

Design and Analysis of 1x4 and 1x8 Circular Patch Microstrip Antenna Array for IWSN Application

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Abstract

A 1x4 and 1x8 circular micro strip patch antenna array operating at 2.4GHz are simulated for Industrial Wireless Sensor Network (IWSN) applications using CST studio suite and MATLAB based simulator software. The circular patch antenna designed on a FR4 substrate with dielectric constant of 4.4 and a substrate height of 1.6mm is fed using inset-fed technique. Several antenna characteristics such as return loss, radiation pattern, bandwidth, directivity, antenna gain, radiation efficiency is analyzed. The compact size and higher directivity help to improve the network performance by alleviating contention, increasing communication range, and mitigating interference of the system. Hence, the advantages gained, make the system more useful for IWSN applications as achieved in this research.

Keywords: Circular microstrip patch antenna, FR-4 Substrate, Inset fed and probe technique, Linear Array, IWSN

1. Introduction

Large-scale industrial networks have benefited from the development of industrial wireless sensor networks (IWSNs), which have evolved into a productive, affordable network solution for process control and industrial automation in factories (Pu et al., 2022). No matter the IWSN's application profile, highly effective antennas are required for every wireless communication transmission. As a result, the antenna's function is crucial and should not be disregarded. Due to the increased demand for IWSNs applications, there is a continuing need to advance antenna technologies, which include new antenna designs in order, to boost IWSN performance and efficiency by enabling long-range and low error-rate communication link (Anchidin et al., 2023). IWSNs are subject to a number of risks from radio frequency interference. In addition to the tried-and-true techniques like deterministic assignment multiple access or random multiple access, equipping sensor nodes with antenna arrays is a workable solution to interference issues (Chinwewe et al., 2015).

Microstrip Patch Antennas (MPAs) have grown in popularity in recent years due to its qualities such as light weight, high efficiency, high gain, high directivity, and low return loss, which will aid in communication with a wide variety of frequencies and be utilized in applications such as remote sensing, medical areas, etc. (Shravan et al., 2019). One of the most widely used printed antennas for wireless applications is the microstrip patch antenna. Its features, like compact size, lighter weight, and simpler construction, enable it to be employed in military and satellite & mobile communications applications. The most popular type of antenna that can also be utilized in an array configuration is the patch antenna. It is a narrowband and widebeam antenna that can be easily built using fabrication processes like etching.

On one side of the dielectric substrate, there is a metal structure, and on the other, there is a ground plane. Microstrip antennas have many benefits, including low cost, mass production, the dual polarization concept, and simpler integration with other intricate circuits. Less bandwidth, reduced gain, the development of surface waves, and radiation from the edges are a few of the downsides (Pradeep, 2018).

Since circular MPA (CMPA) outperforms other varieties in terms of return loss and VSWR, it will be discussed. A circular antenna also performs better when side lobes and bandwidth are taken into account (Shravan et al., 2019). It is also more comparatively helpful for IWSN applications because of its small size and higher directivity, which reduces contention, expands communication range, and reduces interference (Tarter et al., 2016). The design and analysis of 2.4 GHz 1x4 and 1x8 CMPA arrays with excellent efficiency that are appropriate for Industrial Wireless Sensor Network applications will be the focus of this paper.

The remainder of the paper is structured as follows: The related works are described in Section 2, the design of the 1x4 and 1x8 arrays from a single element CMPA is described in Section 3, the results obtained are presented in Section 4, and the discussion of the results of the single element CMPA and the 1x4 and 1x8 CMPA arrays is described in Section 5, after which conclusions and recommendations are highlighted in Section 6.

2. Related Works

The following is a survey of various related works on the design and analysis of linear microstrip patch antenna arrays undertaken by researchers:

Gurudev and Bakhar (2022) designed and implemented a 1x2 and 1x4 rectangular microstrip patch antenna arrays at 2.4 GHz applications using Flame Retardant-4 (FR-4) substrate. The single element, two (1x2) array and four (1x4) array antennae with microstrip line feeding technique were designed by using the 3DEM of mentorgraphics software. The results showed that the simulated value of return loss of the single element microstrip patch antenna was -40.5 dB, the 1x2 array antenna as -28.5 dB and the 1x4 array is -27.7 dB.

