hand typifies the radiation fields of Yagi-Uda array of varying lengths of directors when the spacings employed between the directors are varied (YVDNS), by using the design specification given as: *Length of reflector* $=0.495\lambda$, *length of driven element* $=0.47\lambda$, *length of director 1 and 2* $=0.41\lambda$, *length of director3* $=0.406\lambda$, *length of director4* = 0.405λ, *length of director5* $=0.403\lambda$, *length of director6* $=0.402\lambda$, *length of director7 and 8* $=0.401\lambda$, *length of director 9 and 10* $=0.40\lambda$, *spacing between reflector and driven element* $=0.25\lambda$, *spacing between driven element and director1* $=0.325\lambda$, *radius of wires* $=0.033\lambda$, *spacing between director 1 and 2* $=0.3\lambda$, *spacing between director 2 and 3* $=0.31\lambda$, *spacing between director 3 and 4* $=0.315\lambda$, *spacing between director 4 and 5* = 0.315λ, *spacing between director 5 and 6* $=0.32\lambda$, *spacing between director 6 and 7* $=0.32\lambda$, *spacing between director 7 and 8* $=0.321\lambda$, *spacing between director 8 and 9* $=0.325\lambda$, *spacing between director 9 and 10*= 0.325λ.

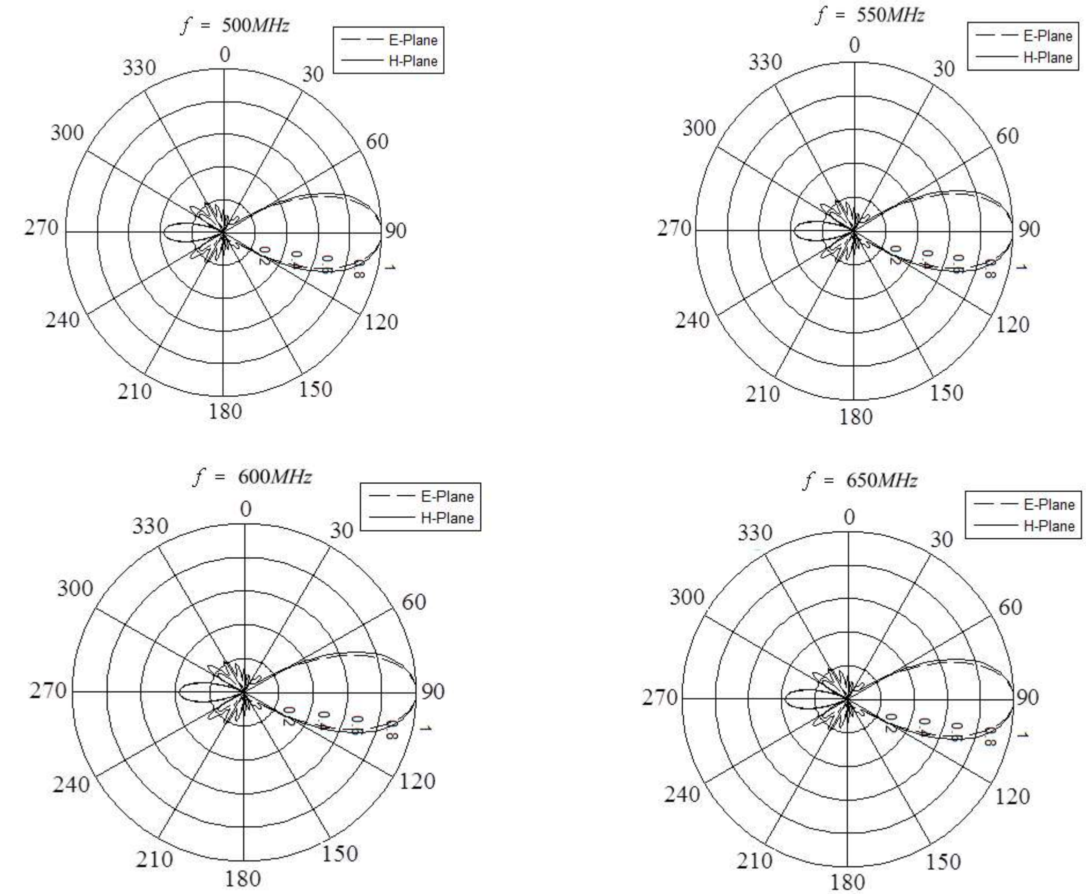
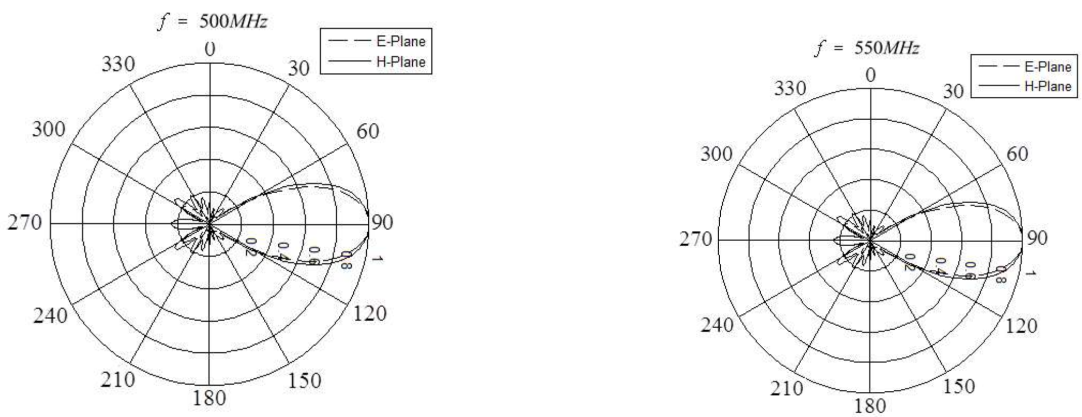
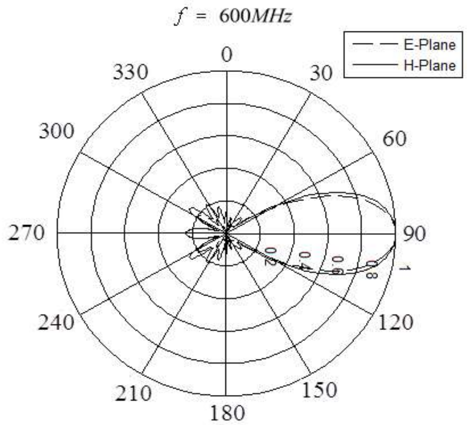


