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Comparative Study of Rectangular and Circular Microstrip Patch Antenna Using Duroid Substrate for 5g Application

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Gain,
Bandwidth.

ABSTRACT
Microstrip patch antennas (MPAs) are widely employed in wireless communication systems because of their low profile, lightweight structure, low fabrication cost, and ease of integration with planar circuits. However, selecting the most suitable patch geometry remains a major design challenge, as antenna shape significantly influences impedance matching, bandwidth, gain, and radiation characteristics. Despite the extensive use of rectangular and circular microstrip patch antennas, limited studies have provided a comprehensive comparison of their performance using RT/Duroid 5880 substrate at the 3.5 GHz 5G band. This study addresses this gap by comparatively evaluating rectangular and circular microstrip patch antennas to identify the geometry best suited for 5G applications. The antennas were designed and simulated using the High Frequency Structure Simulator (HFSS), and their performance was assessed based on return loss (S11), voltage standing wave ratio (VSWR), realized gain, bandwidth, and directivity. Both antenna geometries resonated successfully at 3.5 GHz; however, the rectangular antenna exhibited superior overall performance, achieving a lower return loss of −28.85 dB, lower VSWR of 0.6297, higher realized gain of 7.8059 dB, and greater directivity of 2.5882 dB compared to the circular antenna, which recorded −24.89 dB return loss, 0.999 VSWR, 7.1306 dB gain, and 2.4898 dB directivity. Although the circular antenna provided a slightly wider bandwidth (200 MHz) than the rectangular antenna (188 MHz), the results demonstrate that the rectangular microstrip patch antenna offers superior impedance matching and radiation performance, making it a more suitable candidate for efficient and reliable sub-6 GHz 5G wireless communication systems.

INTRODUCTION

The rapid evolution of fifth-generation (5G) wireless communication systems has significantly increased the demand for compact, lightweight, and high-performance antennas capable of supporting enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC). Among the frequency bands allocated for 5G deployment, the 3.5 GHz band has become particularly important because it provides an effective compromise between coverage, penetration capability, spectrum efficiency, and data throughput (Balanis, 2016; Alshortan *et al*., 2021; Al-Yasir *et al*., 2020). Consequently, antenna miniaturization has become one of the major design challenges in modern wireless communication systems.

Electrically small antennas (ESAs) have attracted considerable attention because they occupy limited space while maintaining acceptable radiation characteristics, making them suitable for smartphones, tablets, wearable devices, Internet of Things (IoT) terminals, and other portable wireless equipment. However, reducing antenna size inevitably introduces several design challenges, including narrow impedance bandwidth, reduced radiation efficiency, lower gain, increased quality factor, stronger mutual coupling, and more difficult impedance matching (Colcao & Lohami 2020; Kyama *et al*., 2023; Sowe & Langat 2022). These limitations have motivated researchers to develop improved microstrip antenna configurations such as the Planar Inverted-F Antenna (PIFA), slot-loaded microstrip antennas, defected ground structures (DGS), electromagnetic band-gap (EBG) structures, stacked patches, fractal antennas, metamaterial-inspired antennas, and multiple-input multiple-output (MIMO) antennas. Although these techniques improve one or more antenna characteristics, they generally increase fabrication complexity, optimization requirements, and production cost (Djouimaa & Bencherif 2024; Ngoc 2020).

Despite these developments, the conventional microstrip patch antenna (MPA) remains one of the most widely used antenna structures because of its low-profile configuration, lightweight construction, ease of fabrication, low manufacturing cost, and compatibility with printed circuit board (PCB) technology and microwave integrated circuits (Balanis, 2016; Li 2023; El-Hakim & Mohaned 2023; Olabisi *et al*., 2024). A typical MPA consists of a metallic radiating patch printed on one side of a dielectric substrate backed by a conducting ground plane. The radiating patch determines the resonant characteristics, while the substrate influences bandwidth, resonant frequency, radiation efficiency, and impedance matching through its dielectric constant, thickness, and loss tangent. The ground plane suppresses backward radiation and improves antenna directivity (Balanis, 2016).

