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Design and Analysis of a Triple-Band L-Shaped Microstrip Patch Antenna on FR4 Substrate for 5G and 6G Wireless Communications

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***Abstract*—This research presents a compact patch antenna featuring a microstrip feed configuration. The antenna measures 20 × 30 × 1 mm³ and is built on an FR4 substrate with a dielectric constant of 4.4. A microstrip feedline facilitates the connection between the antenna and a connector, achieving optimal impedance matching at 50 Ω. The antenna exhibits resonant performance across three distinct frequency bands: 31.9–32.8 GHz (Passive Band), 36.9–38.4 GHz (5G Band), and 39.5–41.1 GHz (6G Band), with key resonant points identified at 32.3 GHz, 37.6 GHz, and 40.3 GHz. At these frequencies, the voltage standing wave ratio (VSWR) remains below 2, recording values of 1.14, 1.05, and 1.15—indicating strong impedance matching and high-performance efficiency. Designed to achieve broad impedance bandwidth at the -10 dB return loss threshold and minimal VSWR at each resonant frequency, this triple-band antenna is well-suited for advanced wireless communication systems, particularly within nuclear submarine environments. The proposed design delivers robust performance metrics, including sufficient gain, low VSWR, acceptable return loss, and a consistent radiation pattern—making it ideal for high-frequency applications. Parametric analysis further validates its suitability for 5G and 6G operations, underscoring its reliability in maritime defense communication.**

***Index Terms*—Patch, Triple-band, 5G, 6G band.**

1. INTRODUCTION

The development of satellite and wireless communication technologies during the last few decades has had a major influence on modern living. Reliable solutions for electromagnetic wave transmission and reception are required for many applications, including local area networks (LANs) and communication systems. For meeting these needs, microstrip patch antennas (MPAs) have become a popular option because to their low profile, structural simplicity, and ease of manufacture. Because MPAs have inherent design flexibility, many designs and methodologies have evolved to optimize antenna performance over a variety of frequency bands. [1-5]. The growing popularity of compact mobile devices has led to an increased demand for miniaturized, highly efficient components—especially antennas, which are central to wireless communication. As handheld devices continue to shrink while striving for higher performance, antenna design has emerged as a key challenge in mobile technology development.

Microstrip patch antennas (MPAs) have become the preferred solution for portable systems due to their slim form factor, lightweight nature, and ease of fabrication. Their ability to integrate seamlessly with planar circuits makes them ideal for space-constrained environments like smartphones and IoT devices. The antenna's physical parameters—particularly the length and width of the radiating patch—play a vital role in determining its resonant frequency, bandwidth, and overall radiation characteristics. with the rollout of fifth-generation (5G) mobile networks, the performance requirements for antennas have become more stringent. Devices now need to support ultra-high data rates, exceptionally low latency, and robust connectivity across multiple frequency bands. To meet these demands, antenna designs must not only be compact but also highly optimized to ensure efficient operation at high frequencies. [5-10].

The 5G New Radio (NR) interface has been meticulously engineered to address the evolving and increasingly complex demands of next-generation wireless communication systems. As mobile technologies move beyond the year 2020, the landscape is marked by exponential increases in user connectivity, data traffic, and device density—spanning consumer applications, industrial automation, smart cities, and autonomous vehicles.To meet this surge in performance expectations, 5G NR must support a wide array of use cases with varying requirements in terms of bandwidth, latency, reliability, and coverage. These range from enhanced mobile broadband for high-definition streaming, to ultra-reliable low-latency communication (URLLC) for mission-critical operations, and massive machine-type communication for vast IoT deployments.

Central to enabling these capabilities is the efficient allocation and utilization of 5G spectrum across multiple frequency bands—including sub-6G bands, mmWave, and potentially higher frequencies for future expansion. Adequate spectrum access ensures that networks can handle heavy traffic loads while maintaining high throughput, minimal latency, and robust reliability.

To meet the evolving demands of modern wireless communication, strategic spectrum planning has become an essential cornerstone of 5G New Radio (NR) networks. Techniques such as dynamic spectrum sharing and carrier aggregation play a critical role in maximizing spectral efficiency and adapting to a wide array of service requirements. By balancing coverage, performance, and availability across low-, mid-, and high-frequency bands, 5G NR enables the deployment of flexible, scalable infrastructures. These networks are capable of supporting seamless connectivity, ultra-low latency, and high reliability across diverse application domains—including enhanced mobile broadband, massive machine-type communication, and mission-critical services [10–15]

This paper presents a comprehensive framework for the design, development, and performance evaluation of the proposed antenna. Its structure is methodically organized to guide the reader through each critical phase of the antenna's evolution. Section II details the design methodology, elaborating on the architectural strategies and configuration techniques employed during the construction of the antenna prototype. It also specifies the materials and dimensional parameters selected to achieve the intended electrical performance characteristics, including impedance, resonance, and radiation behavior. Section III focuses on the optimization efforts and parametric analysis used to refine the antenna's functional attributes. A series of design parameters—such as patch geometry, substrate properties, and feed placements are systematically adjusted and studied to understand their influence on key performance indicators like return loss, gain, bandwidth, and VSWR.Section IV presents the simulated performance results and conducts a comparative evaluation against existing antenna designs reported in the literature. This section critically examines the proposed antenna's strengths and shortcomings and identifies opportunities for further refinement, potential multi-band expansion, and future research directions relevant to emerging communication technologies.

