Configuration and performance evaluation of UHF non-uniform length star array antenna

A S Adewumi¹,³ and O Olabisi²

¹ Department of Pure and Applied Physics Ladoke Akintola University of Technology, P.M.B 4000, Ogbomoso, Oyo State, Nigeria.
² Department of Science Laboratory Technology, Ladoke Akintola University of Technology, P.M.B 4000, Ogbomoso, Oyo State, Nigeria.
³ Corresponding author's e-mail: asadewumi@lautech.edu.ng

Abstract -This article presents the results of the performance evaluation of three (3) elements non-uniform length Star Array Antenna at UHF frequency band. In very many applications, it is desired to design antenna configuration that has higher directional properties to fulfill some demand in communication systems. Star shapes Pentagram and Hexagram (Penta-Hexa) gram elements were designed and configured to form an antenna array whose radiation properties can be controlled by varying the amplitude allotment of the three antenna elements, so as to obtain smaller side lobes and highly directional star array antenna configuration. The antenna was constructed based on the design specifications using an Aluminum sheet MatlabR2014a was use to plot the radiation pattern of individual element and that of the whole elements combined together. The Performance analysis of the UHF Star array shows a Dolph- Tschebyscheff field pattern with main lobes maximum at \( \theta = \pi \) and \( \theta = 2\pi \) and with infinitesimal side lobes. Further evaluations give the half-power beamwidth (HPBW) of the UHF Star array to be 4.8° and directivity of 5.17dB. The UHF Star Array shows good performance when compared with a standard antenna. The test performance of the UHF (Penta-Hexa)gram Star Array antenna shows that it will be very suitable for the reception of UHF signals in automobiles and homes.

Keywords: configuration, UHF, (Penta-Hexa)gram, star, antenna, radiation, characteristics

1. Introduction

Antennas are a very essential in transmission and reception of radiofrequency energy in communication systems. It can be defined as instrument used in converting radiofrequency energy in conductors to radio wave in free space and vice versa. The process by which an antenna retain the same properties irrespective of it transmitting or receiving is known as reciprocity [1]. There are various types of antennas used for various applications e.g. loop Antennas, wire antennas, patch antennas, parabolic reflector antennas aperture antennas, lens antenna and array antennas. Antenna arrays are employed when it is desired to obtain a highly directional radiation characteristics that are difficult to realize using one element. Meanwhile, configuration of antenna elements electrically and geometrically will give more directional radiation characteristics so desired. It is, possible that combination of radiating elements in an electrical and geometrical structure will give the desired radiation characteristics. The arrangement may be in such a way that the radiation from the elements adds up to give a radiation maximum in a particular direction or directions, minimum in others, or otherwise as desired [2]. The increasing demand for efficient wireless communication services in
recent times has necessitated the need for new configurations of UHF antennas that can meet the required performances. Therefore, a new configuration and performance analysis of (Penta-Hexa)gram Star antenna array suitable for use at UHF band has been realized.

2. Antenna Design and Procedures

In an array design, the geometrical configuration of the total number of elements, the displacement between the elements and the relative shape of each element are very important factor that influence the radiation characteristics like directional properties, beamwidth (half-power) and side lobe extent [2] and [3]. This UHF Pentagram and Hexagram star antenna array was designed in way that its radiation properties can be controlled through the choice of varying the amplitude and phase distribution of all the elements used as shown in figure 1a. During the design process, some of the parameters were determined as highlighted below.