Vijayalakshmi J et al., (2020) designed and analyzed a high gain 2x1, 4x1, 8x1, and 8x8 circular patch antennae for 2.4 GHz applications on an FR-4 substrate with 4.4 dielectric constant using the Ansoft High Frequency Structure Simulator (HFSS) software. The technique of edge-fed microstrip line was used. The 2x1 array had a return loss of -9.4 dB, a gain of 3.6 dB, a VSWR of 2.09, and a bandwidth of 50 MHz.

Santoso et al., (2020) carried out a parametric study of 1x2, 1x4, and 1x8 rectangular microstrip antenna array at 2.2 GHz using FR-4 substrate. Single set of antennae was created first to get the desired parameters and then continued to create antenna arrays of 1x2, 1x4, and 1x8. The range of antenna arrays was fed using the Wilkinson power divider technique on the side of the patch. Array antenna planning aimed at increasing the antenna gain value as well as the antenna directivity value. The simulation results obtained consecutive values ranging from single antennae, as well as 1x2, 1x4, and 1x8 antenna arrays, with return loss of -22 dB, -25.9 dB, -15.3 dB, and -20.2 dB. VSWR values for each were 1, 1.1, 1.4 and 1.2. The gain values were 3.38 dB, 5.52 dB, 7.84 dB, and 9.64, respectively. Also, the respective antenna bandwidths were obtained as 99.4 MHz, 110 MHz, 180 MHz, and 170 MHz.

Islam et al., (2019) designed a 1x2, 1x4, and 1x8 microstrip patch antenna for wearable devices for narrowband and biomedical applications at 2.45 GHz. The single element antenna that made up the array was realized by using defected ground structure. The -10 dB impedance bandwidth of the antenna is 20 MHz (2.442-2.462 GHz), which was the bandwidth of channel 9 the ISM band. The antenna achieved a high gain of 7.04 dBi with an increase of 17.63% antenna efficiency. The antennae were light weighted, low cost, easy to fabricate and with better performance that made it suitable for biomedical WLAN applications.

Shanthi P. et al., (2019) utilized Ansys-based HFSS simulator software to design and analyze a 1x2 circular microstrip patch antenna array at 2.4 GHz. The circular patch antenna was built on a FR4 substrate with a dielectric constant of 4.4 and a height of 1.6 mm using the edge feeding microstrip line technique. The maximum gain attained by

the proposed simulation architecture was 11.7 dB, with a return loss of -11.6. Based on the need for a smaller area, the design used a circular patch rather than a rectangular patch. However, the circular patch had the disadvantage of having high input impedance along its circumference. The return loss of -11.6 was only marginally better than the acceptable operation range of -10 dB. Slots of various shapes could be added to the radiating patch to improve this.

Ahmed, (2019) designed and analyze a 1x4 microstrip patch antenna for 2.4 GHz application using FR-4 substrate. HFSS software was used for the simulation of the 1x4 antenna array using edge feed technique. The results showed that the antenna array possessed a return loss of -20.5 dB, VSWR of 1.0 and maximum gain of 8.25 dB.

Qurratul Ayn et al., 2017 used HFSS software to design and simulate high-gain 2x1 and 4x1 circular patch antenna arrays for 2.4 GHz applications on a FR-4 substrate. The single patch antenna used the probe feeding technique, while the arrays of 2x1 and 4x1 employed the edge fed microstrip line technology. The maximum gains attained from the simulation design were 8.2572 dB for a 4x1 array and 5.7414 dB for a 2x1 array. As expected, the 4x1 array outperformed the 2x1 array in terms of performance.

According to these literatures reviewed, most existing CMPA utilizes edge fed microstrip transmission line technology for the antenna arrays, which though is superior in performance to probe fed technology, it is inferior to inset-fed microstrip line technology. This research uses inset-fed microstrip transmission line for the design and analysis of the 1x4 and 1x8 CMPA arrays. In conclusion, from the analysis of the performance parameters used in this research, it has been shown that the inset-fed CMPA arrays are suitable and superior in performance for IWSN applications when compared to other types of MPA in literatures.

3. Microstrip Patch Antenna Array

The design procedure is broken down into two stages viz., Single element CMPA design as well as the 1x4 and 1x8 CMPA linear array design.