Among the numerous patch geometries, the rectangular microstrip patch antenna (RMPA) and circular microstrip patch antenna (CMPA) remain the most widely investigated because of their simple analytical design procedures and predictable radiation characteristics. The rectangular geometry generally provides wider bandwidth, higher gain, and simpler impedance matching, whereas the circular geometry offers improved symmetry, lower cross-polarization, and more uniform current distribution. Although several advanced antenna configurations have been proposed for 5G systems, conventional rectangular and circular patch antennas continue to serve as benchmark designs for evaluating new antenna concepts because of their simplicity, reproducibility, and ease of fabrication.

Another critical factor influencing antenna performance is substrate selection. The electrical properties of the substrate, particularly dielectric constant, loss tangent, and thickness, significantly affect antenna size, bandwidth, gain, radiation efficiency, and impedance matching. These parameters involve unavoidable engineering trade-offs. A low dielectric constant increases bandwidth and radiation efficiency but results in larger antenna dimensions. Conversely, a high dielectric constant reduces antenna size at the expense of narrower bandwidth and increased dielectric losses. Similarly, increasing substrate thickness may improve bandwidth but can also enhance surface-wave excitation and feed radiation. Therefore, selecting an appropriate substrate requires balancing antenna miniaturization with overall electromagnetic performance according to the intended application.

Among commercially available microwave substrates, RT/Duroid 5880 is widely recognized as one of the most suitable materials for high-frequency antenna applications because of its low dielectric constant ($\varepsilon r \approx 2.2$), very low loss tangent ($\tan\delta \approx 0.0009$), excellent thermal stability, and low moisture absorption. These characteristics reduce dielectric losses and surface-wave propagation while improving radiation efficiency, gain, and impedance matching, making the material particularly suitable for 5G antenna systems (Saeed et al., 2026; Teresa & Umamaheswari 2022).

Although numerous studies have investigated either rectangular or circular microstrip patch antennas for wireless communication applications, relatively few have performed a direct comparison of both geometries under identical substrate properties, feeding techniques, operating frequency, and simulation conditions. Consequently, the influence of antenna geometry on return loss, voltage standing wave ratio (VSWR), bandwidth, realized gain, directivity, and radiation characteristics has not been comprehensively established for RT/Duroid 5880-based antennas operating at 3.5 GHz.

Therefore, this study presents a comparative investigation of rectangular and circular microstrip patch antennas designed on RT/Duroid 5880 substrate for sub-6 GHz 5G applications. Both antennas were designed using identical substrate properties and operating conditions and analysed using the High Frequency Structure Simulator (HFSS). Their performance was evaluated in terms of return loss (S11), VSWR, bandwidth, realized gain, directivity, and radiation characteristics. Unlike previous studies that focused primarily on single antenna geometries or more complex antenna configurations, this work provides a systematic benchmark comparison of two widely used conventional patch geometries on the same substrate. The findings provide practical design guidance for selecting an appropriate antenna geometry for compact, efficient, and cost-effective 5G wireless communication systems while clearly illustrating the performance trade-offs associated with each design.

MATERIALS AND METHODS

Antenna Design Configuration

Two single-element microstrip patch antennas, namely the rectangular microstrip patch antenna (RMPA) and the circular microstrip patch antenna (CMPA), were designed to operate at the 3.5 GHz sub-6 GHz 5G frequency band. Both antennas were designed using identical substrate properties and simulated using ANSYS High Frequency Structure Simulator (HFSS) 2024 R2 to ensure a fair performance comparison.