2.1 The (Penta-Hexa)gram Star Array Antenna Boundary Conditions Design

At the beginning, the limit conditions for designing the UHF (Penta-Hexa)gram Star antenna array in the UHF frequency band of 900MHz-2000MHz were deduced as depicted in Table 1.

| Frequency Band | Lower Frequency (900MHz) | Upper Frequency (2000MHz) | Bandwidth | Center Frequency |
|----------------|-------------------------|---------------------------|-----------|------------------|
| UHF            | 900MHz                  | 2000MHz                   | 2.22      | 1450MHz          |

2.2 The (Penta-Hexa)gram Structural Geometry Design

The structural geometry design of the UHF (Penta-Hexa)gram Star Array was developed using the fundamental formula for wire antenna length determination is given by [1], [2], and [4] as;

\[ \lambda = \frac{\mu}{f} \] (m)

(1)

f is the frequency, \( \nu \) is the speed of light \( (3 \times 10^8 m/s) \) and \( \lambda \) is the wavelength. The design shows that the Pentagram element has 10 edges and 5 pointed angles while the hexagram element has 12 edges and 6 pointed angles or vertex. Individual edge is taken as dipole of point source while the vertex line in-between the two edges was taken to be the amplitude. Therefore, the Pentagram has 10 point sources while the Hexagram has 12 point sources, and the Length was designed using \( L = \lambda/10m \) for Pentagram and \( L = \lambda/12 m \) for Hexagram separately. The spacing between individual element was deduced from \( d = \lambda/2(m) \). The calculated geometrical dimensions of the three (3) elements UHF Star antenna array are as depicted in table 2.

| 1st Element (Hexagram) | 2nd Element (Pentagram) | 3rd Element (Hexagram) | (Penta-Hexa)gram Star Array |
|-----------------------|-------------------------|------------------------|---------------------------|
| \( \lambda \) (m)     | 0.33                    | 0.21                   | 0.15                      | 0.27                       |
| L (m)                 | 0.027                   | 0.021                  | 0.013                     | 0.3305                     |
| d (m)                 | 0.135                   |                         |                          |                            |
2.3 The UHF (Penta-Hexa)gram Star Antenna Array Radiation Pattern Evaluation

Theoretically, the radiation pattern of electrically minute antenna of any geometry be it rectangular, circular, square, elliptical and so on is the same as that of extremely small dipole with its null at right angle to the plane of the loop and greater along the plane of such loop [2, 5, 6, and 9]. Therefore, the radiation pattern of this newly arranged UHF Pentagram-hexagram Star antenna array is also compared to exceedingly minute dipoles with the edges acting as minute linear dipoles of unchanging current $I_o$ and length (L). This antenna is designed as a non-uniform amplitude antenna with uniform spacing between elements.

The total field $E_n$ from even number of sources is written as an Even Fourier series given by [1] as;

$$E_{ne} = 2 \sum_{k=0}^{N-1} A_k \cos \left( \frac{2k+1}{2} \psi \right)$$  \hspace{1cm} (2)

where $\psi = \frac{2\pi d}{\lambda} \sin \theta = d_r \sin \theta$ and $N = \frac{n_e}{2}$; $k = 0, 1, 2, 3, \ldots \ldots$, $A_k$ is the amplitude of the each element point source.

Hence the 3 elements UHF Star Array (figure 1a) have 34 points sources whose total electric field pattern ($E_{ne}$) is deduced from (2) as

$$E_{34} = 2A_0 \cos \left( \frac{1}{2} \psi \right) + 2A_1 \cos \left( \frac{3}{2} \psi \right) + 2A_2 \cos \left( \frac{5}{2} \psi \right) + \ldots + 2A_{16} \cos \left( \frac{33}{2} \psi \right)$$  \hspace{1cm} (3)

The electric field pattern of an even number of point sources is a Fourier series but one which has no unchanging term and only odd harmonics. The coefficients are irrational and express the amplitude distributions [1] and [10]. The length of the line of individual point source in a non-uniform antenna array is commensurable with the "amplitude" [7]. Therefore, the coefficients ($A_k$) of the amplitude of the first element (Hexagram) of the Star array was designed as [1];

$$2A_0 = 2A_1 = 2A_2 = 2A_3 = 2A_4 = 2A_5 = 1$$  \hspace{1cm} (4)

The amplitude of the remaining two elements were deduced relative to the first element designed parametric ratio of table 2 as shown in (5) and (6).