3.1 Single Element Design

The design parameters of the proposed circular inset-fed microstrip patch antenna are discussed in this section. Figure 1 shows the geometry of the designed circular inset-fed microstrip patch antenna. The various equations needed to achieve the designed single element model are shown in section (3.1.1) through (3.1.8), respectively, and the derived parameters are shown in Table 1.

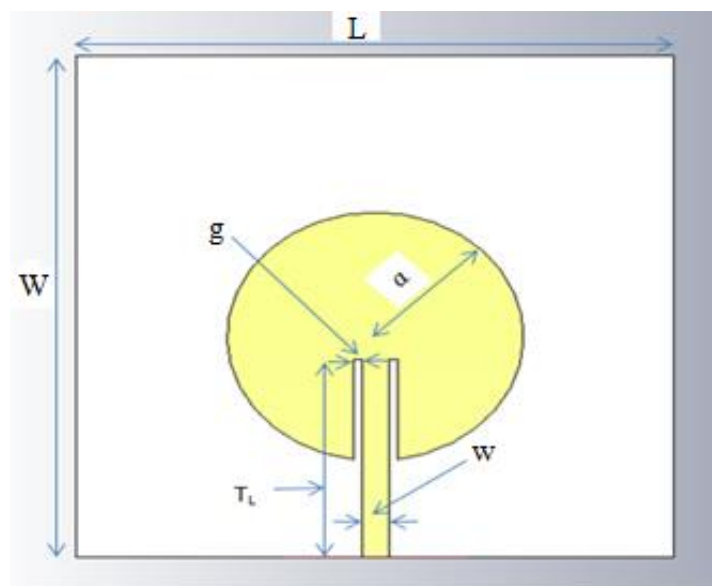


Figure 1. Structure of an Inset-Fed CMPA

3.1.1 Initial Antenna Parameter

The initial antenna parameter is specified, which includes the operating frequency, velocity, wavelength, substrate permittivity (ϵ_r) and substrate type and thickness (h).

Operating frequency is 2.4 GHz

Free space velocity of light c or v_0 is 3×10^8 m/s

Substrate type is FR-4

The substrate plays a vital role in antenna design. Normally, substrates should have permittivity of $2.2 \leq \epsilon_r \leq 12$. The dielectric constant of FR-4 substrate (ϵ_r) varies from 4.3 to 4.7. Here $\epsilon_r = 4.4$ was adopted from the work of Shravan et al., 2019 to allow for comparison. The wavelength.

$$\lambda = \frac{c}{f_0} \tag{1}$$

The height of dielectric substrate h is chosen such that:

$$h \geq \frac{0.06\lambda_{air}}{\sqrt{\epsilon_r}} \tag{2}$$

h was chosen to be 1.6mm to allow for comparison with the work of Shravan et al., (2019).

3.1.2 Calculating the Radius of a Circular Patch

The radius of a circular patch is calculated according to Shanthi et al., (2019) using the following equation:

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi\epsilon_r F} \left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726 \right] \right\}^{1/2}} \tag{3}$$

where:

$$F = \frac{8.791 \times 10^9}{f_r \sqrt{\epsilon_r}} \tag{4}$$

3.1.3 Calculating the Length and Width of the Substrate

According to Rahman et al., (2020), the length and width of the substrate are normally taken as two times the radius of the circular patch.

$$L = 2 \times \text{PatchDiameter} \tag{5}$$

$$W = 2 \times \text{PatchDiameter} \tag{6}$$

3.1.4 Calculating the Length of the Microstrip Transmission Line

The microstrip transmission line length (T_L) is calculated as (Rahman et al., 2020):

$$T_L = 2a \tag{7}$$

3.1.5 Calculating of Effective Dielectric Constant

This is considered due to the presence of E and H-field lines partially in air and in the substrate. The effective dielectric constant ($\epsilon_{r_{eff}}$) is calculated according to Prabhakar et al., (2016) using equation (8):

$$\epsilon_{r_{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{1/2} \tag{8}$$

3.1.6 Calculating the Notch Width

The notch width, (g) is calculated as Prabhakar et al., (2016):

$$f_r = \frac{v_0}{\sqrt{2x\epsilon_{r_{eff}}}} \frac{4.6x10^{-14}}{g} + \frac{f}{1.01} \tag{9}$$