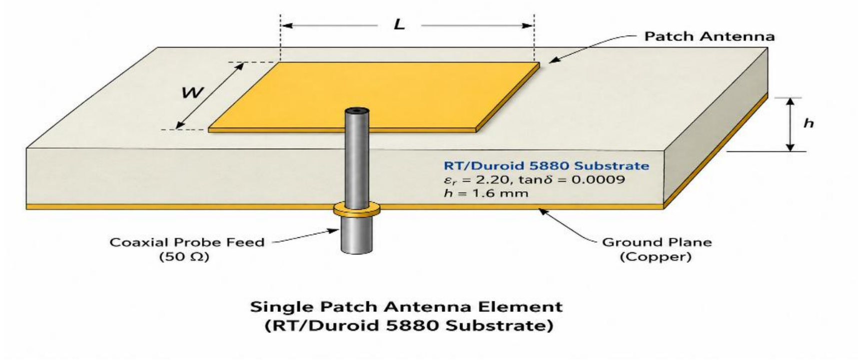

Figure 1: Rectangular Microstrip Patch Antenna

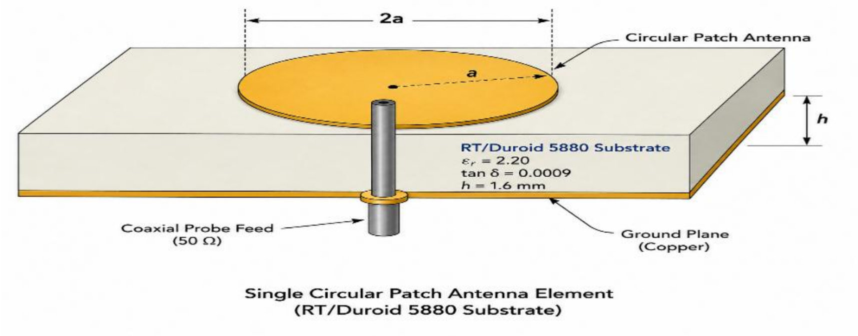

Figure 2: Circular Patch Microstrip Antenna

Unlike the generic illustration shown in Figures 1 and 2, which depict the basic structure of a microstrip patch antenna, the actual antenna models used in this study employed Rogers RT/Duroid 5880 substrate. Therefore, Figures 1 and 2 have been replaced with antenna geometries showing RT/Duroid 5880 instead of FR4 to maintain consistency between the methodology and the simulated models.

Substrate Material

The substrate selected for this study is Rogers RT/Duroid 5880, which is widely used in microwave and 5G antenna applications because of its excellent electrical characteristics. The substrate properties are summarized in Table 1.

Table 1: Electrical properties of RT/Duroid 5880 substrate

Parameter	Value
Relative dielectric constant (εr)	2.20
Loss tangent (tan δ)	0.0009
Substrate thickness (h)	1.6 mm
Relative permeability (μr)	1.0
Conductive material	Copper
Copper thickness	0.035 mm

The low dielectric constant minimizes surface-wave losses and improves radiation efficiency, while the low loss tangent reduces dielectric losses at microwave frequencies.

Feeding Technique

Both antennas were excited using a 50-Ω coaxial probe feed, which is a contacting feeding technique. The coaxial feed was selected because it provides simple implementation, accurate impedance matching, and minimal spurious radiation at the operating frequency. The feed position for each antenna was optimized in HFSS to achieve the minimum return loss and VSWR at 3.5 GHz.

Ground Plane Design

A finite ground plane was employed for both antenna configurations. The ground plane dimensions were selected according to standard microstrip antenna design recommendations and maintained constant throughout the investigation to ensure a fair comparison.

Ground plane dimensions:

i. Length (Lg): 60 mm
ii. Width (Wg): 60 mm
iii. Thickness: 0.035 mm (Copper)