$$2A_6 = 2A_7 = 2A_9 = 2A_{10} = 2A_{15} = 0.67$$  \hspace{1cm} (5)

$$2A_{11} = 2A_{12} = 2A_{13} = 2A_{14} = 2A_{15} = 2A_{16} = 0.33$$  \hspace{1cm} (6)

Hence, (3) becomes;

$$E_{34} = \cos \left( \frac{1}{2} \psi \right) + \cos \left( \frac{3}{2} \psi \right) + \cos \left( \frac{5}{2} \psi \right) + \cos \left( \frac{7}{2} \psi \right) + \cos \left( \frac{9}{2} \psi \right) + \cos \left( \frac{11}{2} \psi \right)$$

$$+ 0.67 \cos \left( \frac{13}{2} \psi \right) + 0.67 \cos \left( \frac{15}{2} \psi \right) + 0.67 \cos \left( \frac{17}{2} \psi \right) + 0.67 \cos \left( \frac{19}{2} \psi \right) + 0.67 \cos \left( \frac{21}{2} \psi \right)$$

$$+ 0.33 \cos \left( \frac{23}{2} \psi \right) + 0.33 \cos \left( \frac{25}{2} \psi \right) + 0.33 \cos \left( \frac{27}{2} \psi \right) + 0.33 \cos \left( \frac{29}{2} \psi \right) + 0.33 \cos \left( \frac{31}{2} \psi \right)$$

$$+ 0.33 \cos \left( \frac{33}{2} \psi \right)$$  \hspace{1cm} (7)
Note: \( \psi = \frac{2\pi d}{\lambda} \sin \theta \); and \( d \) is taken to be \( \frac{\lambda}{2} \).

The polar plot of the radiation pattern of the newly arranged (Penta-Hexa)gram star antenna array at \( 0 \leq \theta \leq 360 \) were simulated using Matlab R2014a, and the results are as depicted in figure 2a to figure 2d. The "beamwidth" (half-power) and the "directivity" of the newly arranged UHF (Penta-Hexa)gram Star antenna Array was obtained from figure (2) using (8), (9), (10) and (11) given by [7] and [8] as:

\[
\theta_h = \cos^{-1} \left[ \cos \theta_o - 0.443 \frac{\lambda}{(L+d)} \right] - \cos^{-1} \left[ \cos \theta_o + 0.443 \frac{\lambda}{(L+d)} \right] \tag{8}
\]
\[
f = 1 + 0.636 \left( \frac{2}{R_o} \cosh \left[ \sqrt{(\cosh^{-1} R_o)^2 - \pi^2} \right] \right)^2 \tag{9}
\]
\[
\text{HPBW} = \theta_h \times f \tag{10}
\]
\[
\text{Directivity} \ D_o = \frac{2 R_o^2}{1 + (R_o^2 - 1)(f - \frac{\lambda}{L+d})} \tag{11}
\]

f is the array beam broadening factor \( R_o \) is the major to minor lobe ratio.

3. Results and Discussion

Figures 2a, 2b, 2c, and 2d represent the field pattern of the first, second, third, and UHF Array elements of the (Penta-Hexa)gram Star antenna simulated using matlab R2014a. The two nulls are at \( 90^\circ \) and \( 270^\circ \) respectively. The first element field pattern (figure 2a) shows maximum directivity at \( \theta = \pi \) and \( \theta = 2\pi \) with few smaller side lobes. The second and third elements (figure 2b and figure 2c) show some broadside Dolph-Tschebyscheff field patterns with multiple main and side lobes in different directions which implies non highly directive scenarios. Figure 2d shows the combined (Penta-Hexa)gram three (3) elements star array antenna field pattern of highly directed main lobes at \( \theta = \pi \) and \( \theta = 2\pi \) with infinitesimal side lobes. Figure 2d specifically shows the field pattern of the UHF non-uniform amplitude (Penta-Hexa)gram elements Star Array antenna. This depicted infinitesimal side lobes field pattern of a higher directional Star Array antenna with a half-power beamwidth of 4.8° and directivity of 5.17dB at \( \theta = \pi \) and \( \theta = 2\pi \). More also, the performance shows that as the elements number increases from one to three the star array antenna field pattern becomes more directional and the side lobe suppressed.