To obtain the desired resonance (f_r) at the operating (f_o), that is, $f_r = f_o = f$. The equation (9) becomes:

$$f = \frac{v_0}{\sqrt{2x\epsilon_{r_{eff}}}} \frac{4.6x10^{-14}}{g} + \frac{f}{1.01} \tag{10}$$

Rearranging this expression of f as a function of g , it becomes:

$$g = \frac{v_0}{\sqrt{2x\epsilon_{r_{eff}}}} \frac{4.6x10^{-12}}{f_{GHz}} \tag{11}$$

3.1.7 Calculation of Inset-Fed Depth

This arrangement for feeding a microstrip antenna is known as the “inset-feeding”. It has been shown that the resonant input resistance can be varied by using an inset-fed (F_i) distance (Pradeep, 2018) because it provides a method of impedance control with a planar feed configuration (Hu *et al.*, 2006). The feed-line inset impedance is calculated according to Hasan et al., (2017) as:

$$F_i = 10^{-4}(p - q. \epsilon_r + r. \epsilon_r^2 - s. \epsilon_r^3 + t. \epsilon_r^4 - u. \epsilon_r^5 + v. \epsilon_r^6 - w. \epsilon_r^7) \frac{L}{2} \tag{12}$$

where the values of the parameters are $p = 6697$, $q = 4043$, $r = 2561.9$, $s = 682.69$, $t = 93.187$, $u = 6.1783$, $v = 0.13761$, $w = 0.001699$.

3.1.8 Feed-line Width

The supply from microwave source fed through a coaxial feed-line is further distributed amongst elements using inset microstrip feed-lines, whose widths (w) are determined using the transmission line equation given by Shravan et al., (2019) as:

$$Z_0 = \frac{81.0}{(\epsilon_r + 1.41)^{1/2}} \ln \frac{5.98h}{0.8w + t} \tag{13}$$

$$W = \frac{e^{-t \frac{5.98h}{\left(\frac{Z_0 \times 81.0}{(\epsilon_r + 1.41)^{1/2}}\right)}}}{0.8} \tag{14}$$

where, h is the height of the substrate and t is thickness of the tract. The design parameters of the circular inset-fed Microstrip Patch Antenna (MPA) are shown in Table 1 and the single element simulated from these parameters using CST software is shown in Figure 2

Table 1. Design Parameter Definition and Values of Single Element MPA.

Parameter	Definition	Value
f	Frequency	2.4 GHz
a	Patch radius	17mm
h	Substrate height	1.6mm
w	Feed line width	0.21mm
ϵ_r	Dielectric Constant	4.4

L	Substrate Length	68mm
W	Substrate Width	68mm
T_L	Transmission line length	34mm
g	Notch width	1.9×10^{-4} mm
t	Copper metal thickness	0.035mm

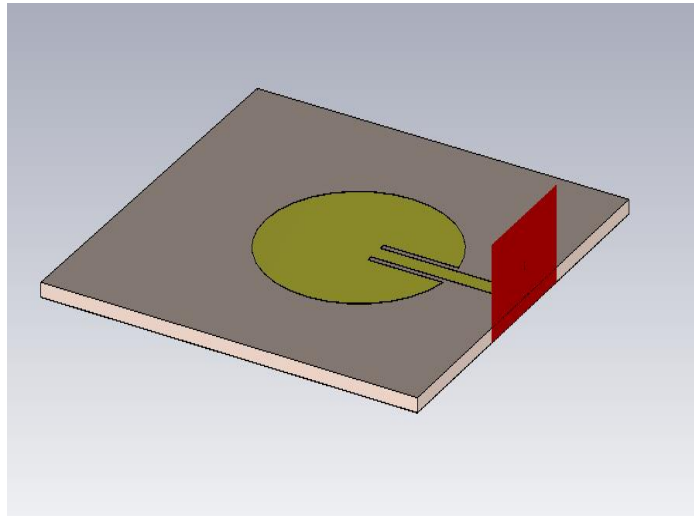


Figure 2: Simulated Model of the Inset-Fed Circular Patch Antenna

3.2 Design Analysis of 1x4 and 1x8 Linear Array

The design procedure for the MPA array is similar to the design of the single microstrip patch antenna, but here the four patches are arranged in a linear form to create a linear array.