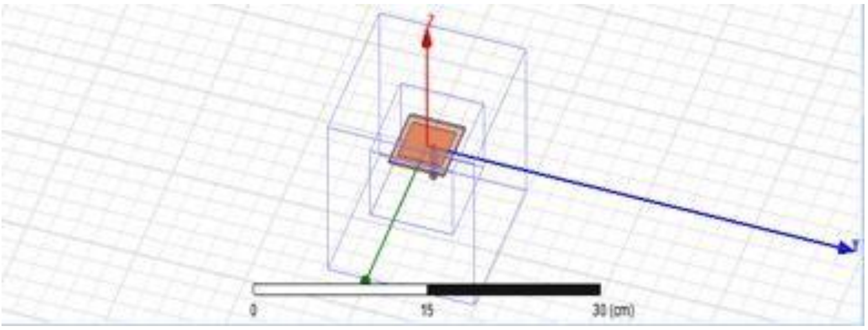

Figure 3: Rectangular Shape Microstrip Antenna Simulation

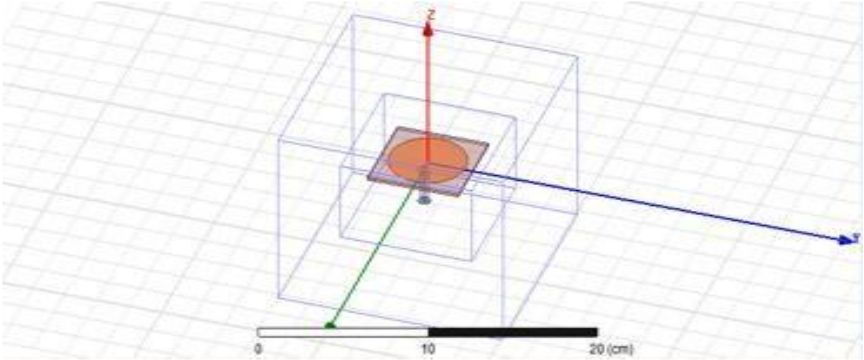

Figure 4: Circular Shape Microstrip Antenna Simulation

Using identical ground-plane dimensions eliminates variations caused by higher-order mode excitation and ensures that differences in antenna performance arise primarily from the patch geometry.

Antenna Dimensions

The design parameters used in both antenna models are summarized in Table 2.

Table 2. Antenna Design Parameters

Parameter	Rectangular Antenna	Circular Antenna
Operating frequency	3.5 GHz	3.5 GHz
Feed technique	50-Ω Coaxial Probe	50-Ω Coaxial Probe
Substrate	RT/Duroid 5880	RT/Duroid 5880
Er	2.20	2.20
Thickness (h)	1.6 mm	1.6 mm
Ground plane	60 × 60 mm²	60 × 60 mm²
Patch width (W)	33.80 mm	—
Patch length (L)	27.04 mm	—
Patch radius (a)	—	15.56 mm

Design Equations

The dimensions of the rectangular and circular microstrip patch antennas were determined using the conventional transmission-line model and cavity-model formulations developed for microstrip antennas. These analytical models provide accurate initial dimensions for the radiating patch and are widely adopted in antenna design because of their simplicity and reliability (Balanis, 2016; Garg *et al*., 2001; Olabisi *et al.*, 2025). The calculated dimensions were subsequently optimized using ANSYS High Frequency Structure Simulator (HFSS) 2024 R2 to achieve resonance at the target frequency of 3.5 GHz.

The width of the rectangular microstrip patch antenna is calculated as

$$w = \frac{c}{2fr}\sqrt{\frac{2}{\epsilon_{r+1}}} \qquad (1)$$

w = patch width (mm)
C= speed of light (3×10^8 m/s)
fr = resonant frequency (Hz)
ϵ_r= dielectric constant

The effective dielectric constant is

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left(1+12\frac{h}{w}\right) \qquad (2)$$

Where
ϵ_{reff}= effective dielectric constant
h= substrate thickness
W= patch width

The extension in patch length caused by fringing fields is

$$\Delta L = 0.412\,\frac{(\epsilon_{reff)}+0.3)(wh+0.264)}{(\epsilon_{reff}-0.258)(wh+0.8)} \qquad (3)$$

The effective patch length is

$$w = \frac{c}{2fr}\sqrt{\frac{2}{\epsilon_{r+1}}} \qquad (4)$$

While the actual patch length is

$$l = l_{eff} - 2\Delta l \qquad (5)$$

For the circular microstrip patch antenna, the effective radius is first determined using

$$F = \frac{8.791\times10^9}{f_r\epsilon_r} \qquad (6)$$

Where F is the radius parameter (cm), *fr* is the resonant frequency (GHz), and $\varepsilon r$is the dielectric constant of the substrate.

