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Design of Tri-Band Millimeter Wave Microstrip Patch Antenna Array with Finite Ground Structure for 5G Applications

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Abstract— **The microstrip patch antenna array represents an effective and attractive solution for next-generation wireless communication systems. Antenna array design continues to be a major focus of research, particularly for contemporary mobile and electronic devices requiring compact size and high performance. Communication in the upper Ka-band region, commonly known as the millimeter-wave spectrum above 18 GHz, enables high data rates and ultra-low latency transmission. In this work, a tri-band millimeter-wave microstrip patch antenna array with a finite ground structure is proposed for 5G mobile communication applications. The antenna is designed and analyzed using CST Microwave Studio, featuring a simple and compact configuration with overall dimensions of approximately 12 × 35 × 1.6 mm³. Simulation results demonstrate that the antenna operates effectively over the 20–28 GHz frequency range, with resonant frequencies at 21.8 GHz, 24.26 GHz, and 26.53 GHz. At these bands, the antenna achieves a VSWR below 2, return loss values of −32.85 dB, −22.64 dB, and −18.12 dB, and impedance bandwidths of 435.62 MHz, 608.9 MHz, and 507.82 MHz, respectively.**

Keywords— MM-wave, Microstrip, Antenna, Array, Bandwidth, Return loss, VSWR.

I. INTRODUCTION

The rapid evolution of wireless communication systems has created an ever-increasing demand for higher data rates, lower latency, enhanced connectivity, and efficient spectrum utilization. Fifth Generation (5G) mobile communication systems are designed to meet these requirements by exploiting new frequency bands, particularly the millimeter-wave (mmWave) spectrum[1]. Millimeter-wave frequencies, typically ranging from 18 GHz to 100 GHz, offer large unused bandwidths that enable multi-gigabit data rates and ultra-low latency communication. Among the various antenna technologies proposed for 5G, millimeter-wave microstrip patch antenna arrays have emerged as one of the most promising solutions due to their compact size, low profile, ease of fabrication, and compatibility with modern integrated circuits[2].

Microstrip patch antennas are widely used in wireless systems because of their planar structure, lightweight nature, and low manufacturing cost. When operated at millimeter-wave frequencies, these antennas become extremely compact, making them highly suitable for space-constrained 5G user equipment, base stations, and small-cell deployments. However, a single microstrip patch antenna suffers from limitations such as low gain and narrow bandwidth. To overcome these drawbacks, antenna arrays are employed, where multiple radiating elements are arranged in a specific geometry and fed appropriately to enhance gain, directivity, and radiation efficiency. As a result, microstrip patch antenna arrays play a critical role in achieving the performance requirements of 5G mmWave communication[3].

Millimeter-wave propagation is fundamentally different from that of sub-6 GHz frequencies. At mmWave bands, signals experience higher free-space path loss, increased atmospheric absorption, and greater sensitivity to blockage by obstacles such as buildings, foliage, and even the human body. To compensate for these losses, high-gain and directional antennas are essential. Microstrip patch antenna arrays enable beamforming and beam-steering capabilities, which are key technologies in 5G systems. By electronically controlling the phase and amplitude of signals feeding each antenna element, the radiation beam can be dynamically steered toward the desired user, thereby improving link reliability, coverage, and spectral efficiency[4].

Another important advantage of millimeter-wave microstrip patch antenna arrays is their suitability for massive multiple-input multiple-output (MIMO) systems. 5G networks rely heavily on massive MIMO to serve multiple users simultaneously and improve overall network capacity. The small wavelength at mmWave frequencies allows a large number of antenna elements to be packed into a compact area, making it feasible to implement dense antenna arrays on printed circuit boards. This capability significantly enhances spatial multiplexing and supports advanced communication techniques required for next-generation wireless networks[5].

Despite their advantages, designing microstrip patch antenna arrays for millimeter-wave 5G applications presents several challenges. At high frequencies, fabrication tolerances, conductor losses, dielectric losses, and mutual coupling between antenna elements become more pronounced. Even minor dimensional inaccuracies can lead to significant shifts in resonant frequency and degradation in antenna performance[6]. Therefore, careful design optimization, accurate electromagnetic modeling, and advanced simulation tools are essential to ensure reliable operation. Techniques such as finite ground structures, defected ground planes, substrate optimization, and array configuration tuning are commonly employed to improve bandwidth, impedance matching, and radiation characteristics[7].