3.2.1 Geometry

The geometrical arrangement of 1x4 and 1x8 are chosen for the antenna array while other parameters are as determined from Table 1.

3.2.2 Inter-Element Spacing

Recall from equation (1), the wavelength (λ) of the antenna is 0.125m. The inter-element spacing between two patches in an antenna array is specified as a fraction of λ , which according to Noor *et al.*, (2018), the higher values of it contribute to higher number of side lobes, narrower main lobe, higher directivity, and lower Half Power Beam Width (HPBW). The inter-element spacing that is equal to $\lambda/2$ is found to be the most suitable value for circular array antenna design based on analysis (Noor *et al.*, 2018).

The space between two elements is thus chosen as $\lambda/2$ (that is, 62.5mm in this research). This is chosen in order to obtain uniform symmetric radiation pattern in both directions, that is, along $\theta = 0^\circ$ and $\theta = 180^\circ$. The simulated model of the 1x4 and 1x8 inset-fed CMPA from the single element model using MATLAB 2020a is shown in Figure 3 and Figure 4, respectively.

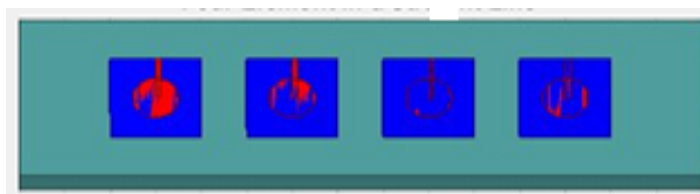


Figure 3. Simulated Model of 1x4 Linear Antenna Array

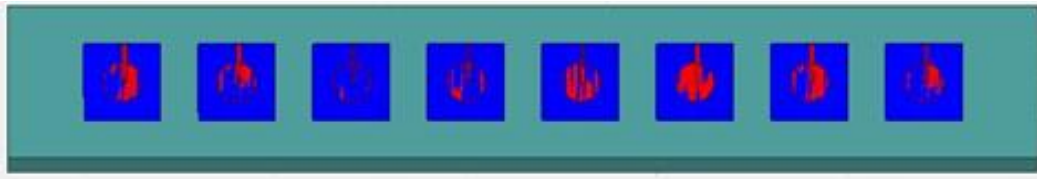


Figure 4. Simulated Model of 1x8 Linear Antenna Array

4. Results

The simulation results of the single element inset-fed CMPA, the 1x4 inset-fed CMPA, and the 1x8 CMPA array are presented in this section.

4.1 Single Element MPA

The single patch antenna provides a maximum gain of 5.4dB and the directivity is 6.35dBi. Figures 5, 6 and 7 show the return loss of -38 dB, Voltage Standing Wave Ratio (VSWR) of 1.73 and the 3D radiation of the single element inset-fed CMPA.