The actual radius of the circular patch is calculated from

$$a = \frac{F}{\sqrt{1+\frac{2h}{f\pi\epsilon_r}(\ln\frac{\pi f}{2h})+1.7726)}} \qquad (7)$$

Where $a$the actual patch radius (m), F is is the radius parameter, h is the substrate thickness, and εr is the substrate dielectric constant. The ground-plane dimensions for both antenna geometries were selected according to standard microstrip antenna design practice to minimize edge diffraction and surface-wave effects. The dimensions were determined using

$$L_g = 6h + l \qquad (8)$$

$$W_g = 6h + w \qquad (9)$$

Where L_g and W_g are the ground-plane length and width, respectively.

The designed antenna dimensions obtained from Equations (1) – (9) were used as the initial design parameters in HFSS, after which parametric optimization was performed to obtain optimum impedance matching, return loss, bandwidth, gain, and radiation characteristics at 3.5 GHz.

Simulation Procedure

The complete antenna models were developed and analyzed using ANSYS HFSS, which employs the finite-element method (FEM) for full-wave electromagnetic analysis.

The simulation procedure consisted of the following steps:

i. Selection of RT/Duroid 5880 substrate properties.
ii. Calculation of antenna dimensions using standard microstrip antenna equations.
iii. Construction of rectangular and circular antenna geometries.
iv. Implementation of a 50-Ω coaxial probe feed.
v. Assignment of radiation boundaries and solution setup.
vi. Frequency sweep from 3.0 GHz to 4.0 GHz.
vii. Extraction of S11, VSWR, gain, directivity, bandwidth, current distribution, and radiation patterns.
viii. Comparative evaluation of both antenna geometries.

RESULTS AND DISCUSSION

Radiation Characteristics

Figures 5 and 6 present the three-dimensional radiation patterns of the circular and rectangular microstrip patch antennas operating at 3.5 GHz. Both antennas exhibit the expected broadside radiation pattern characteristic of microstrip patch antennas, with maximum radiation occurring perpendicular to the patch surface.

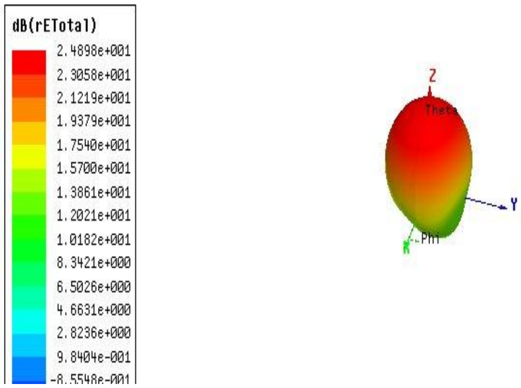

Figure 5: Radiation in 3D of Circular MSA

Figure 6: Radiation in 3D of Rectangular MSA

The rectangular antenna achieved a directivity of 2.5882 dB, while the circular antenna produced 2.4898 dB. Although the difference is relatively small, the rectangular geometry concentrates electromagnetic energy slightly more effectively in the desired direction, resulting in improved directional performance. Conversely, the circular antenna exhibits a more symmetrical radiation distribution, which may be advantageous for applications requiring uniform coverage.

Return Loss (S11)

Figures 7 and 8 illustrate the simulated return loss characteristics of both antennas