Figure 3 shows one of the screen copies of the received signal strength obtained in dBm from GPS 730 spectrum analyzer used during measurement at different UHF band when compared with standard antenna. The data obtained on the GSP 730 from several measurements using the two antennas are shown in table 3 and figure 4 show the comparison of the results.

Figure 4 shows that the configured UHF Pentagram-hexagram Star Array antenna also has quality Received Signal Strength (RSS) when compared with standard antenna during field measurement of available UHF signal in all directions ranging from angle 0degree to 360degree at an interval 15degree. Table 4 shows the comparison results of the received Signal Strength (RSS) of the two antennas when subjected to two sample test using t-Test statistics. With the Null hypothesis mean1-mean2=0 and Alternative hypothesis of mean1-mean2 less than or greater than 0. At the 0.05 level, the difference of the population means it is not significantly different with test difference (0). This implies that the fabricated UHF Pentagram-hexagram Star Array antenna has equal RSS with that of standard UHF antenna and that, it will equally performed well if it is used as an alternative to standard UHF antenna of the same frequency band.
Figure 2: (a) Field pattern of first element (b) Field pattern of second element (c) Field pattern of third element (d) Total field pattern of the UHF (Penta-Hexagram Star Array) antenna (3 elements)
Figure 3: UHF(Penta-Hexagram) Star Array Antenna Performance Test Response on GSP-730 Spectrum Analyzer

Table 3. Experimental Data obtained from comparison measurement

| Angle (°) | 0    | 15   | 30   | 60   | 75   | 90   | 105  | 120  | 150  | 180  | 195  |
|----------|------|------|------|------|------|------|------|------|------|------|------|
| Fabricated Antenna | -46.1 | -54.65 | -47.1 | -50.1 | -56.1 | -59.4 | -47.1 | -59.4 | -53.1 | -52.3 | -51.1 |
| Standard antenna    | -48.2 | -75.2 | -52.15 | -54.15 | -53.2 | -56.6 | -55.2 | -59.1 | -57.2 | -55.2 | -51.2 |

| Angle (°) | 210  | 225  | 240  | 255  | 270  | 285  | 300  | 315  | 330  | 360  |
|----------|------|------|------|------|------|------|------|------|------|------|
| Fabricated Antenna | -54.65 | -51.2 | -52.65 | -53.1 | -63.1 | -58.1 | -53.1 | -58.2 | -50.1 | -46.1 |
| Standard antenna    | -56.1 | -54.2 | -58.65 | -54.2 | -48.3 | -50.2 | -53.15 | -53.1 | -53.65 | -48.2 |
**Figure 4**: UHF (Penta-Hexa)gram Star Array comparison with standard UHF Antenna

**Table 4**: t-Test Statistics of the Received Signal Strength (RSS) of figure 4

| Two Sample Test                      | t statistic | DF | Prob>|t| |
|--------------------------------------|-------------|----|-----|
| Equal Variance Assumed               | 1.11202     | 40 | 0.27277 |
| Equal Variance Not Assumed           | 1.11202     | 38.08599 | 0.2731 |

4. Conclusion
In this work a newly configured 3 elements UHF (Penta-Hexa)gram Star array antenna of non-uniform amplitude with uniform spacing has been realized. The configured UHF (Penta-Hexa)gram Star array antenna has demonstrated higher directivity (pencil-like beam) with infinitesimal side lobes, good reception quality, and ability to receive signals at different UHF transmitting frequencies. The test performance of this UHF Star Array antenna has shown that it is suitable for use as a receiving antenna at UHF band in automobiles and homes, and can as well be used as an alternative to standard UHF antenna.

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