SSRG International Journal of Electronics and Communication Engineering
ISSN: 2348-8549/ https://doi.org/10.14445/23488549/IJECE-V11I10P108

Volume 11 Issue 10, 102-108, October 2024

Original Article

Antenna Array Design and its Integration with Beamforming Network

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Received: 08 August 2024 Revised: 09 September 2024 Accepted: 08 October 2024 Published: 30 October 2024

Abstract - *This paper describes the design of an antenna array and its integration with a beamforming network that operates at 2.6 GHz and uses circular microstrip patch antennas and their arrays over a frequency range of 2–3 GHz. This design is implemented on a substrate (RT5880) with a dielectric constant (ε = 2.2), loss tangent (tanδ = 0.0009), and thickness (h = 0.0813 cm). The microstrip antenna's dimensions were calculated and subsequently determined through simulations. The Antenna Feeding Network with Beamforming exceeds Single and Array Antennas, providing superior directional radiation. With an amazing 9.02 dBi gain, 32.6 dBi front-to-back ratio, and 67% Total radiation efficiency at 2.6 GHz. A comparison and observation are made between the effectiveness of the designs and the suggested techniques. CST Microwave Studio is a full-wave electromagnetic simulation software program for design and analysis.*

Keywords - *Circular patch, Microstrip antenna, Gain, S-parameters, Antenna array, Beamforming network.*

1. Introduction

The microstrip patch antenna comprises very thin radiating elements, or conductors, placed in the ground plane and separated from the radiation field by a dielectric substrate. Microstrip antennas operate on multiple frequency bands, ranging from X band (5.2–10.9 GHz) to Ultra High Frequency (UHF) (300 MHz–3 GHz) [1, 2]. The coupling between the microstrip line and the patch could be in the form of an edge coupling or gap between them. Due to its unique characteristics, which include its small size, low weight, low profile, low fabrication cost, conformability to various shapes, extremely low space consumption, ease of integration with printed circuit boards, ease of fabrication, and effectively directed radiation pattern, microstrip patch antennas are now used in a wide range of applications, from military to commercial [3].

The circular Microstrip patch antenna is easier to design and has easily controlled radiation because it only has one degree of freedom (radius). Additionally, at the same design frequency, the circular patch antenna's size is 16% smaller than the rectangular Microstrip patch antennas [4, 5]. The microstrip patch antenna's ability to have different polarizations is a special feature [6, 7]. Antennas with circular polarization are known as Circular Polarized (CP) antennas. Since circular polarization is so good at reducing fading and multipath interference, it is far superior to linear polarization antennas [8].

Figure 1 depicts a circular microstrip patch antenna fed by an edge feed or microstrip line feed. A quarter wave transformer can be positioned between the microstrip feed and the circular patch edge to match their impedances [9]. The circular patch antenna constructed on a substrate with a thickness and dielectric constant is depicted in Figure 1.

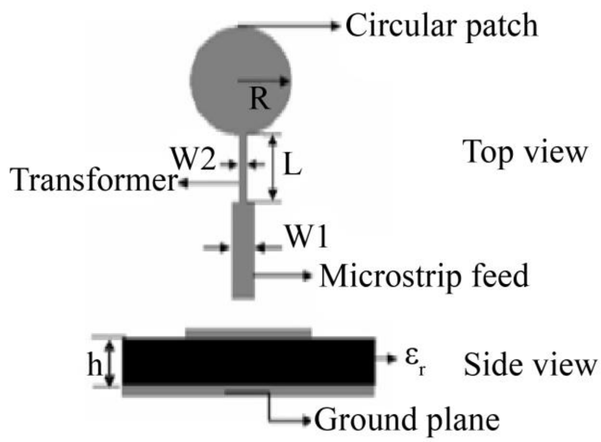

Fig. 1 Microstrip circular patch antenna

A branch line coupler is a passive microwave device frequently used in power combining and splitting applications. It splits an input signal into two equal amplitude signals with a 90-degree phase shift and two output signals with a specific phase relationship [10, 11]. Power dividers, or splitters, divide an input signal into multiple output signals with controllable or equal power distribution. They also disperse the input power among several output ports, facilitating the splitting or combining of signals. Transceiver systems require affordable passive microwave components like phase shifters, couplers, and Power Dividers (PD) [12].