II. GEOMETRY ANALYSIS

Figure 1 illustrates the development of asymmetric configurations of antenna that have been created and studied. The proposed antenna design, inner and outer curve has a diameter of 16.96 mm and 14.96 mm. Angular displacement between these two curves are 258.45 and 41.18 degrees as shown in Fig.1.
The steps for calculating geometric design parameters are shown below.

Step 1: Calculation of the Width (W):
The width of the Microstrip patch antenna is given as:

$$\mathbf{W} = \frac{\mathrm{C}}{2\mathrm{fo}\sqrt{\frac{\in \mathrm{r}+1}{2}}}$$

Step 2: Calculation of Effective dielectric constant (ε_{reff}):

The effective dielectric constant is:

$$\mathcal{E}\mathrm{reff.} = \frac{\in r+1}{2} + \frac{\in r+1}{2}\sqrt{1+12\frac{h}{w}}$$

Step 3: Calculation of the Effective length (L_{eff}):
The effective length is:

$$Leff = \frac{c}{2fo\sqrt{\text{Ɛreff}}.}$$

Step 4: Calculation of the length extension (ΔL):
The length extension is:

$$\Delta L = 0.412h\frac{(\text{Ɛreff} + 0.3)(\frac{W}{h} + 0.264)}{(\text{Ɛreff} - 0.258)(\frac{W}{h} + 0.8)}$$

Step 5: Calculation of actual length of patch (L):
The actual length is obtained by:

$$L = Leff - 2.\Delta L$$

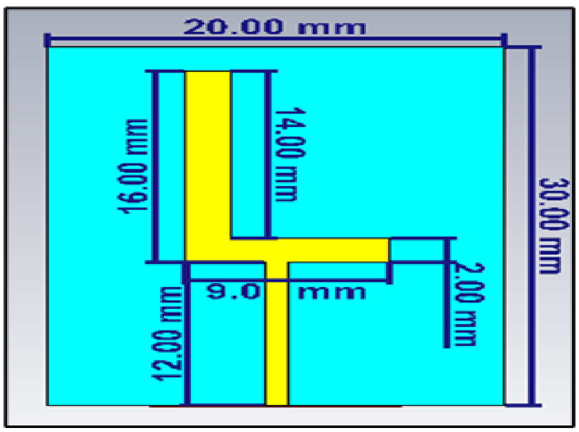

Fig.1 Proposed antenna design

III. PARAMETRIC RESULT ANALYSIS

The electromagnetic (EM) simulation program CST Studio Suite Version 17, which makes use of the Finite Integration Technique (FIT) in the transient solver mode of the antenna template, was used to model the suggested antenna design. According to the simulation results, the antenna performs admirably in terms of all evaluation criteria. The results of CST simulations showed a significant connection with theoretical predictions in terms of radiation pattern, gain, directivity, impedance bandwidth (IBW), return loss, and voltage standing wave ratio (VSWR). A summary of the simulation's optimized electrical parameters can be found in Table I.

Antenna Geometry (mm^3)	VSWR (< 2)	Resonance frequency (f_r) in GHz	Antenna Bandwidth (GHz)	S_{11} (-dB)	Number of Bands
	1.14	32.3	31.9–32.8	26	
20×30×1 mm^3	1.05	37.6	36.9–38.4	33	Triple
	1.15	40.3	39.5–41.1	25	

Table 1: Result Analysis

The voltage standing wave ratio (VSWR) of the proposed patch antenna is presented in Fig. 2. Fig. 3 shows the return loss characteristics of the antenna. The directivity and antenna gain are depicted in Figs. 4 and 5, respectively. Finally, the radiation pattern of the antenna is shown in Fig. 6.

3.1 VSWR

The Voltage Standing Wave Ratio (VSWR) represents the ratio of transmitted to reflected voltage standing waves in a radio frequency (RF) transmission system. It is a key parameter used to evaluate the efficiency of power transfer from the source, through the transmission line, and into the load. As illustrated in Fig. 2, the VSWR at the resonance frequencies of 32.3 GHz, 37.6 GHz and 40.30 GHz are 1.15, 1.05 and 1.14, respectively, indicating excellent impedance matching at both frequencies.

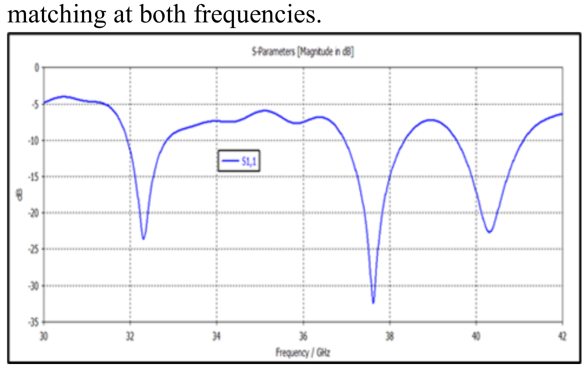

Fig. 2 VSWR of the proposed antenna

3.2 Return Loss

Return loss is the ratio of reflected power to incident power, measured in decibels (dB). For resonance frequencies of 32.3 GHz, 37.6 GHz, and 40.3 GHz, the return loss is −26 dB, −33 dB and −25 dB respectively as shown in Fig. 3.