5G systems often require multi-band or wideband operation to support different frequency allocations and communication standards. Millimeter-wave microstrip patch antenna arrays can be designed to operate at multiple resonant frequencies, such as 24 GHz, 26 GHz, 28 GHz, and beyond, making them flexible and adaptable for global 5G deployment. Their planar nature also facilitates easy integration with radio-frequency front-end circuits, beamforming networks, and compact wireless modules[8].

Millimeter-wave microstrip patch antenna arrays form a cornerstone technology for 5G wireless communication systems. Their compact size, scalability, compatibility with beamforming and massive MIMO, and ease of integration make them highly suitable for meeting the stringent performance demands of 5G networks[9]. As research continues, ongoing advancements in antenna materials, design methodologies, and fabrication techniques are expected to further enhance the efficiency, bandwidth, and reliability of millimeter-wave microstrip patch antenna arrays for future high-speed wireless applications[10].

II. BACKGROUND

C K Ali rif [1] presented a dual-band millimeter-wave microstrip patch array antenna specifically designed for 5G smartphone applications. The antenna was optimized to operate at two distinct mmWave frequency bands suitable for high-speed mobile communication. Compact size and low-profile structure were emphasized to meet smartphone integration requirements. Simulation results demonstrated good impedance matching and stable radiation patterns. The presented design achieved a peak gain of approximately 9.2 dBi with VSWR below 2 at both bands. The study highlighted improved bandwidth performance compared to single-band designs. The antenna showed strong potential for modern 5G handheld devices.

Preethi et al. [2] presented the design and implementation of a circular microstrip patch array antenna using Rogers RT5880 substrate for 5G communication. The use of a low-loss dielectric substrate enhanced radiation efficiency and gain performance. The antenna array was optimized for mmWave frequency operation. Experimental and simulated results showed close agreement, validating the design methodology. The presented antenna achieved a gain of nearly 10.1 dBi with return loss better than –25 dB. Radiation patterns were stable and directional. The work demonstrated suitability for high-frequency 5G systems.

Chakraborty [3] presented a comparative performance analysis of a slotted mmWave microstrip patch antenna and its array configuration for 5G applications. The introduction of slots was aimed at improving bandwidth and impedance matching. Both single-element and array structures were analyzed and compared. The array configuration significantly enhanced gain and radiation efficiency. The presented results showed a gain improvement from 6.5 dBi (single element) to 11.8 dBi (array). Bandwidth enhancement of nearly 18% was observed. The study confirmed the effectiveness of array-based designs for mmWave communication.

Khabba et al. [4] presented a high-gain double U-shaped slotted microstrip patch antenna array operating at 28 GHz for 5G applications. The slot configuration was used to enhance bandwidth and gain characteristics. The antenna array was designed with optimized inter-element spacing to reduce mutual coupling. Simulation results demonstrated excellent impedance matching and radiation efficiency.

Tayyab et al. [5] presented a circularly polarized patch antenna array for 5G automotive satellite communication systems. Circular polarization was employed to reduce polarization mismatch losses. The antenna array was designed to provide stable performance under vehicular movement conditions. The presented design achieved axial ratio values below 3 dB, ensuring effective circular polarization. A peak gain of about 9.8 dBi was reported. Radiation patterns were stable across the operating band. The work demonstrated applicability in automotive and satellite-based 5G systems.

Raj and Mandal [6] presented a novel substrate cylindrical cavity-based 4×4 fractal-inspired MIMO antenna for 5G n258 satellite communication. The fractal geometry enabled miniaturization while maintaining multiband characteristics. MIMO performance parameters such as isolation and envelope correlation coefficient were evaluated. The presented antenna showed isolation better than –20 dB between elements. Gain values reached approximately 11 dBi. The design supported high data rate satellite links. The study highlighted enhanced MIMO performance for 5G satellite applications.