The Power Dividers (PD) and Branch Line Coupler (BLC) are frequently utilized in antenna feed networks, mixers, modulators, and other devices. Circuit size is the main disadvantage of designing a PD and BLC because quarter wavelength (λ/4) lines are necessary. These undesirable reactions impair the transceiver system's overall response and impact adjacent circuits [11].

The practical application of antenna arrays in high-precision applications like 5G is limited by several design issues, including beam splitting at different frequencies and mutual coupling [13]. This paper presents an improved circular microstrip patch antenna array with a beamforming network. It is designed to operate at 2.6 GHz and enhance efficiency and directional radiation.

The circular microstrip patch configuration's array antenna improves signal strength and coverage while enabling beamforming, making it appropriate for various applications like wireless networks and radar systems.

2. Design Specifications and Consideration

In this paper, a circular microstrip patch antenna that operates at 2.6GHz frequency is designed. The patch antenna is designed with a substrate having dielectric constant Ɛr =2.2 and height of the substrate h= 0.0813cm. Using CST, the circular patch antenna is designed. Table 1 addresses all the specifications for designing and analyzing a circular microstrip patch antenna.

Table 1. Frequency and substrate specifications

Parameters	Specifications
Design Frequency / Centre Frequency	2.6 (GHz)
Substrate Dielectric Constant	(RT5880) εr 2.2
Substrate thickness,	h (cm) 0.0813
Loss tangent (tan δ)	0.0009
Metal Thickness	35µm copper

2.1. Design Equations

For the design of a circular microstrip patch antenna, equations such as the following can be used to find the radius of the radiating elements [14]:

$$a = \frac{F}{\left\{1+\frac{2h}{\pi \varepsilon r F}\left[\ln\left(\frac{\pi F}{2h}\right)+1.7726\right]\right\}^{\frac{1}{2}}}$$

a = circular radius dimension (mm)
h = Thick of substrate (cm)
ε_r = Relative dielectric permittivity of substrate (F/m)
F = logarithmic function (F) of radiating element
While the equation determines the logarithmic function (F) of the radiating element:

$$F = \frac{8\cdot 791\times 10^9}{f_{r\sqrt{\varepsilon_r}}}$$

Z0 is the impedance of the line. The width of the 50 Ω line (W1) and the width of the transformer line (W2) can be calculated using the following equations.

$$\frac{\omega}{h} = \{\frac{2}{\pi}\left\{B-1-ln(2B-1)+\frac{\varepsilon_r-1}{2\varepsilon_r}\left(L_n(B-1)+0\cdot 39-\frac{0.61}{\varepsilon_r}\right)\right\}\mathrm{W/d} > 2$$

The value of B can be found as follows: $B = \frac{377\pi}{2z_0\sqrt{\varepsilon_r}}$

After calculating the value of the width, it is needed to compute the length of the microstrip line:

L= λ/4, $\lambda = \frac{c}{F\sqrt{\varepsilon_e}}$ and Effective dielectric constant:

$$\varepsilon_e = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{I+12\frac{d}{\omega}}}$$

To determine the elements' dimensions, after calculating the radius (a) of the radiating elements of the microstrip antenna using the above equations and the material specification, we were able to determine the operating frequency (fr) of the antenna, which is 2.6 GHz. For this frequency, the patch radius is 22.16 mm, and the logarithmic function value is 2.28. According to Table 2, the transformer line values for 2.6 GHz are 0.3 mm with Lt = 21.4 mm, and the width of the microstrip transmission line with 50 Ω impedance is 2.5 mm with a length (Lt) of 21.08.

Table 2. Calculated parameters of circular antenna

Parameters	Z0	ZQT
Radius of the Patch	a = 22.16	
The wavelength	84.34mm	85.6mm
Width (W) in mm	2.5mm	0.3mm
Length (L) in mm	21.08	21.4
Spacing between Antenna Arrays	$5\,\lambda/_8 = 52\cdot 5$	

From the calculated values of the antenna parameters, CST software is used to design the circular microstrip patch antenna in Figures 2, 3, and 4 to represent the single circular patch antenna, 4x1 antenna array, and integration of the patch antennas with the designed feeding network.