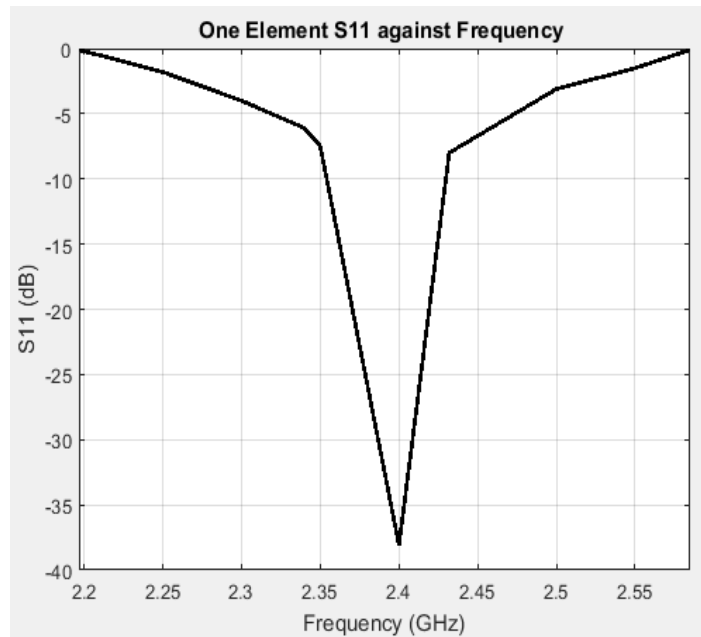


Figure 5: Return Loss of a Single Element Inset-Fed CMPA

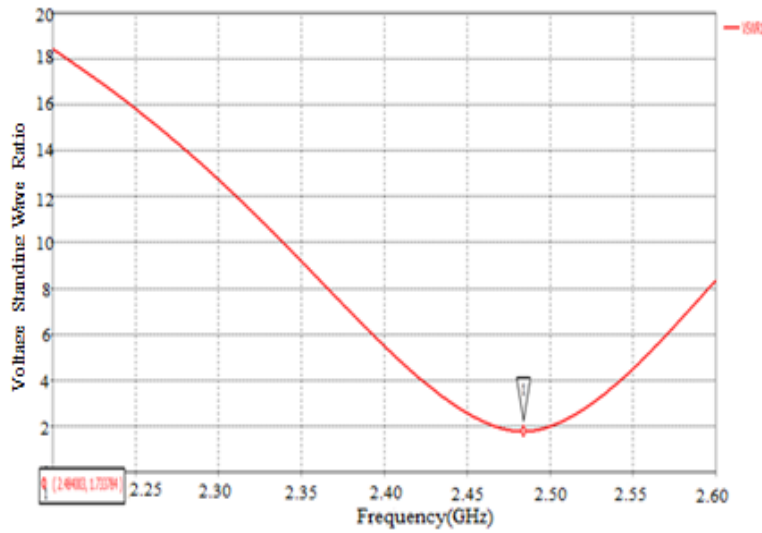


Figure 6: VSWR of an Inset-Fed CMPA

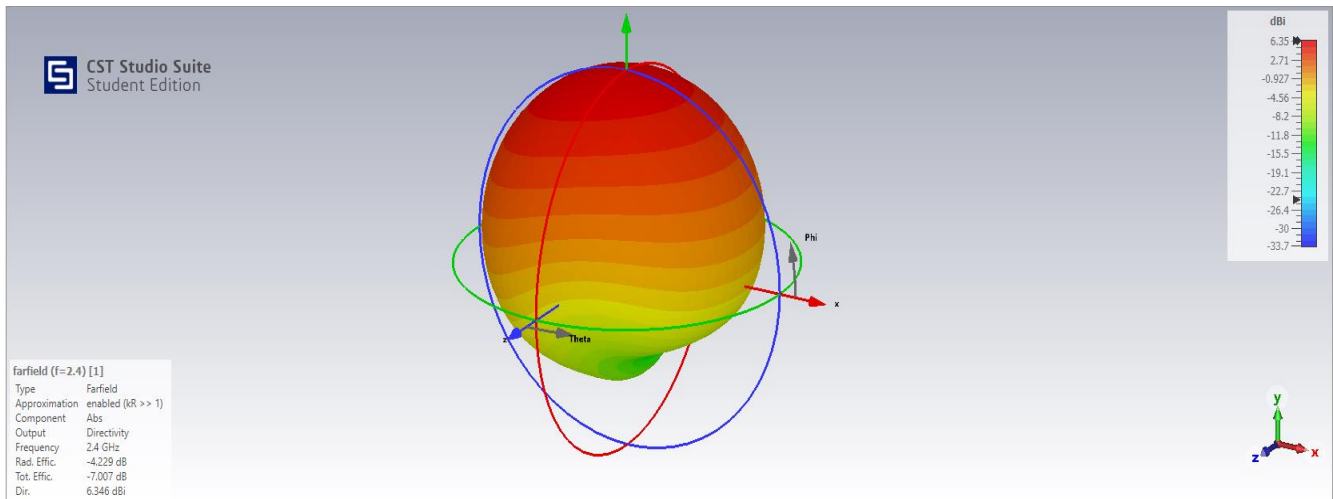


Figure 7: 3D Radiation Pattern of Inset-Fed CMPA

The results obtained from the modeling and simulation of the circular inset-fed MPA are presented in Table 2.

Table 2. Simulation Results of a Single Element Inset Fed CMPA.