Figure 3a: Far field patterns radiated by Yagi-Uda array of uniform lengths of directors with unequal spacings between directors (YUDNS), operating within the frequency band $500\,MHz \leq f \leq 650\,MHz$





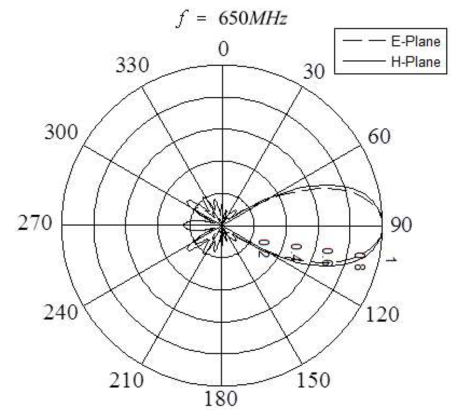


Figure 3b: Far field patterns radiated by Yagi-Uda array of varying lengths of directors with non-uniform spacings between directors (YVDNS), operating within the frequency band $500\,MHz \le f \le 650\,MHz$

It is noticeable that, radiation patterns for the all the versions of Yagi-Uda antenna considered are characterized by maximum radiation energy concentrated at the main lobes in the y-axis with passable side lobe and back lobe radiation. However, it is observed that the side lobe radiation reduces when the physical parameters of the antenna are varied with Yagi-Uda array of varying lengths of directors and unequal spacings between directors (YVDNS) exhibiting the lowest side lobe and backlobe radiation as portrayed in Fig. 3(b). This reveals that the radiation field patterns of Yagi-Uda antenna are sensitive to physical dimensions or characteristics of the antenna.

Directivity Profiles

By using equation (17), characteristic profile of directivity behaviours of various versions of Yagi-Uda antenna considered for numerical investigation are illustrated in Figure (4), wherein directivity is plotted against frequency of operation in the range of $500\,MHz \le f \le 650\,MHz$. It is evident that Yagi-Uda array of varying lengths of directors with non-uniform spacings (YVDNS) portrays higher directivity than other forms of Yagi over considerable range of frequency of interest which suggests that the directivity of the antenna improves when the spacing and lengths of directors are varied.