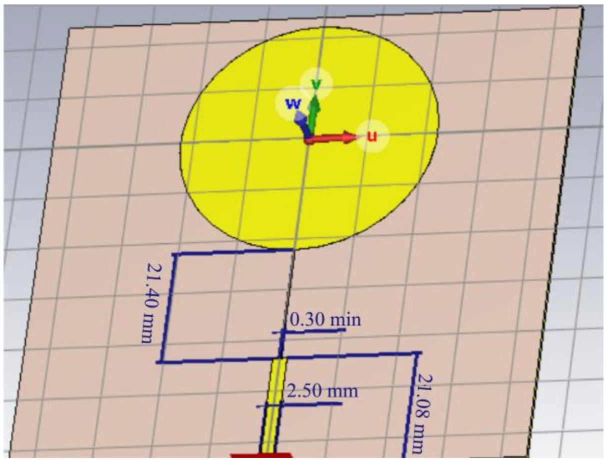

Fig. 2 Microstrip circular patch antenna using CST

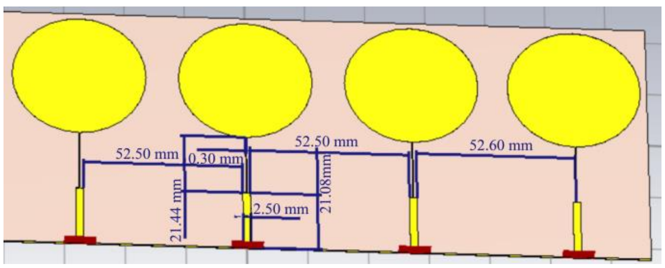

Fig. 3 Array circular microstrip patch antenna using CST

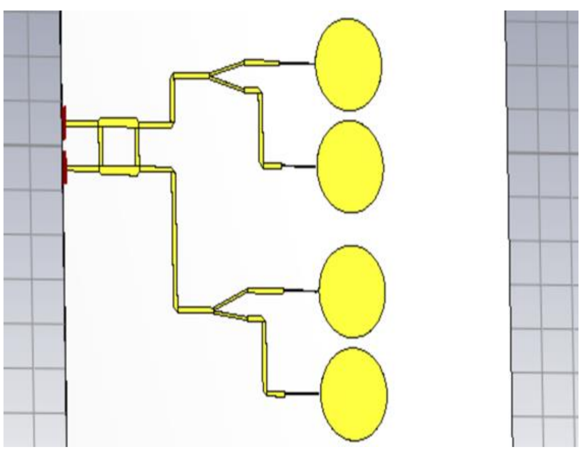

Fig. 4 Antenna array and integration with beamforming network

Optimizing the radiation patterns, mutual coupling, and spacing of antenna elements is a key component in designing and integrating an antenna array with a beamforming network and Ports Used.

3. Simulation Results and Analysis

The findings of the Section are divided into four subsections, each of which presents and discusses a comparison of the three simulated designs—Single Circular Microstrip Patch Antenna, Array Antenna, Antenna Array Design, and its Integration with Beamforming Network and Comparison of Three Designs. The S-parameter of the designs are compared.

3.1. Single Circular Microstrip Patch Antenna

This section presents the analysis of the simulated results for the Single Circular Microstrip Patch Antenna designed in Figure 2. The discussion covers the reflection coefficient, bandwidth, 3D and 2D radiation patterns in polar coordinates, front-to-back ratio at the E and H-planes, as well as the gain and efficiency.

Figures 5 and 6 show the Reflection Co-efficient of −11.825413 dB, and bandwidth of 15.21 MHz (ranging from 2.607484 to 2.591881 GHz) and VSWR of 1.6892154 respectively, which operate at 2.6 GHz of resonant frequency.