Parameter	Definition	Value
G	Gain	5.4 dB
D	Directivity	6.35 dBi
ϵ_R	Radiation Efficiency	82.4%
S_{11}	Return Loss	-38 dB
B	Antenna Bandwidth	130 MHz
VSWR	Voltage Standing Wave Ratio	1.73
Γ	Reflection Coefficient	0.013

4.2 Results of 1x4 and 1x8 Inset-Fed CMPA Array

The 1x4 inset-fed CMPA array provides a maximum directive gain of around 13 dB and the directivity is 11.1 dB. It also possesses a return loss of -36 dB. Figure 8 shows the return loss for the 1x4 inset-fed CMPA and Figure 9 shows the return loss of the 1x8 inset-fed CMPA. The 1x8 Inset fed CMPA array provides a maximum directive gain of

around 16.1 dB and the directivity is 14.2 dB. It also possesses a return loss of -32 dB. Full details of the results are shown in Table 3.

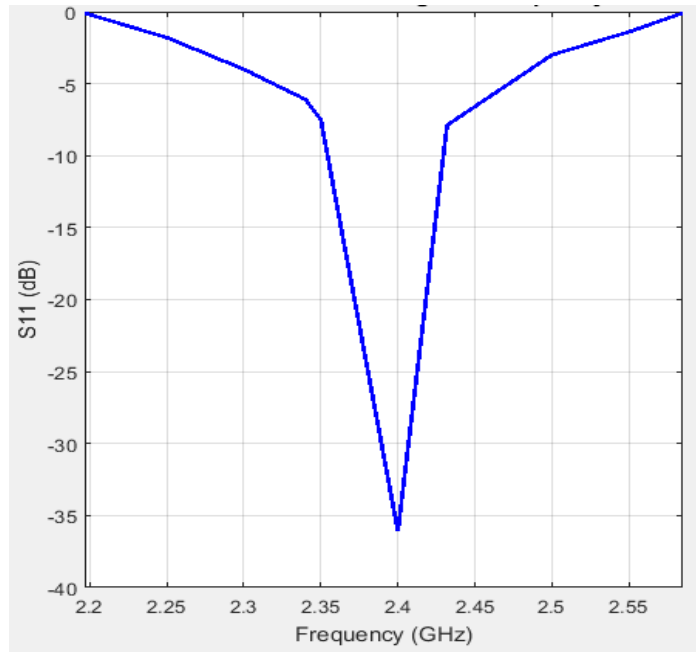


Figure 8: Return Loss of a 1x4 CMPA Array

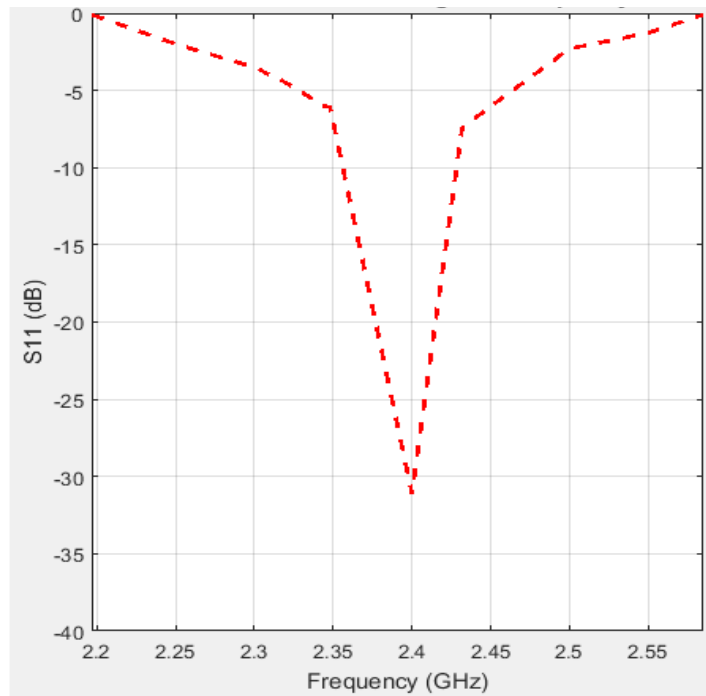


Figure 9: Return Loss of a 1x8 CMPA array

4.3 Performance of Single Element CMPA with 1x4 and 1x8 Inset-Fed CMPA Array

The performance comparison of the results obtained from modeling and simulation of the single element, 1x4 and 1x8 circular inset-fed CMPA array are presented in Table 3.