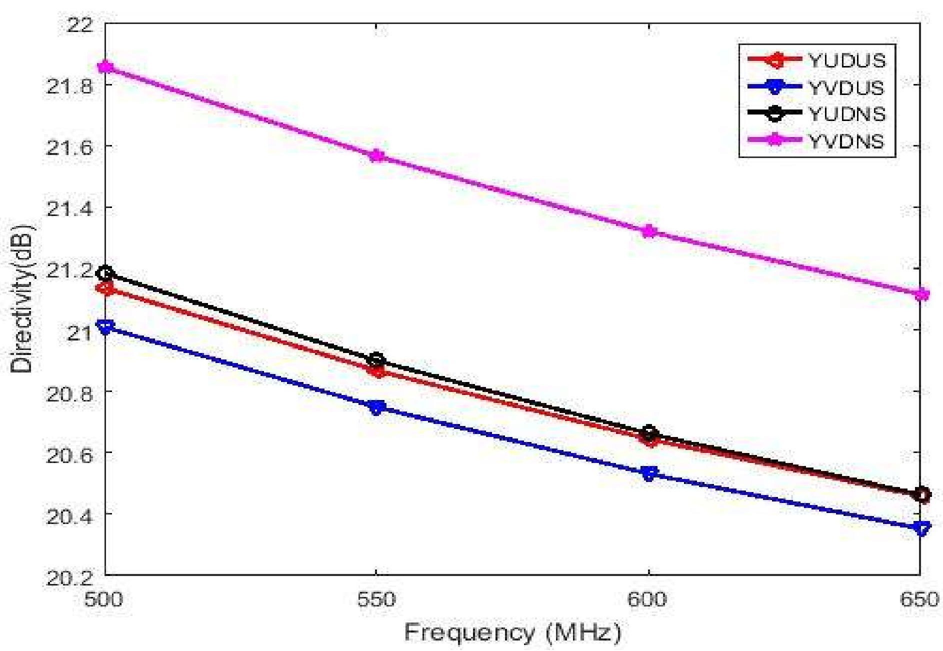


Figure 4: Directivity against frequency for Yagi-Uda antenna of different configurations

Side lobe profiles

When equation (18) is computed, figure 5 depicts side lobe suppression characteristics of all the forms of Yagi-Uda antenna employed for numerical computation. A critical look at the design profile reveals that side lobe levels of all the Yagi-Uda antennas do not change with frequency.

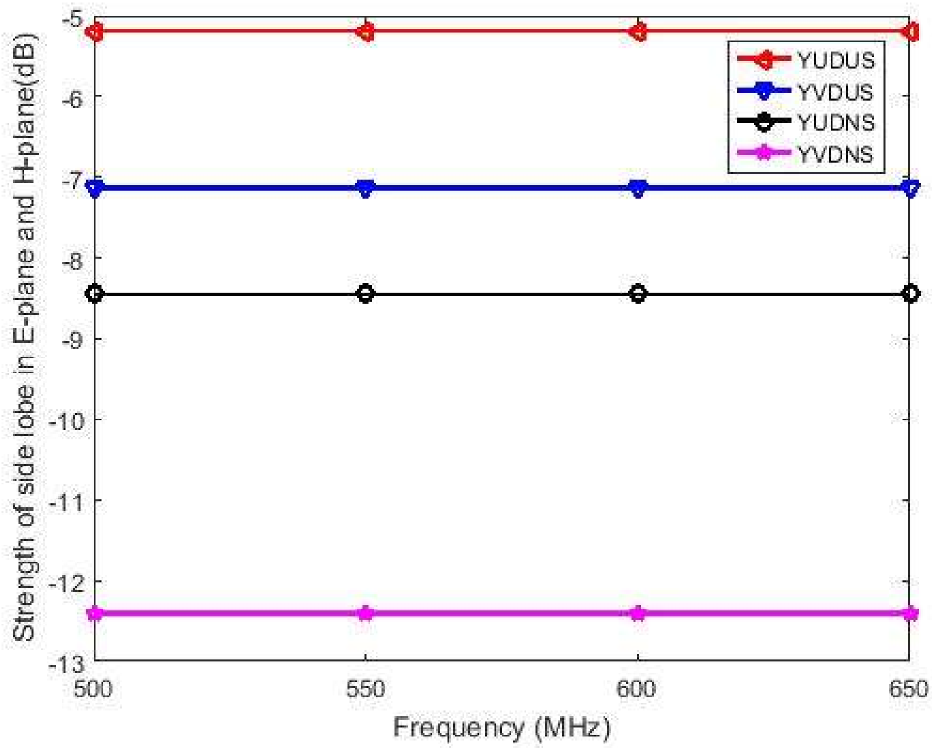


Figure 5: Side lobe Radiation in E-plane and H-plane against frequency for different Yagi-Uda antenna configurations

It is however observed that Yagi-Uda array of varying lengths of directors with uniform spacings (YVDUS) exhibits better side lobe control than Yagi-Uda antenna of uniform lengths of directors with equal spacings (YUDUS). However, when the spacings between directors are varied, Yagi-Uda array of varying lengths of directors with unequal spacings (YVDNS) has greatest reduction of side lobe radiation.