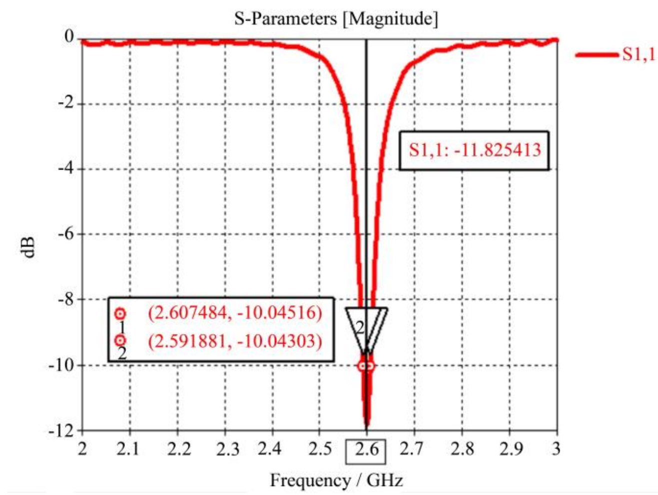

Fig. 5 S-parameters of single circular patch antenna

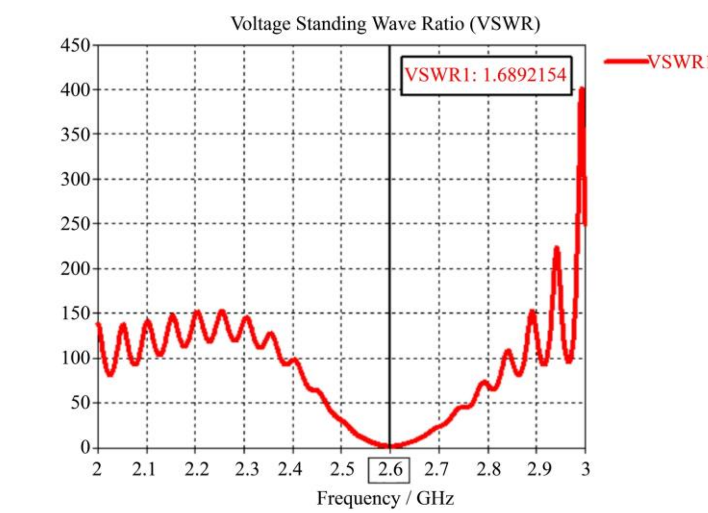

Fig. 6 VSWR of single circular patch antenna

From Figure 5, we can find the percentage bandwidth of the antenna to measure whether the bandwidth is narrow or wide: % BW = (FH - FL)/f0 x 100% = (2.607484 - 2.591881 GHZ)/2.6GHz x 100% = 0.6% This can be said to be a narrow bandwidth. But, the reflection coefficient indicates good matching.

From Figure 7. The radiation pattern for the polar form, whose angular displacement measures about 74.1 degrees from the radiation center, when Φ = 0° the main lobe of radiation was found to be 0 degrees, and the Main lobe Magnitude is 6.08 dBi. At the resonant frequency 2.6 GHz.

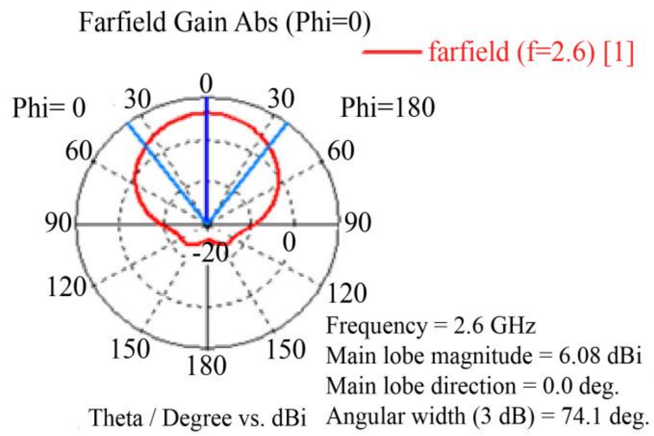

Fig. 7 2D E-Field in polar form Φ = 0°

From Figure 8 the radiation pattern for the polar form, whose angular displacement measures about 69 degrees from the radiation center, when Φ = 90°, the main lobe of radiation was found to be 15 degrees, and the Main lobe Magnitude is 6.67 dBi. At the resonant frequency of 2.6 GHz. and The FBR is 22.75 dB.

