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Design and Implementation of Hexagonal Shaped 2x2 Array Antenna for 5G Applications

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Abstract

Array antennas have become increasingly significant in modern communication and sensing systems. This project explores the key aspects of wearable antennas, emphasizing their design considerations, challenges and applications. The miniaturization and integration of antennas into clothing or accessories pose unique engineering challenges such as limited space, flexibility, and user comfort. Various techniques, including flexible materials, conformal designs and innovative geometries, address these challenges.This project presents a geo-textile material that is a polypropylene-based meta material-loaded wearable Hexagonal - shaped 2x2 micro strip patch antenna array, having Substrate Size=230*260*0.2mm^3, Ground plane size = 230*260 mm^2, Patch Radius=34mm, operating at 2.45GHz, a frequency band widely adopted in 5G and having high gain i.e.,31.14dB at 2.42GHz for public safety band applications. Under the unloaded condition of the micro strip patch antenna, poor matching is observed in the public safety band. Further, this antenna is loaded with hexagonal shaped 2x2 antenna array. This array loading provides better-matched conditions in the public safety band.

Keywords: Hexagonal Shaped, 2x2 Array Antenna, Gain, VSWR, Bandwidth, 5G, HFSS.

INTRODUCTION

An antenna is a sensor that converts electrical energy from space into electricity. The 8x1 patch antenna array is designed to achieve high gain and directivity for "accuracy detection" applications at operating frequencies in the X band. Different array designs of microstrip patch antennas provide higher bandwidth, higher gain and higher efficiency. Mathematical modelling and optimization of microstrip patch antennas is done using the HFSS simulator.A microstrip or patch antenna is made by placing a thin piece of metal (called a patch) on top of a flat surface (called the ground). Between them, there is a layer of special material called a dielectric, which helps the antenna work properly. These are very low size antennas. Patch antennas are low cost, have a low profile and are easily fabricated. Wearable antennas are designed to function while being worn. The term 5G refers to wireless communication technology's fifth generation, which is expected to have a major impact on many aspects of modern civilization, including healthcare and wearable devices. 5G makes use of higher bandwidth technologies such as sub-6 GHz and mm Wave.By installing a micro strip antenna (MSA) on a substrate made of dielectric consisting of wide and narrow walls without changing the waveguide itself, the grid lobes emanating from the slot array in a given wavelength range will be reduced. Using the proposed arrangement, a polarized MSA array can be constructed from the wide and narrow walls width of the rectangular ring, respectively, parallel to the axis and perpendicular to the axis.

Wearable antennas are gaining significant traction in fields such as healthcare monitoring, military gear, and smart textiles, where unobtrusive and reliable communication is crucial. However, designing antennas that can sustain performance in dynamic and conformal environments presents several challenges. This research explores a metamaterial-loaded, hexagonal-shaped 2x2 microstrip patch antenna array, fabricated on a polystyrene-based geo-textile substrate. The hexagonal geometry has been selected due to its symmetrical structure and enhanced radiation characteristics, which outperform conventional rectangular or circular shapes in parameters like gain, bandwidth, and directivity. The antenna operates at 2.45 GHz, a frequency band widely adopted in 5G and Wireless Body Area Network (WBAN) applications. The chosen substratenon-woven polypropylene supports flexibility and wearability without compromising electromagnetic performance.

Section 2 presents the literature survey conducted. Section 3 covers the antenna analysis, design, and simulation results, along with a corresponding discussion. Finally, the conclusions are summarized in Section 4.

LITERATURE SURVEY

The transition to fifth-generation (5G) wireless communication demands high-performance antenna systems that can operate efficiently at millimeter-wave (mmWave) frequencies. These systems must exhibit high gain, broad bandwidth, and directional radiation patterns to meet the requirements of increased data rates, reduced latency, and reliable connectivity. Among various antenna technologies, microstrip patch arrays are widely adopted due to their compactness, low profile, and compatibility with integrated circuit technologies. Recent studies have explored diverse patch geometries and array configurations to improve the performance of these antennas in 5G environments.