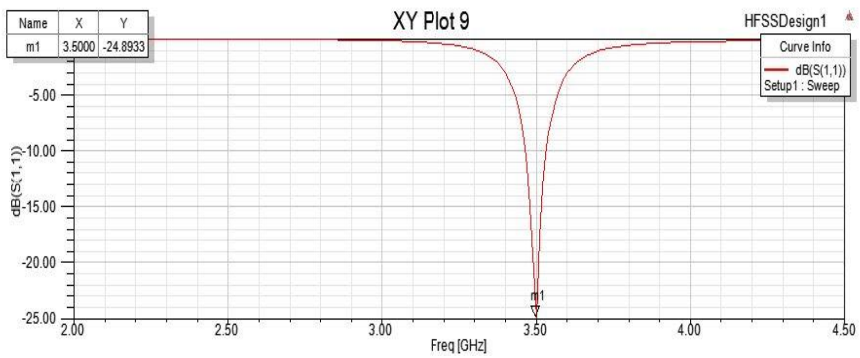

Figure 7: Return Loss of the Circular MSA

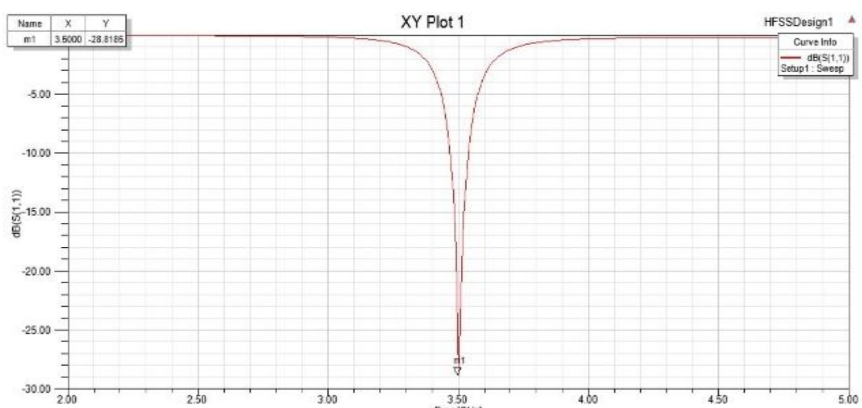

Figure 8: Return Loss of the Rectangular MSA

The circular antenna achieved a minimum return loss of −24.89 dB, whereas the rectangular antenna achieved −28.85 dB at the operating frequency of 3.5 GHz. Both values are considerably lower than the commonly accepted −10 dB criterion, confirming satisfactory impedance matching for practical 5G operation.

However, the rectangular antenna reflects less incident power and transfers more energy to free space, resulting in improved radiation performance.

Voltage Standing Wave Ratio (VSWR)

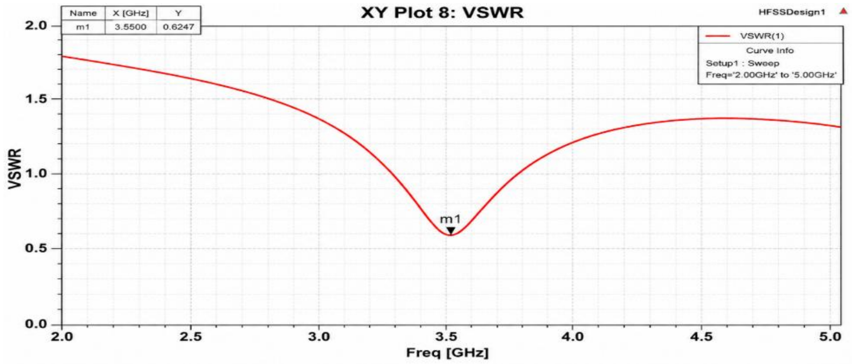

Figure 9: VSWR of circular MSA

Figure 9 presents the simulated VSWR response of the circular microstrip patch antenna. The antenna exhibits a minimum VSWR of 0.6247 at 3.55 GHz, which is close to the intended 3.5 GHz operating frequency. The 0–2 vertical scale provides improved visualization of the VSWR response and facilitates assessment against the commonly used VSWR ≤ 2 criterion for acceptable impedance matching.

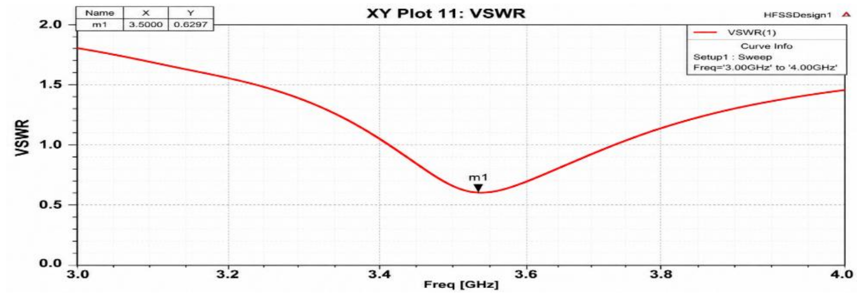

Figure 10: VSWR of rectangular MSA

Figure 10 presents the simulated VSWR response of the rectangular microstrip patch antenna over the 3.0–4.0 GHz frequency range. The antenna achieves a minimum VSWR of 0.6297 at 3.5 GHz, indicating good impedance matching at the target 5G operating frequency. The revised vertical scale of 0–2 provides clearer visualization of the antenna response and facilitates direct comparison with the generally accepted VSWR ≤ 2 criterion for practical antenna operation.4.4 Bandwidth Performance.