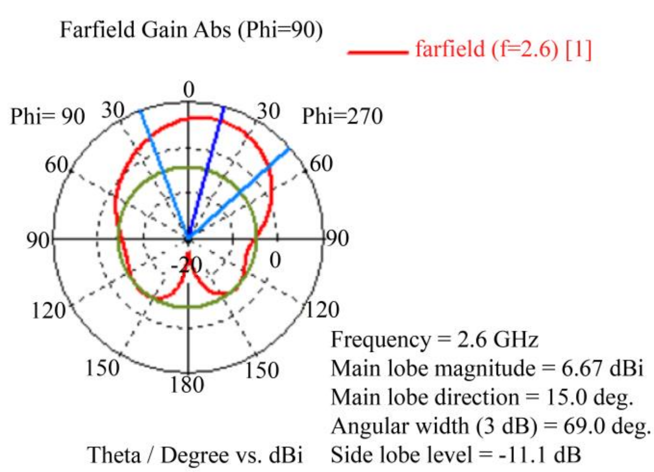

Fig. 8 2D H-field in polar form Φ = 90°

The gain and Radiation efficiency can be illustrated through the three-dimensional simulation pattern of the used antenna, as shown in Figure 9. The Radiation Efficiency is -1.303dB, the Total radiation efficiency is -1.337dB and The Gain is 6.7 dB.

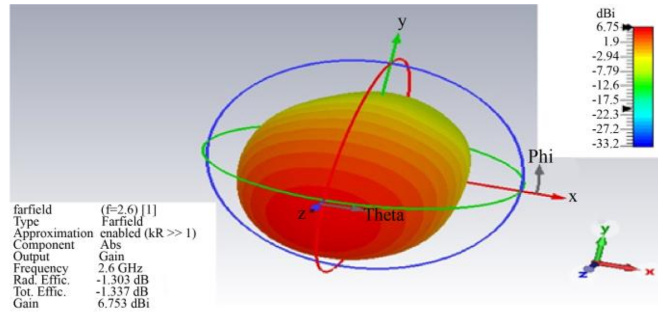

Fig. 9 3D Gain and radiation efficiency

The radiation efficiency is 74%, the total is 74% linear, and the gain is 6.75 dBi.

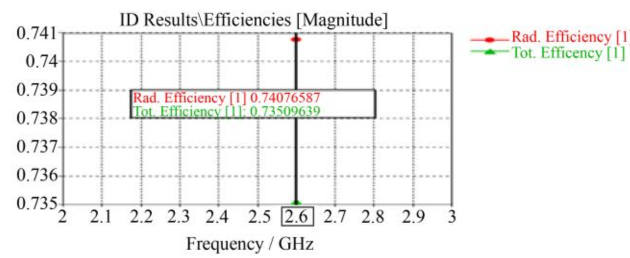

Fig. 10 Radiation efficiency in linear

3.2. Array Antenna of Circular Patch Antenna

This section presents the analysis of the simulated results for the Array Circular Microstrip Patch Antenna designed in Figure 3. The discussion includes the reflection coefficient, S21, S32, and S43 parameters, 3D and 2D radiation patterns in polar coordinates, front-to-back ratio at the E- and H-planes, and the gain and efficiency, as illustrated in Figures 11 to 16.