Table 3. Simulation Results of a Single Element CMPA, 1x4 and 1x8 Inset Fed CMPA Array

Parameter	Single Element CMPA	1x4 CMPA Array	1x8 CMPA Array
G	5.4 dB	13 dB	16.1
D	6.35 dBi	11 dBi	14.2
ϵ_R	82.4%	84.6%	88.2
S_{11}	-38 dB	-36 dB	-32 dB
B	130 MHz	120 MHz	110 MHz
Γ	0.013	0.016	0.025

5. Discussion

The simulation results for the single inset-fed CMPA shows an antenna gain of 5.4 dB and an antenna directivity of 6.35 dBi for a single element CMPA. This shows an acceptable gain and directivity for a microstrip patch antenna. For an acceptable antenna operation, the return loss of an antenna must be less than -10 dB (Dalli et al., 2013). The return loss of the single element CMPA of -38 dB and reflection coefficient of 0.013 thus shows a good performance result. For an acceptable antenna operation, the VSWR of an antenna must be less than 2.0 (Dalli et al., 2013). The VSWR of the single element CMPA is 1.7 which shows a good performance result. The 3D radiation pattern result shows a radiation efficiency of 82.4% for the single element CMPA. The simulation results show an antenna gain of 13 dB and an antenna directivity of 11.1 dBi for a 1x4 inset-fed CMPA array. This shows an increase in gain and directivity for a 1x4 CMPA array compared to a single element CMPA. For an acceptable antenna operation, the return loss of an antenna must be less than -10 dB (Dalli et al., 2013). The return loss of the single element CMPA of -36 dB (less than -10dB) and reflection coefficient of 0.016 shows a good performance result. The 3D radiation pattern result shows a greater radiation efficiency of 84.6% for the 1x4 CMPA array than the single element CMPA.

The simulation results show an antenna gain of 16.1 dB and an antenna directivity of 14.2 dBi for a 1x8 inset-fed CMPA array. This shows an increase in gain and directivity for a 1x8 CMPA array compared to the 1x4 CMPA array. The return loss of the single element CMPA of -32 dB and reflection coefficient of 0.025 shows a good performance result. The 3D radiation pattern result shows a greater radiation efficiency of 88.2% for the 1x8 CMPA array than the single element CMPA and 1x4 CMPA antenna array.

Furthermore, Table 3 shows the return loss (S_{11}) simulation results of a single element, 1x4 and 1x8 CMPA array. In terms of performance, the S_{11} parameter of a single element of -38 dB is better than that of all other antenna arrays. But in terms of antenna gain, antenna directivity and antenna efficiency the antenna arrays showed better performance. It is observed from the results that there is an inverse relationship between the return loss and the number of antenna elements. This means that there must be a trade-off between gain, directivity, efficiency performances compared to the S_{11} parameter as the number of elements increases in an antenna array. Also, it is observed from Table 3 that the antenna bandwidth reduces with an increase in the antenna efficiency for single element, the 1x4 and the 1x8 CMPA arrays. This results tally with the Fano limits which states that for lossy circuits, the increase in the bandwidth leads to a decrease in the efficiency (Hansen, 2005).

6. Conclusion

Microstrip patch antenna arrays of circular shaped radiating elements were successfully designed and implemented using the FR-4 Epoxy glass substrate. Through analysis using CST and MATLAB simulation software, it was observed that the antennae resonated at 2.4 GHz frequency. In this work, inset-fed technique was used for the simulation of single element, 1x4, and 1x8 CMPA arrays. From the simulation, the maximum achieved gain and directivity of all the three antennae array arrangements were obtained by the 1x8 array with 16.1 dB and 14.2 dB, respectively. However, the 1x8 array has the lowest return loss of -32 dB. The results basically showed that there was need for a tradeoff between the various parameters depending on the application for a specific antenna to be adopted for use. In summary, although antennae may be considered old technology, researchers are still finding ways to innovate the antenna for the next generation of electronics and applications required to meet the changing wireless technologies.

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