Vinay Kumar K. S. et al. (2023) [1] proposed a 2×2 rectangular microstrip patch array operating at 28 GHz, utilizing a Rogers RT/Duroid 5880 substrate and a corporate feed network for efficient power distribution and impedance matching. Simulated using CST Microwave Studio, the design achieved return loss better than -10 dB and VSWR < 2, confirming its suitability for mmWave 5G beamforming. The array configuration significantly enhanced gain and produced a directional radiation pattern, validating its effectiveness for high-frequency wireless systems.

Poonam Tiwari et al. (2020) [2] developed a dual-band 2×2 microstrip antenna array targeting the 5G C-band (4–7 GHz), with resonant frequencies at 4.91 GHz and 6.08 GHz. The antenna exhibited VSWR below 2, return loss under -10 dB, and favorable bidirectional radiation characteristics. Despite operating at lower frequencies, this study emphasized the importance of compact, multiband microstrip designs for modern wireless systems, underlining the relevance of array configurations for enhanced field performance.

Beyond conventional base station applications, wearable antenna technologies have introduced challenges relevant to miniaturization, efficiency, and material selection. R. G. Smith (2020) [3] provided a comprehensive overview of the design constraints in wearable antennas, highlighting concerns such as body conformity, biocompatibility, and proximity effects on antenna performance. The study addressed how human interaction impacts critical parameters like return loss, radiation efficiency, and SAR, and it offered insights into substrate selection for flexible electronics.

Similarly, A. D. S. R. Kumara (2018) [4] conducted an extensive review of wearable textile antennas, focusing on flexible structures, material durability, and fabrication techniques for body-worn communication systems. The research underscored the trade-offs between flexibility, robustness, and performance, with attention to challenges like signal degradation from bending and movement, which are also relevant in compact and embedded antenna designs.

Although the above works successfully demonstrate the effectiveness of rectangular geometries, wearable adaptability, and corporate feeding techniques, the exploration of non-conventional geometries such as hexagonal patch structures remains limited. Given their symmetrical shape and compact form factor, hexagonal patches have the potential to offer improved bandwidth and radiation characteristics while maintaining array compatibility.

Existing literature reveals significant advancements in 2×2 microstrip patch antenna arrays designed for 5G communications. These studies primarily focus on rectangular geometries and conventional feed structures to achieve desired performance in the mmWave and sub-6 GHz ranges. However, the potential benefits of hexagonal patch geometries—such as better current distribution, reduced mutual coupling, and symmetrical radiation—remain underexplored. The proposed work addresses this research gap by designing and implementing a hexagonal-shaped 2×2 antenna array, optimized for mmWave 5G applications, with the goal of enhancing gain, bandwidth, and beamforming capability.

Objectives of the Proposed Work:

The proposed research aims to design, simulate, and implement a high-performance hexagonal-shaped microstrip patch antenna array tailored for 5G wireless communication applications, particularly in the millimeter-wave (mmWave) frequency band. In contrast to conventional rectangular or circular patch antennas, the hexagonal geometry offers potential advantages in terms of symmetry, compactness, and radiation performance.

The specific objectives of the work are outlined as follows:

- To design a novel hexagonal-shaped microstrip patch antenna element, optimized to operate within the mmWave spectrum relevant to 5G (e.g., 28 GHz), ensuring improved bandwidth, gain, and radiation efficiency compared to standard geometries.
- To implement and analyze three different array configurations1×2, 2×2, and 1×4using the designed hexagonal patch as the unit element, with the goal of evaluating the effect of array topology on performance metrics such as gain, beamwidth, side-lobe levels, and directivity.
- To perform extensive simulation and performance analysis of key antenna parameters including return loss (S11), VSWR, gain, bandwidth, efficiency, and radiation pattern using electromagnetic simulation tools such as CST Microwave Studio or HFSS.
- To fabricate and experimentally validate the antenna design, comparing measured results with simulated outcomes to assess real-world performance, fabrication viability, and practical deployment readiness.
- To benchmark the proposed design against conventional rectangular and circular patch arrays, highlighting the advantages of the hexagonal structure in terms of size, radiation behavior, and 5G applicability.