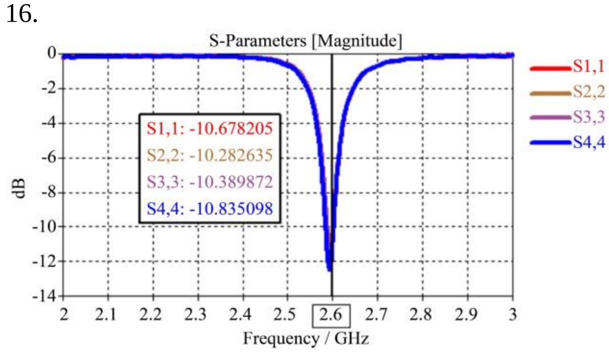

Fig. 11 S-parameters of array antenna

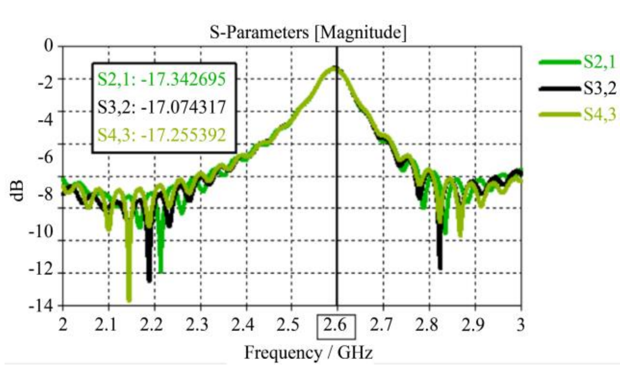

Fig. 12 Coupling of array antenna

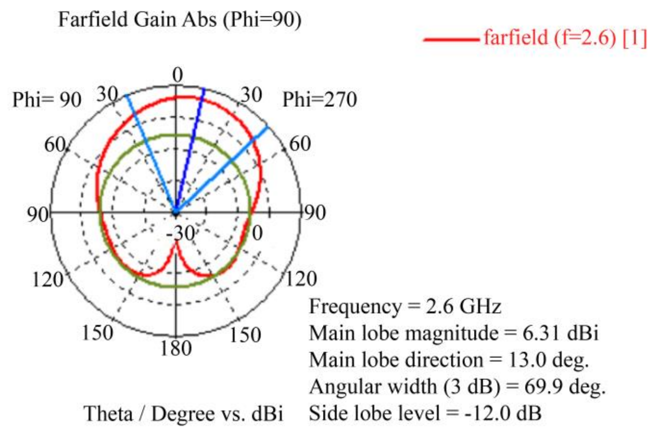

Fig. 13 2D H-field in polar form Φ = 90° of array antenna

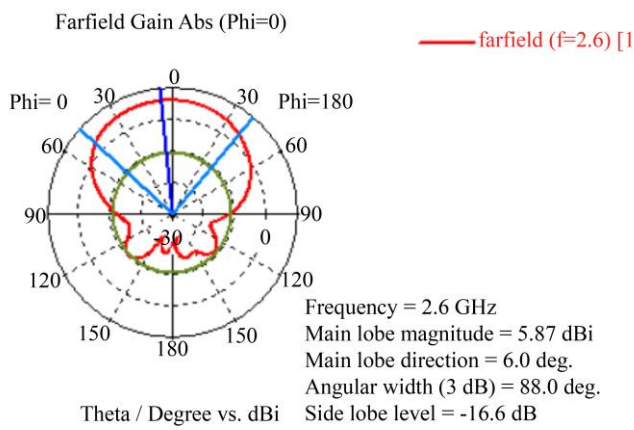

Fig. 14 2D H-field in polar form Φ = 0° of array antenna

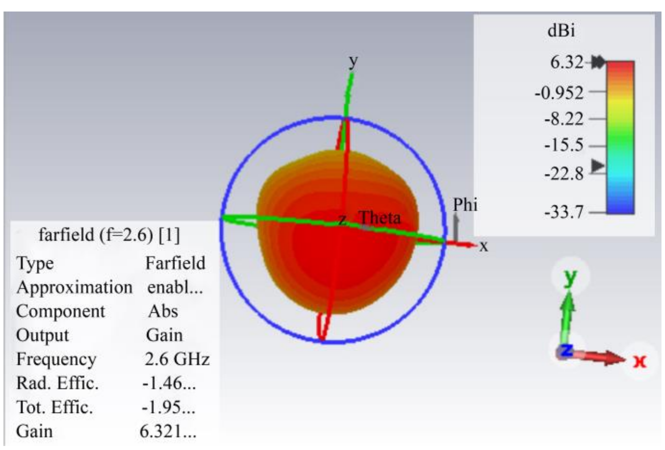

Fig. 15 3D Gain and radiation efficiency of array antenna

The array antenna's reflection coefficient is satisfactory, with S11 = 10.68 dB, S22 = -10.28 dB, S33 = -10.39 dB, and S44 = -10.84 dB. Mutual coupling between the antenna elements shows acceptable levels, with S21 = -17.3 dB, S32 = -17.1 dB, and S43 = -17.3 dB. The radiation efficiency is -1.469 dB, and the total radiation efficiency is 1.953 dB, indicating efficient radiation performance. The antenna array achieves a gain of 6.321 dBi at the resonant frequency of 2.6 GHz, with improvements in gain and radiation efficiency attributed to the increased number of antenna elements. The Front-to-Back Ratio (FBR) stands at 28.5 dBi, demonstrating the antenna's strong directional radiation capability.