Li et al. [7] presented a broadband circularly polarized magnetoelectric dipole antenna and array for K-band and Ka-band satellite communication. The antenna combined electric and magnetic dipole elements to achieve wide bandwidth. Circular polarization ensured stable signal reception in satellite links. The presented array achieved a wide impedance bandwidth exceeding 30%. A peak gain of nearly 13 dBi was reported.

Mallani et al. [8] presented a penta-band slotted microstrip patch antenna for wireless communication applications. Multiple slots were introduced to enable operation across five distinct frequency bands. The antenna was designed for compactness and multiband versatility. Simulation results showed good impedance matching at all operating bands. The presented antenna achieved gains ranging from 3.5 dBi to 6.8 dBi across bands. VSWR remained below 2. The study confirmed suitability for multi-service wireless systems.

Khokher et al. [9] presented a comprehensive study on wearable microstrip patch antennas for biomedical applications. The review analyzed antenna performance under body-worn conditions. Parameters such as SAR, flexibility, and radiation efficiency were discussed. The presented findings indicated that wearable antennas typically achieve gains between 2–5 dBi. SAR values were maintained within IEEE safety limits.

Attar et al. [10] presented the design and implementation of a microstrip patch antenna for 5G and beyond-5G applications. The antenna geometry was optimized for wide bandwidth and compact size. Simulation and measurement results were used for validation. The presented design achieved a bandwidth of approximately 1.2 GHz. Gain values of around 8.7 dBi were reported. Radiation patterns showed good directivity. The study demonstrated feasibility for future wireless systems.

M. C et al. [11] presented an inset-fed Z-slot compact microstrip patch antenna for IoT-based healthcare applications. The Z-slot structure enabled miniaturization and multiband behavior. The inset feed improved impedance matching. The presented antenna operated efficiently in the ISM band. A gain of approximately 5.1 dBi was achieved. Return loss was better than –20 dB. The design was suitable for low-power medical IoT devices.

Soni et al. [12] presented a flexible and wearable antenna design aimed at tumor detection in healthcare applications.

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The antenna was fabricated using flexible substrates to conform to the human body. Performance was evaluated under bending conditions. The presented antenna achieved stable operation with minimal frequency shift. Gain values of around 4.6 dBi were observed. SAR analysis confirmed safety compliance. The study demonstrated strong potential for non-invasive biomedical diagnostics.

III. PROPOSED DESIGN

The proposed research work is summarized is as follows-

- To design mm wave micostrip patch antenna array for 5G smart phone communication networks.
- To enhance bandwidth and number of band between 18GHz-28GHz frequency range.
- To calculate other parameters and compare with existing design results.