DESIGN METHODOLOGY OF THE PROPOSED ANTENNA ARRAYS

The dielectric medium and resonance frequency are selected for designing the MSA. Antenna width is measured.

$$W = \frac{C_o}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

Where W, C_0, and ε_r are the width of the patch, speed of light, and dielectric substratevalue, respectively.An effective refractive index parameter is needed to calculate for design an MSA. It is from patch to ground, radiations are travelling through air and substrate (is called fringing), but dielectric values of substrate and air are different. So, an effective dielectric constant is needed to find out. The effective dielectric constant (ε_{reff}) is measured by using the equation[19]

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2} \quad \frac{W}{h} > 1 \quad (2)$$

The antenna size (ΔL) is increased electrically due to fringing. The patch of the length increment (ΔL) is estimated from equation [19]

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{reff}-0.258)(\frac{W}{h}+0.8)} \quad (3)$$

Then patch length (L) is measured by the equation [18] $L = \frac{C_0}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L$ (4)

Where, L, h, C0, f_r, ε_{reff}, and ΔL are effective antenna length, substrate height, speed of light in free space, resonant frequency, effective dielectric constant and length extension, respectively[18].

Suppose the patch dimensions are known and then the width, length of the substrate equal to the ground plane. The ground plane length (Lg) and width (Wg) are evaluated a

L_g=6h + L (5)

W_g=6h + W (6)

Construction design:

It is a geometrical sketch of metamaterial loaded wearable Hexagonal-shaped 2x2 microstrip patch array antenna on geotextile polystyrene substrate. The polypropylene is a non-woven type of geo-textile which is used as a substrate.In this antenna, there are 4 microstrip patches which are in the shape of hexagon of equal dimensions by placing them on the substrate. The design depicts a 2×2 hexagonal patch antenna array designed in Ansys HFSS. The structure consists of four hexagonal-shaped microstrip patch elements arranged in a matrix on a rectangular dielectric substrate, typically made of a material like FR4 or Rogers.

The hexagonal shape is chosen for its advantages in bandwidth and radiation characteristics compared to conventional square patches. Each patch is individually fed using a microstrip line, which together form a corporate feed network to evenly distribute power to all elements.

The entire array is placed within a surrounding air box, representing the radiation boundary used for electromagnetic simulation in HFSS. The ground plane, though not visible, is located beneath the substrate to provide a return path for currents and enhance directional radiation, primarily along the Z-axis. This configuration is commonly used in applications requiring directional gain, beamforming, or MIMO systems.

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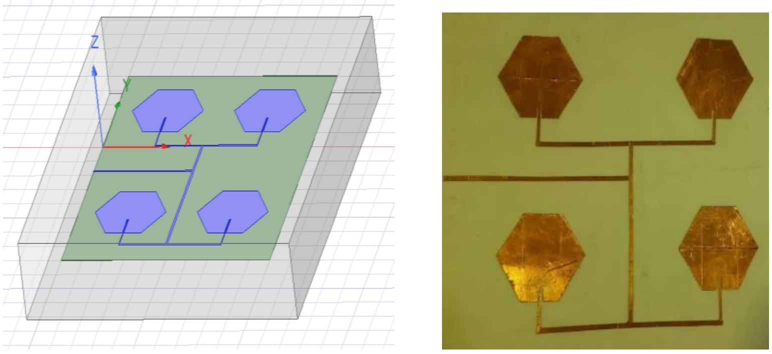