Bandwidth

Figures 11 and 12 show the bandwidth of circular and rectangular MPA. Bandwidth is one of the most important parameters for modern wireless communication systems because it determines the frequency range over which the antenna maintains acceptable impedance matching.The circular antenna achieved a bandwidth of 200 MHz, while the rectangular antenna achieved 188 MHz.

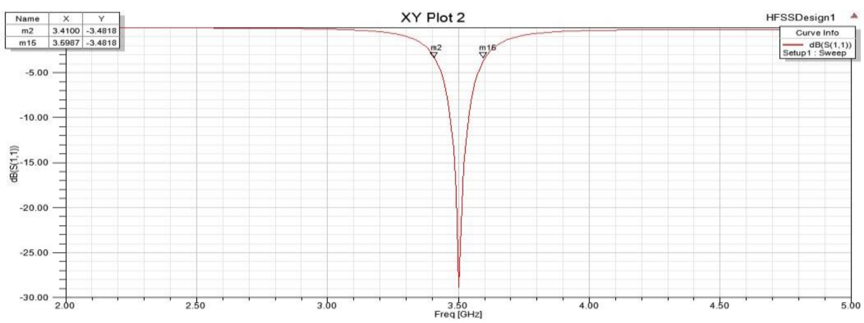

Figure 11: Bandwidth of the Circular MPA

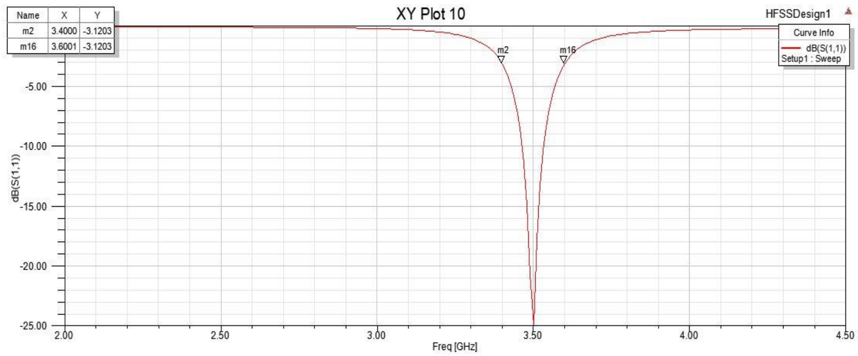

Figure 12: Bandwidth of the Rectangular MPA

Although the circular antenna offers a slightly wider operating bandwidth, both antennas comfortably satisfy the bandwidth requirement for 5G communication systems.

Gain and Directivity

The realized gain of the rectangular antenna was 7.8059 dB, compared with 7.1306 dB for the circular antenna.

Figure 13: Gain plot for rectangular MSA

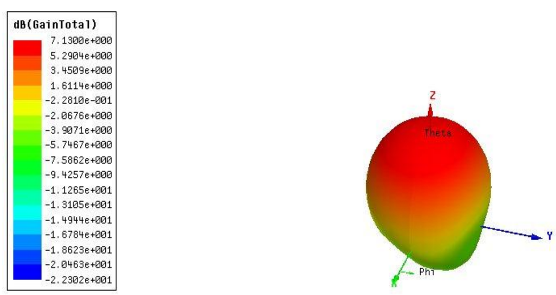

Figure 14: Gain plot for circular MPA

Higher gain indicates that the rectangular antenna radiates electromagnetic energy more efficiently toward the desired direction. Similarly, the rectangular antenna achieved a slightly higher directivity (2.5882 dB) than the circular antenna (2.4898 dB). These improvements make the rectangular geometry particularly attractive for base stations and fixed wireless access applications where directional coverage is desirable.