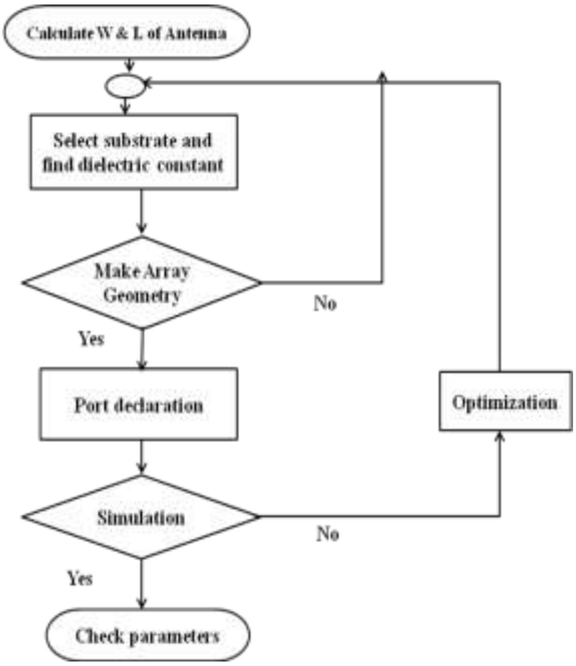

Figure 1: Flow Chart

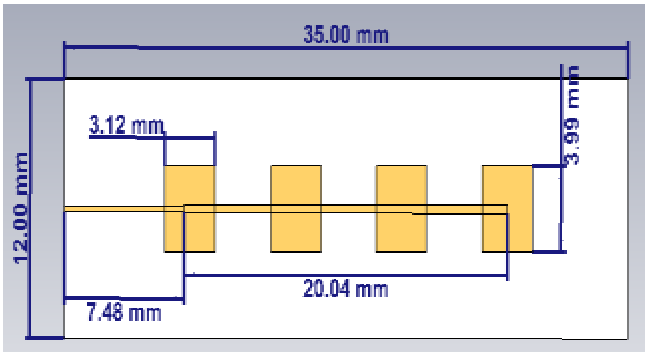

Figure 2: Dimension of proposed antenna

Figure 2 is showing dimension of different component of proposed antenna. This dimension is calculated based on standard formulas and optimization. Therefore the dimension of antenna is (LxWxH) 12x35x1.67 mm^3. The proposed antenna is based on array pattern so the dimension of single component is 3.99x3.12 mm^2. The length of feed patch is 7.48mm and width is 0.3mm. The substrate material which is using in proposed antenna is rogers lossy material.

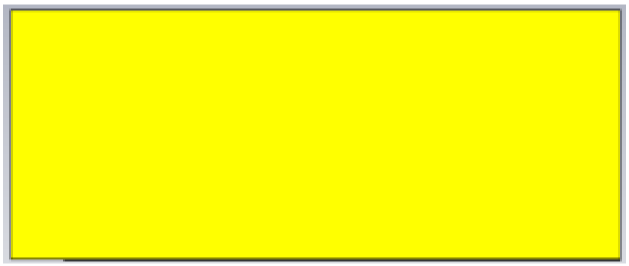

Figure 3: Bottom view of proposed antenna

Figure 2 is showing bottom view of antenna, this is also known as ground structure. There are two types of ground structure, finite and defected ground structure. Proposed antenna is using finite ground structure.

IV. SIMULATION AND RESULTS

Scattering parameters (S-parameters) describe the electrical behavior of linear electrical systems when subjected to various steady-state stimuli from electrical signals. In antenna design, S11 represents the amount of power reflected back from the antenna, and is therefore referred to as the reflection coefficient or return loss. When S11 = 0 dB, it indicates that all the power is reflected and no power is transmitted by the antenna.

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Return loss is defined as the difference, in decibels (dB), between the forward power and the reflected power measured at a given point in an RF system.

Figures 4, 5, and 6 illustrate the return loss (S11) characteristics of the proposed antenna, highlighting its multi-band operation across the frequency range of 20 GHz to 28 GHz. For the proposed design, S11 values are consistently below –10 dB across the operating bands, indicating efficient power transmission and minimal reflection. The frequency response also demonstrates that the antenna offers an improved bandwidth compared to conventional microstrip antenna designs, making it well-suited for high-frequency communication applications.

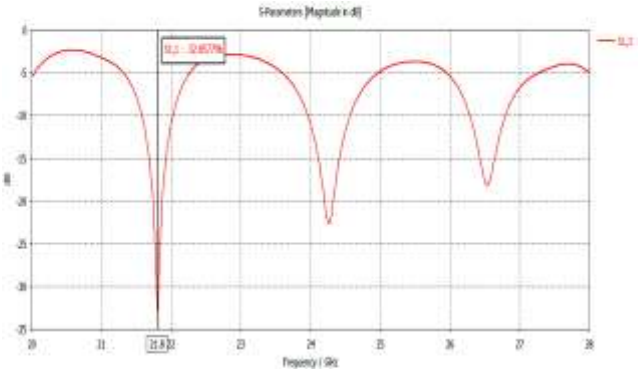

Figure 4: Return loss of band-I

The obtained value of S_{11} or return loss is -32.85 dB for 21.8 GHz resonant frequency, where antenna efficiency is higher.

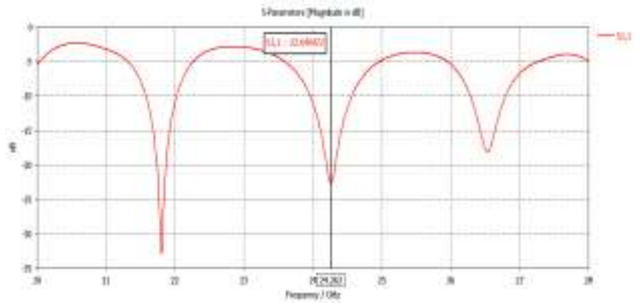

Figure 5: Return loss of band-II

The obtained value of S_{11} or return loss is -22.64 dB for 24.26 GHz resonant frequency, where antenna efficiency is higher.