Figure 1 a. Simulated model of the proposed antenna ,b. Fabricated model of the proposed antenna

Table 1 Dimensions of the Proposed 2x2 Array

S.No	Parameter	Values (mm)
1	Ground plane	230*260
2	Substrate Length	230
3	Substrate Length	260
4	Line width	1.7
5	L1 Length	96.27
6	L2 Length	94.57
7	L3 Length	90.55
8	L4 Length	55.00

The Figure 1 shows the Top view of proposed 2x2 array antenna geometry,figure 1.a represents the Simulated model of the proposed antenna and the figure 1.b.represents the Fabricated model of the proposed antenna. The Hexagonal shape of 34mm radius with 6 segments of four elements of the array is designed as a patch with gap of 22mm for the proposed design and a feed line with length and width of 21.66mm x1.7mm is used to give the input to the patch from excitation input, the L1 is of 96.27mm x 1.7mm length, L2 is of 94.57mm x 1.7mm , L3 is of 90.55mm x 1.7mm and L4 is of 55mm x 1.7mm Polystyrene material is used as a substrate for the proposed antenna with the dimensions of width, length, and height are 230 mm, 260 mm, and 0.2 mm, respectively, and these are shown in table 1.

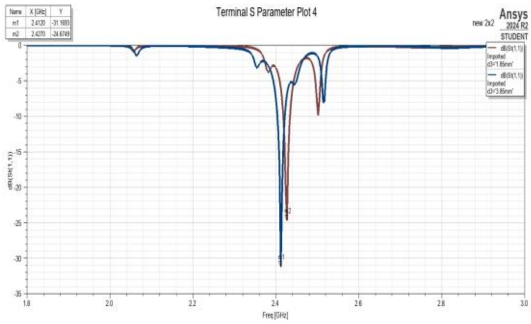

Figure 2Return loss (S11) of Proposed Antenna

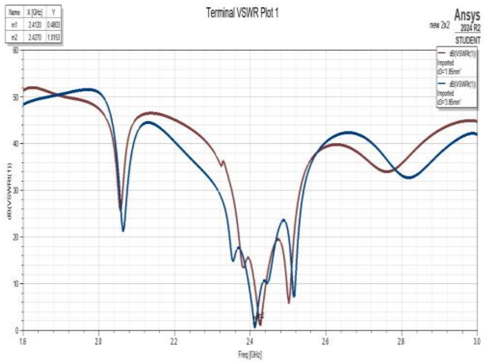

Figure3VSWR Vs Frequency plot

Figure 2 illustrates the return loss (S11) graph of the proposed antenna with simulated the fabricated models.The Blue line represents the Simulated model , Brown line represents the fabricated models and the other colour lines represents the optimized outputs of the proposed antenna. The S11 parameter reflects the antenna’s performance, where values below -10 dB indicate efficient operation. The proposed antenna achieves a return loss of -31.17 dB at 2.41 GHz, identifying its resonant frequency of Simulated model with the blue colored line and -24.68 dB at 2.42 GHz, identifying its resonant frequency of Simulated model with the brown colored line. The measured bandwidth of simulated model is 240 MHz and 243MHz for Fabricated model, confirming that the antenna operates within a narrow frequency range. Figure 3 shows the Voltage Standing Wave Ratio (VSWR) curve of the proposed antenna as a function of frequency with simulated and fabricated models Blue and Brown lines respectively.