Front-to-back ratio Profile

By employing equation (19), the numerical values obtained for front-to-back ratio for Yagi-Uda arrays are depicted in Fig. (6), and which describes the characteristic behaviour of front-to-back ratio of Yagi-Uda antennas to variation in the frequency.

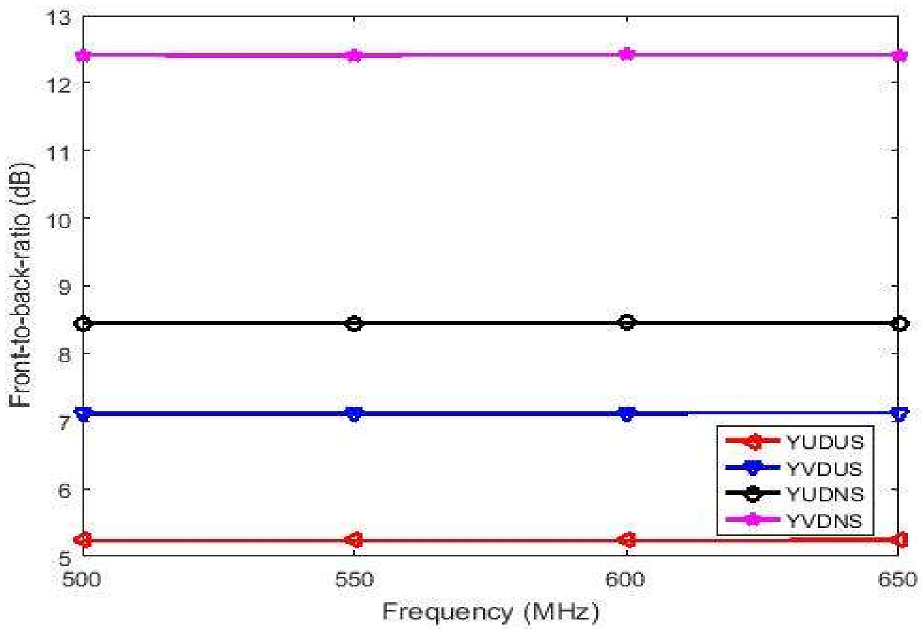


Figure 6: Front-to-back ratio versus frequency for Yagi-Uda antenna of different configurations

An observation of the figure reveals that, the front-to-back ratio for all versions of Yagi-Uda antenna is relatively stable over a range of frequency spectrum. It is observed also that, the front-to-back ratio improves significantly when the lengths and spacing between directors are varied. It is found that, Yagi-Uda array of varying lengths of directors and non -uniform spacings (YVDNS) has the highest front-to-back ratio, and which implies the antenna concentrates greater electromagnetic energy in the main lobe than all other versions of Yagi-Uda antenna.

CONCLUSION

In this paper, we have examined the performance characteristics of four configurations of Yagi-uda antenna. One is Yagi-Uda antenna of uniform lengths of directors with uniform spacings, the second configuration is Yagi-Uda array consisting of equal lengths of directors with non-uniform spacings. Another entity is Yagi-Uda array with varying lengths of directors and equally spaced directors while the last is Yagi-Uda antenna design consisting of unequal directors' lengths and unequal spacings. By using computational method of moment procedure, the electric current on all the versions of Yagi-uda antenna emerges through solution of Ohm law circuit parameters in matrix form which related voltage matrix with unknown current coefficient and impedance matrix. Once the current distribution is known, other performance parameters including directivity, radiated electric and magnetic field patterns, side lobe radiation and front-to back ratio, are obtained and constitute basic metrics through which the performances of those Yagi-Uda antenna types are assessed. It is therefore found that out of all the Yagi Uda antenna configurations used for numerical investigation, Yagi-Uda array of varying length of directors and non- uniform spacings between directors (YVN) has better radiation behaviours than others, concentrating significant energy at teh main lobe in the axial direction. It is also observed that Yagi-Uda array of varying lengths of directors with non-uniformly spaced directors has better directivity, highest front-to-back ratio, better side lobe suppression characteristics, and greater electromagnetic signal coverage than Yagi-Uda antenna of other types.

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