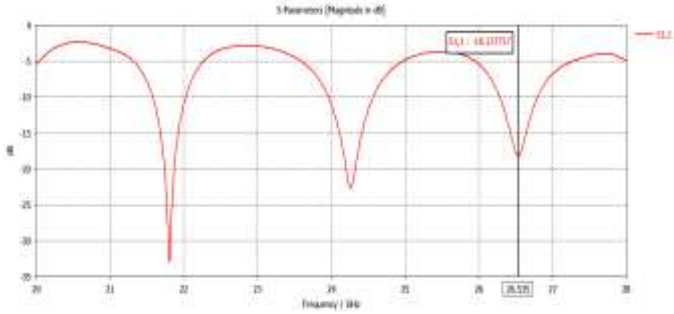

Figure 6: Return loss of band-II

The obtained S11, or return loss, at the 26.53 GHz resonant frequency is –18.12 dB, indicating higher antenna efficiency at this frequency.

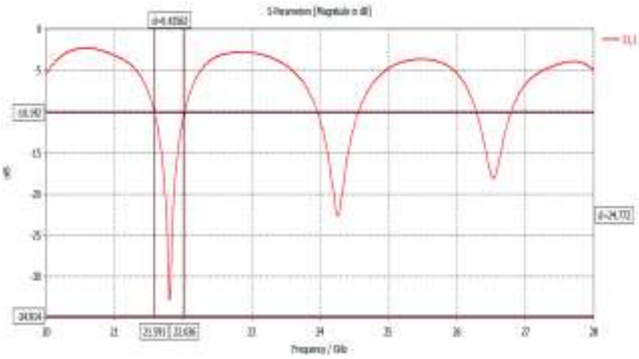

Figure 7: Bandwidth calculation of band-I

For broadband antennas, the bandwidth is expressed as a percentage of the frequency difference (upper minus lower) over the center frequency of the bandwidth. The bandwidth of proposed antenna is 435.62 MHz, (22.026GHz – 21.591GHz), for first band.

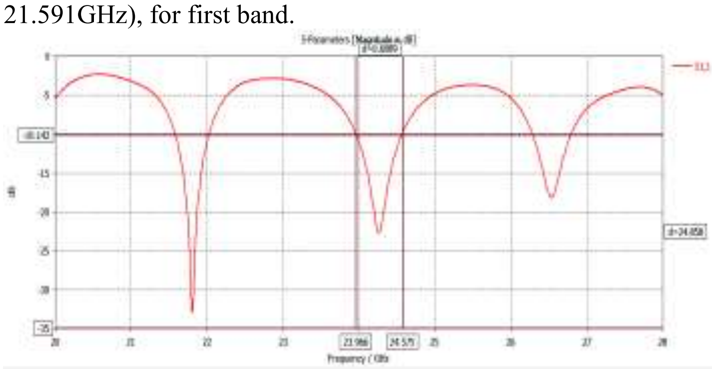

Figure 8: Bandwidth calculation of band-II

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The bandwidth of antenna is 608.9 MHz, (24.575 GHz – 23.966 GHz), for second band.

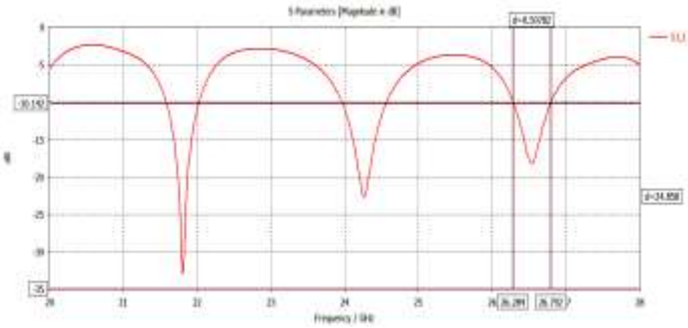

Figure 9: Bandwidth calculation of band-III

The bandwidth of antenna is 507.82 MHz, (26.792 GHz – 26.284 GHz), for third band.