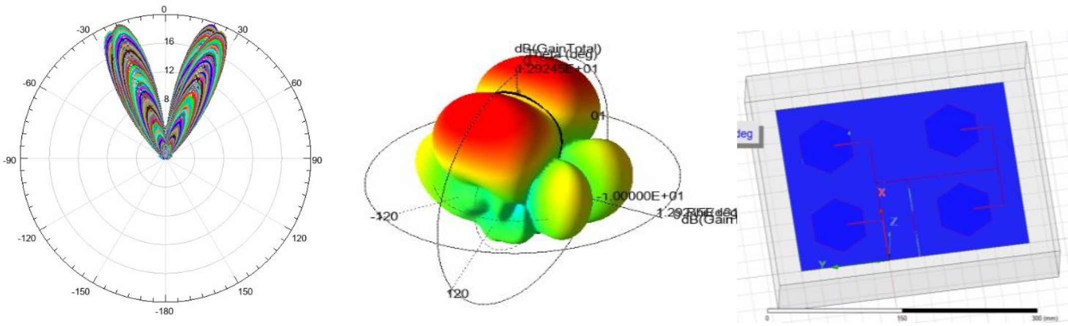

Figure 4a.2d Radiation pattern b. 3d Radiation pattern c. Field Distribution of Proposed antenna

Table 2 Simulated Design parameters of Proposed single hexagonal antenna

S.No	Parameter	Simulated	Fabricated
1	Incident Power	1.00W	1.00W
2	Accepted Power	250.75	252.75
3	Radiated Power	258.26	260.28
4	Radiation Efficiency	102.99%	102.97%
5	Total Efficiency	35.82	34.92
6	Peak system gain	4.917	4.68
7	Peak gain(dB)	19.61	19.32

The designed antenna was evaluated through both simulation and fabrication, and the results demonstrate strong agreement in terms of performance metrics. In the simulated analysis, the antenna operated at a center frequency of 2.41 GHz, with a return loss (S_{11}) of -31.14 dB and a Voltage Standing Wave Ratio (VSWR) of 0.48, indicating excellent impedance matching and minimal signal reflection. The incident power was 1.00 W, from which an accepted power of 250.75 units and a radiated power of 258.26 units were observed, resulting in a radiation efficiency of 102.99% and a total efficiency of 35.82%. The antenna also exhibited a peak system gain of 4.917 and a peak gain of 19.61 dB, confirming efficient radiation characteristics.
In comparison, the fabricated prototype operated at a slightly shifted frequency of 2.42 GHz, with an S_{11} value of -24.68 dB and a VSWR of 1.01, which still indicates a good impedance match for practical use. The incident power remained at 1.00 W, while the accepted power increased slightly to 252.75 units and radiated power to 260.28 units, yielding a radiation efficiency of 102.97% and a total efficiency of 34.92%. The peak system gain was measured at 4.68, with a peak gain of 19.32 dB. Overall, the fabricated results closely align with simulation, validating the antenna's design effectiveness for real-world implementation.

Table 3 Comparison of 1 x 1, 2 X 1, 4 X 1 and 2 X 2 hexagonal shaped array antenna

Parameters	1 x 1	2 x 1	4 x 1	2 x 2 (Simulated)	2 x 2 (Fabricated)
Frequency(GHz)	2.46	2.439	2.42	2.41	2.42
Return loss(S_{11})	-17.72	-28.66	-14.43	-31.14	-24.68
Bandwidth(MHz)	140	170	220	180	170
Incident Power(W)	1	1	1	1	1
Accepted Power(mW)	109.23	364.69	339.72	250.75	252.75
Radiated Power(mW)	111.2	374.25	347.61	258.26	260.28
Radiation Efficiency	101%	102.62%	102.32%	102.99%	102.97%
Total Efficiency	11%	37.42%	34.76%	35.82	34.92
Peak system gain(dB)	0.866	5.76	4.20	4.917	4.68
Peak gain(dB)	7.93	15.05	12.38	19.61	19.32

A comprehensive performance analysis was conducted on hexagonal-shaped microstrip patch antennas configured as 1×1, 2×1, 4×1, and 2×2 arrays, with the 2×2 array further validated through fabrication. The operating frequency for all designs remained centered around the 2.4 GHz ISM band, with a slight downshift observed as the array complexity increased. The 1×1 configuration operated at 2.46 GHz, while the 2×2 array (simulated and fabricated) showed excellent alignment at 2.41 GHz and 2.42 GHz, respectively. Return loss (S_{11}) improved significantly with arraying, decreasing from -17.72 dB in the single-element antenna to -31.14 dB in the simulated 2×2 array, indicating excellent impedance matching. The fabricated version still maintained a strong return loss of -24.68 dB, validating the design's robustness.