Antenna Size

The physical size of an antenna is an important consideration for portable 5G devices. The circular patch occupies a smaller footprint because its geometry provides a more compact radiating element than the rectangular patch designed for the same resonant frequency. Consequently, the circular antenna may be more appropriate for compact mobile terminals where available installation space is limited.

Radiation Efficiency and Total Efficiency

The use of RT/Duroid 5880, with its low dielectric constant and very low loss tangent, minimizes dielectric losses and surface-wave excitation. Consequently, both antennas exhibit high radiation efficiency. However, the superior impedance matching of the rectangular antenna suggests slightly higher total antenna efficiency because less input power is reflected back toward the feed.

Quality Factor

The quality factor (Q-factor) describes the ratio of stored energy to radiated energy. Because the circular antenna exhibits a slightly wider bandwidth, it is expected to have a lower quality factor than the rectangular antenna. Conversely, the rectangular antenna achieves higher gain and better impedance matching, indicating a favorable compromise between bandwidth and radiation performance.

Comparative Performance

Table 3. Comparative Performance of the Two Antenna Geometries

Parameter	Rectangular MPA	Circular MPA	Better Performance
Operating Frequency	3.5 GHz	3.5 GHz	Equal
Return Loss	−28.85 dB	−24.89 dB	Rectangular
VSWR	0.6297	0.999	Rectangular
Bandwidth	188 MHz	200 MHz	Circular
Realized Gain	7.8059 dB	7.1306 dB	Rectangular
Directivity	2.5882 dB	2.4898 dB	Rectangular
Radiation Pattern	Broadside	Broadside	Equal
Radiation Efficiency	Higher	High	Rectangular
Total Efficiency	Higher	High	Rectangular
Antenna Footprint	Larger	More Compact	Circular

Discussion

The comparative analysis demonstrates that both antenna geometries satisfy the basic performance requirements for sub-6 GHz 5G applications. Nevertheless, each geometry offers distinct advantages. The rectangular antenna provides superior return loss, impedance matching, realized gain, directivity, radiation efficiency, and total efficiency, making it suitable for applications requiring high-performance directional radiation. In contrast, the circular antenna offers a slightly wider bandwidth and a more compact footprint, making it attractive for space-constrained mobile devices. These results illustrate the engineering trade-offs involved in antenna selection and provide practical guidance for choosing the most appropriate geometry based on the intended 5G application.

CONCLUSION

This study presented a comparative analysis of rectangular and circular microstrip patch antennas designed on RT/Duroid 5880 substrate for 3.5 GHz sub-6 GHz 5G applications using the High Frequency Structure Simulator (HFSS). The antennas were evaluated based on return loss, voltage standing wave ratio (VSWR), bandwidth, realized gain, directivity, and radiation characteristics under identical design conditions. The simulation results showed that both antenna geometries satisfy the fundamental requirements for practical 5G wireless communication systems. However, the rectangular microstrip patch antenna demonstrated superior overall performance, achieving a lower return loss (−28.85 dB), lower VSWR (0.6297), higher realized gain (7.8059 dB), and greater directivity (2.5882 dB) than the circular microstrip patch antenna. Conversely, the circular antenna provided a slightly wider bandwidth (200 MHz compared with 188 MHz), indicating its suitability for applications where broader operating bandwidth is prioritized.

The findings further demonstrate that antenna geometry significantly influences impedance matching, bandwidth, gain, and radiation characteristics. Therefore, the selection of either rectangular or circular microstrip patch antennas should be guided by the specific requirements of the intended 5G application. Applications requiring higher gain and improved impedance matching may benefit from the rectangular geometry, whereas applications emphasizing compactness and wider bandwidth may favor the circular geometry. Future work will include the evaluation of additional performance metrics such as radiation efficiency, total antenna efficiency, quality factor, envelope correlation coefficient (ECC), and antenna size optimization to provide a more comprehensive assessment of antenna performance for next-generation 5G wireless communication systems.

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