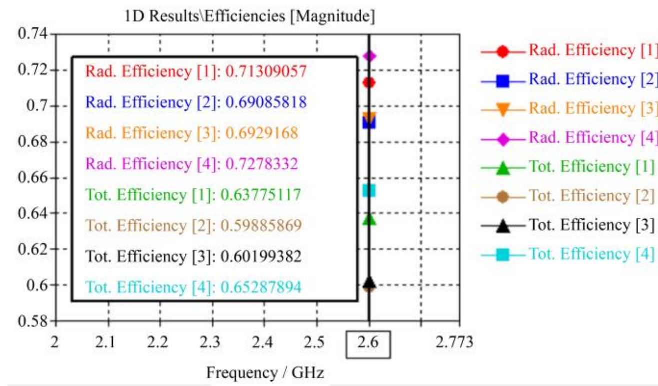

Fig. 16 Radiation efficiency of array antenna

3.3. Circular Microstrip Patch with Antenna Feeding Network

This section analyzes and discusses the simulated results of the circular microstrip patch antenna with the feeding network, as designed in Figure 4. The evaluation covers the reflection coefficient, 3D and 2D radiation patterns in polar coordinates, front-to-back ratio at the E- and H-planes, along with the gain and efficiency, as presented in Figures 17 to 20.