Bandwidth was observed to improve with increasing array size, reaching a maximum of 220 MHz in the 4×1 configuration. The 2×2 array demonstrated a bandwidth of 180 MHz (simulated) and 170 MHz (fabricated), showcasing consistent wideband performance. The accepted and radiated powers also scaled with the array configuration, with the 2×1 array accepting the highest power (364.69 mW) and radiating 374.25 mW. Although the 2×2 array accepted slightly less power (250.75 mW simulated, 252.75 mW fabricated), the radiated power remained high (258.26 mW and 260.28 mW, respectively), resulting in radiation efficiencies exceeding 102%, a value commonly attributed to idealized simulation environments or constructive array effects.

Total efficiency showed a substantial increase from 11% in the 1×1 configuration to over 34%–35% in all arrayed structures, highlighting the improved power handling and radiative performance of multi-element arrays. Gain characteristics followed a similar trend. The peak system gain increased from 0.866 dB (1×1) to 5.76 dB (2×1), while the 2×2 array demonstrated 4.917 dB in simulation and 4.68 dB post-fabrication. Peak gain also improved, with the highest value of 19.61 dB in the 2×2 simulated array and 19.32 dB in the fabricated prototype, confirming strong directional radiation and enhanced signal strength due to constructive interference between elements.

Overall, the results affirm that increasing the number of elements in a hexagonal array significantly enhances key antenna performance parameters. The 2×2 configuration, in particular, offers a well-balanced trade-off between size, efficiency, bandwidth, and gain, with fabricated outcomes closely matching simulation, thereby establishing its suitability for real-world wireless communication applications in the 2.4 GHz band.

CONCLUSION

This study presented a detailed comparative analysis of hexagonal-shaped microstrip patch antenna arrays in various configurations—1×1, 2×1, 4×1, and 2×2—to evaluate their suitability for applications in the 2.4 GHz ISM band. The performance metrics including return loss (S_{11}), bandwidth, gain, accepted and radiated power, and efficiencies were thoroughly examined through simulation, with the 2×2 configuration also validated through fabrication. The results clearly demonstrate that the 2×2 array outperforms the other configurations in multiple aspects. It achieved a simulated return loss of -31.14 dB and a fabricated value of -24.68 dB, indicating excellent impedance matching. Its operating frequency remained highly stable, shifting only slightly from 2.41 GHz (simulated) to 2.42 GHz (fabricated). The bandwidth also remained robust, measuring 180 MHz in simulation and 170 MHz in the fabricated prototype. In terms of power metrics, the 2×2 simulated array accepted 250.75 mW and radiated 258.26 mW, while the fabricated array closely matched with 252.75 mW accepted and 260.28 mW radiated power. These values correspond to radiation efficiencies of 102.99% (simulated) and 102.97% (fabricated), and total efficiencies of 35.82% and 34.92%, respectively—substantially higher than the

11% total efficiency observed in the 1×1 element.Moreover, the peak system gain of the 2×2 configuration reached 4.917 dB in simulation and 4.68 dB in fabrication, while the peak gain was recorded at 19.61 dB and 19.32 dB, respectively—significantly higher than the 7.93 dB gain of the single-element design.These findings confirm that the 2×2 hexagonal array offers the most balanced and optimized performance among all tested configurations. Its consistent results across simulation and fabrication establish it as a reliable, efficient, and high-gain antenna solution suitable for modern wireless communication applications. The compact structure, combined with wide bandwidth and high directivity, makes it a strong candidate for deployment in IoT, WLAN, and other 2.4 GHz-band technologies.

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