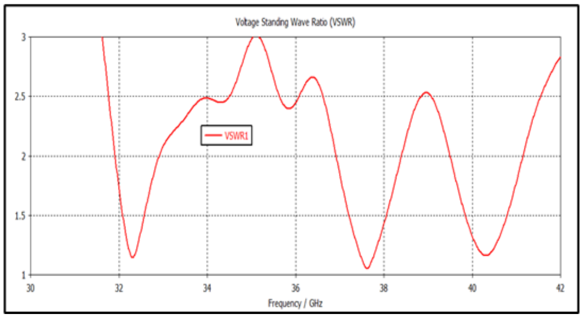

Fig. 3 Return loss of the proposed antenna

3.3 Directivilty

It is measured in relation to the concentration of energy emitted in a certain direction by the transmitting antenna. The primary lobe's directivity magnitude at 32.3 GHz is 5.72 dBi. According to Fig. 4, the major lobe magnitude of directivity is 5.05 and 5.26 dBi, respectively, for resonance frequencies of 37.6 GHz and 40.3 GHz.

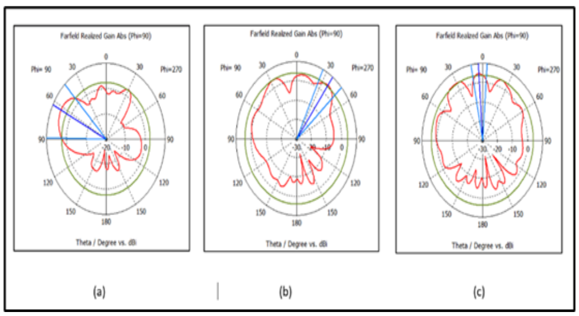

Fig.4 Directivity of proposed antenna at resonance frequencies of 32.3 GHz, 37.6 GHz, and 40.3 GHz

3.4 Gain

The amount of power that is transmitted from an isotropic source to the direction of the peak radiation is referred to as antenna gain. As shown in Fig. 5, the gain is 5.9 dBi,6.3 dBi and 5.4 dBi at resonance frequencies of 32.3 GHz, 37.6 GHz and 40.3 GHz , respectively.

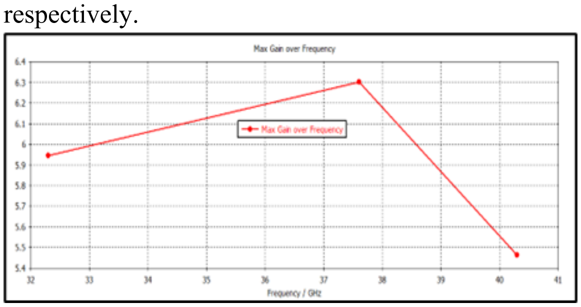

Fig. 5 Gain of the Proposed antenna at 32.3 GHz, 37.6 GHz, and 40.3 GHz

3.5 Radiation Pattern

Voltage and electric field are related; a higher E-field striking an antenna will result in a greater voltage differential between the antenna's terminals. As shown in Fig. 6, the major lobe magnitude of the E-field is 5.33 dB (V/m), 4.6 dB (V/m) and 5.6 dB (V/m) at resonance frequencies of 32.3 GHz, 37.6 GHz, and 40.3 GHz respectively.

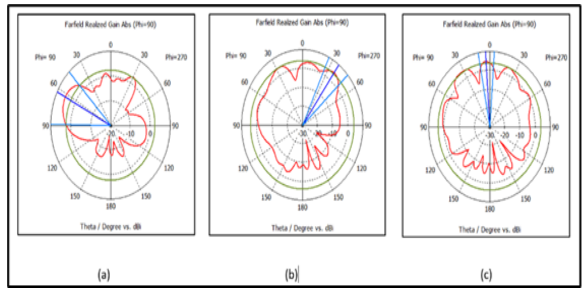

Fig. 6 Radiation pattern of proposed antenna at 32.3 GHz, 37.6 GHz, and 40.3 GHz

IV. CONCLUSION

An innovative and compact CPW-fed patch antenna has been developed to meet stringent performance targets for next-generation wireless systems. It supports tri-band operation with resonant frequencies at 32.3 GHz, 37.6 GHz, and 40.3 GHz, covering three key bands: 31.9–32.8 GHz (Passive Band), 36.9–38.4 GHz (5G Band) and 39.5–41.1 GHz (Extended Band) Designed for 5G, 6G, satellite, and VHF military communications, the antenna exhibits strong performance across diverse wireless applications. By minimizing its physical footprint and incorporating materials with varying dielectric constants, the design enables bandwidth enhancement and broader resonance coverage—making it suitable for emerging high-frequency systems.

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