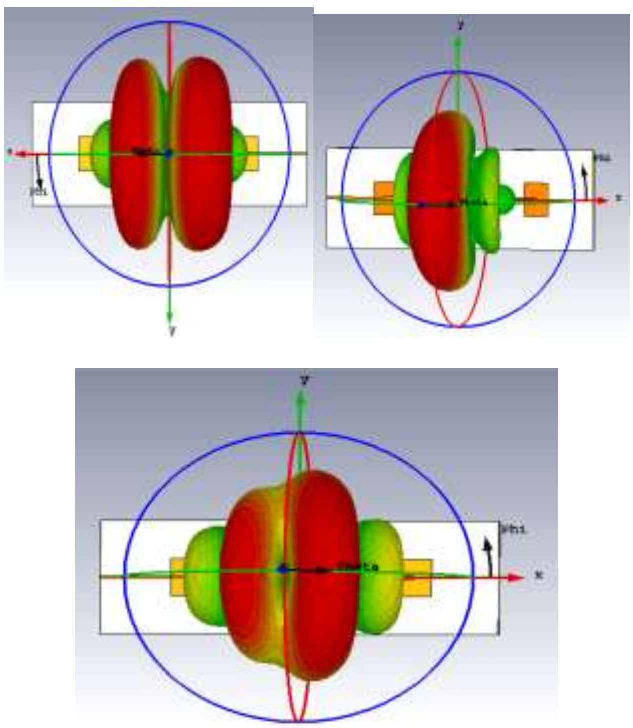

Figure 10: 3D Radiation pattern of proposed antenna

The radiation pattern of a microstrip or patch antenna is typically broad, with relatively low radiation intensity and a limited frequency bandwidth. To achieve greater directivity, an array configuration is often formed by combining multiple patch antennas. In antenna design, the term radiation pattern (also referred to as antenna pattern or far-field pattern) describes the angular dependence of the strength of radio waves emitted from the antenna or another source.

Table 1: Result summary of proposed antenna

Sr. No.	Parameter	Band-I	Band-II	Band-III
1	S11 or Return Loss	-32.85 dB	-22.64 dB	-18.12 dB
2	Band Width	435.62 MHz	608.9 MHz	507.82 MHz
3	VSWR	1.046	1.159	1.283
4	Resonant Frequency	21.8 GHz	24.26 GHz	26.53 GHz
5	Gain	8.970dB	12.41dB	10.84dB
6	Radiated power	- 0.443 W	- 0.434 W	-0.423W

Table 2: Result Comparison

Sr No.	Parameter	Previous work	Proposed work
1	S11 or Return loss	-22 and -35	-32.85 dB, -22.64 dB and -18.12 dB
2	Band Width	300 and 900 MHz (1200MHz)	435.62, 608.9 and 507.82 MHz (1552.34Mhz)
3	VSWR	1.21 and 1.03	1.046, 1.159 and 1.283
4	Resonant Frequency	24.9 and 28 GHZ	21.8, 24.26 and 26.53 GHz
5	Number of bands	2	3

6	Gain	5.375 and 8.42 dBi	12.41dBi
7	Design type	Array	Array

Table 2 showing comparison of proposed antenna results with previous design result in terms of bandwidth, return loss, resonant frequency and VSWR etc.

V. CONCLUSION

The presented CNN-based model exhibits remarkable performance improvements over the existing hybrid method for EMG-based hand gesture recognition across all key evaluation metrics. The CNN approach attained a high classification accuracy of 97.91%, substantially exceeding the 82.41% accuracy achieved by the hybrid technique. In addition, the overall classification error was significantly reduced to 2.09%, compared to the higher error rate of 17.59% observed with the hybrid model. The system's sensitivity showed a notable enhancement from 84% to 97.33%, demonstrating the CNN model's superior capability in correctly recognizing hand gestures. Likewise, specificity improved from 75% to an exceptional 99.06%, indicating a strong reduction in false-positive detections. These results clearly validate the effectiveness of the CNN model in learning discriminative EMG features and ensuring robust classification performance. Consequently, the presented approach provides a reliable and efficient solution for accurate EMG-based hand gesture recognition and establishes a strong benchmark in terms of accuracy, sensitivity, and specificity.

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