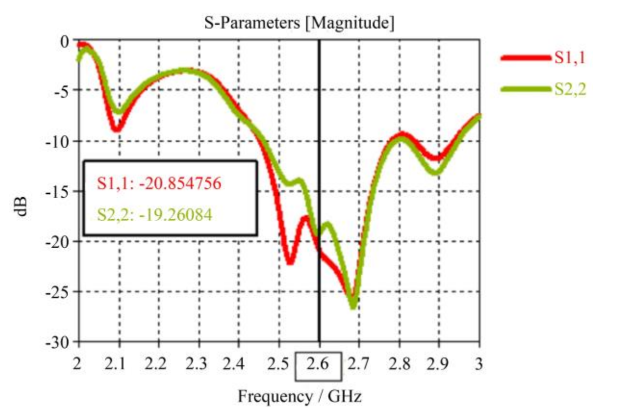

Fig. 17 S-parameters of antenna feeding network

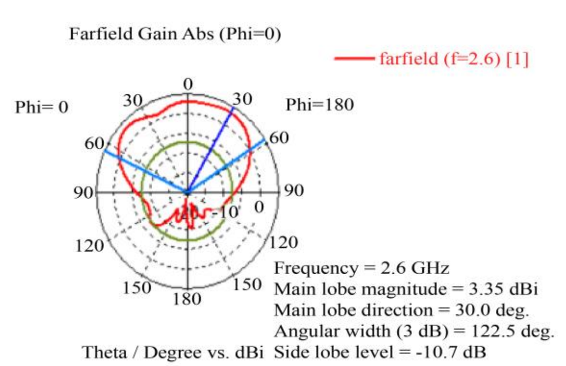

Fig. 18 2D E-field in polar form Φ = 0° of antenna feeding network

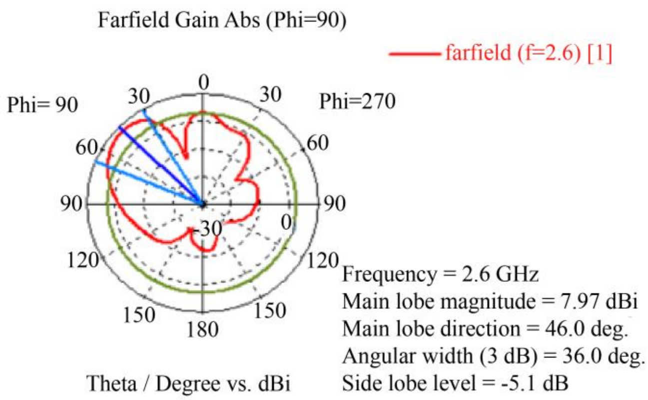

Fig. 19 2D H-field in polar form Φ = 90° of antenna feeding network

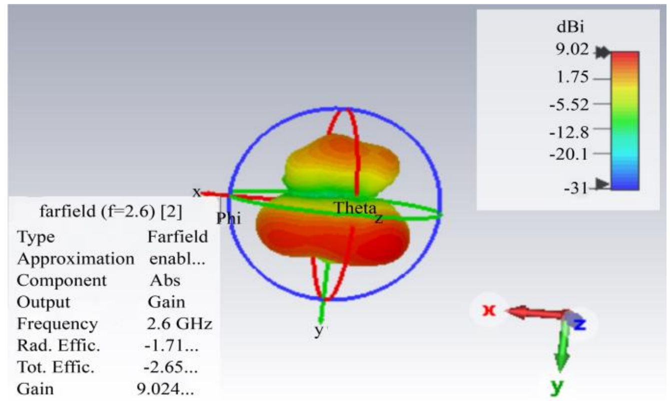

Fig. 20 3D Gain and radiation efficiency of the antenna feeding network

Table 3. Comparison of the three tasks

Parameters	Single Antenna	Array	Antenna Feeding Network
S-Parameters	-11.8 dB	-10.8 dB	-20.85 dB
Gain	6.7 dBi	6.32 dBi	9.02 dBi
FBR	22.75	28.5	32.6
Radiation Efficiency	74%	71%	67%
Total Radiation	74%	63%	54%

The antenna feeding network with beamforming exhibits a good reflection coefficient (S11 = -20.85. dB, S22 = -19.26 dB), while its radiation efficiency stands at -1.713 dB, or 67%. Total radiation efficiency is -2.651 dB, or 54%. The gain is 9.024 dBi, which operates at 2.6 GHz of resonant frequency. The gain and radiation efficiency also increased. And the FBR is 32.6 dBi.

The antenna Feeding Network design indicates the best-desired performance can work at 2.6 GHz with the value of S11 obtained at -20.85 dB, antenna gain of 9.02 dBi and Radiation efficiency of 67%. This antenna has a directional radiation pattern shape.

4. Discussion

The Single Circular Microstrip Patch Antenna has a reflection coefficient of -11.83 dB and a narrow bandwidth of 0.6%. It displays a well-matched design with a gain of 6.7 dBi and 74% radiation efficiency. The Array Antenna With a wider bandwidth, lower reflection coefficients, and improved radiation efficiency (71%) and the Array Antenna increases gain to 6.32 dBi. The Antenna Feeding Network with Beamforming exceeds both, proving superior directional radiation. With an amazing 9.02 dBi gain, 32.6 dBi front-to-back ratio, and 67% radiation efficiency at 2.6 GHz.

Recent circular patch antennas generally achieved gains between 6.9 and 7.1 dBi, with efficiencies reaching up to 97%. Although this design achieves a higher gain, slightly reduced efficiency arises from the added complexity of the beamforming network. The focus here shifts towards enhancing directional performance rather than maximizing efficiency.

5. Conclusion

The designed circular microstrip patch antenna array is integrated with a beamforming network and uses circular microstrip patch antennas and their arrays over a frequency range of 2–3 GHz. This design is implemented on a substrate (RT5880) with a dielectric constant (ε = 2.2), loss tangent (tanδ = 0.0009), and thickness (h = 0.0813 cm) exhibits high performance, achieving a reflection coefficient of -20.85 dB, a high gain of 9.02 dBi, and a directional radiation pattern with a front-to-back ratio of 32.6 dB.

The antenna feeding network demonstrates efficient signal transmission with a radiation efficiency of 67%. Overall, the optimized design showcases excellent characteristics for applications requiring enhanced signal strength, coverage, and beamforming capabilities at the centre of 2.6 GHz.

Funding Statement

Hormuud University funded this publication through the Karama Research Center. The views and conclusions expressed in this publication are those of the authors and do not necessarily represent the official stance of the Karama Research Center or Hormuud University.

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