

BANDWIDTH IMPROVEMENT OF A 2.4 GHZ MICROSTRIP PATCH ANTENNA ARRAY WITH U-SLOT GROUND PLANE FOR WIRELESS APPLICATIONS

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Abstract

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This work presents the design and evaluation of a 1 x 2 series-fed microstrip patch antenna array incorporating a U-slot ground plane structure, introduced specifically to enhance impedance bandwidth at the 2.4 GHz band for wireless communication application. The antenna is implemented on a FR4 substrate, featuring a thickness of 1.6 mm and a relative dielectric constant (ϵ_r) of 4.3, making it suitable for high-performance RF designs. The series-fed network ensures that both elements are excited sequentially with minimal complexity, offering a compact and lightweight structure. Simulation results of the single-element patch demonstrate promising performance, with a return loss of -22.6 dB, excellent impedance matching, a Voltage Standing Wave Ratio (VSWR) of 1.15, and a measured bandwidth of approximately 76.2 MHz around the 2.4 GHz band. The achieved directive gain of 6.52 dB marks a notable improvement compared to a conventional plain patch antenna at the same frequency. When configured as a two-element array, the antenna exhibits significant performance enhancement, achieving a return loss of -42.3 dB, VSWR of 1.01, directive gain of 7.4 dBi and an expanded bandwidth of 202 MHz, both centered around 2.4 GHz. These results confirm the effectiveness of combining a U-slot with series feeding to improve directivity, gain, and impedance bandwidth without substantially increasing the antenna footprint. A comparative analysis with existing 2.4 GHz patch antenna designs highlights the improved performance of the proposed structure in terms of bandwidth efficiency, demonstrating its potential for Wi-Fi, Bluetooth, and other ISM band applications.

1. Introduction

1.1 BACKGROUND AND MOTIVATION

Antennas are fundamental to wireless communication, serving as the key elements for both transmitting and receiving signals. The rapid growth of devices such as smartphones, tablets, laptops, GPS receivers, and radio navigation systems has further emphasized their importance, as these technologies rely on efficient radio links with minimal interference to ensure seamless connectivity (Zakariyya et al., 2025). With the rising number of connected users and devices, there is an increasing demand for compact antennas

that combine high performance with small form factors. Meeting this requirement is essential for modern portable and handheld platforms, where limited space must be balanced with efficiency and reliability.

Microstrip patch antennas (MPAs) have become a cornerstone in modern wireless communication systems because of their attractive attributes, including compact size, lightweight structure, ease of fabrication, and compatibility with both flat and curved surfaces (Zalki and Bakhar., 2022: Kaeib, et al., 2019). Structurally, an MPA consists of a conducting ground plane on one side of a dielectric substrate and a radiating metallic patch, usually rectangular or circular, on the opposite side. Their simple planar geometry and straightforward manufacturing process make them highly suitable for a wide range of wireless applications.

Despite their numerous benefits, microstrip patch antennas (MPAs) still face certain limitations, including restricted gain, narrow bandwidth, and limited power-handling capability (Kaeib, et al., 2019: Ullah et al., 2018: Zakariyya et al., 2016a). Considerable research has been devoted to mitigating these shortcomings, leading to various improvement strategies. One widely explored approach involves antenna feeding techniques and dimensional optimization, where parameters such as patch length, width, and inset depth are fine-tuned. By adopting different feeding methods such as; microstrip line feed, inset feed, or coaxial probe feed, both impedance matching and bandwidth performance can be significantly improved (Naik and Virani ., 2016: Islam et al., 2009).

Another technique for bandwidth enhancement is the use of thicker substrates with higher dielectric constants. Increasing the substrate thickness effectively lowers the resonant frequency of the antenna, making it a favorable option for designs operating at lower frequencies (Liu et al., 2012). However, this advantage often comes at the expense of increased antenna size and potential fabrication challenges, which must be carefully managed during the design process (Liu et al., 2012).

With the growing demand for compact yet high-performance antennas in modern wireless systems, particularly in the 2.4 GHz band that supports advanced broadband services, it becomes essential to explore antenna geometries that strike a balance among size, bandwidth, gain, and fabrication simplicity. In this context, a 1×2 series-fed microstrip patch antenna array has been designed and analyzed for 2.4 GHz wireless communication applications. To further enhance its performance, a U-slot integrated into the ground plane is employed, improving bandwidth and boosting gain. Unlike earlier U-slot or Defected Ground Structure (DGS) techniques which were applied to single-patch geometries or dual-band antennas, this design combines both series feeding and ground-plane slotting, leading to wider impedance bandwidth and stable VSWR at 2.4 GHz.

1.2 LITERATURE REVIEW

Microstrip patch antennas have attracted significant attention due to their lightweight structure, low profile, and ease of fabrication. In the 2.4 GHz band, widely used for Wi-Fi, Bluetooth, and other wireless applications, researchers have proposed various design improvements, including patch geometry modifications, substrate selection, feeding techniques, and array configurations, to enhance gain, bandwidth, and overall efficiency while maintaining compactness.

The work of Ismail et al. (2024) proposed a compact high-gain antenna using Defected Ground Structure (DGS) on a Rogers 5880 substrate developed for biomedical applications. By modifying the patch geometry and ground plane, the design achieved enhanced bandwidth and stable operation at 2.4 GHz. Tests with brain tissue models confirmed its effectiveness for tumor detection while meeting SAR safety standards

The work of Coşkun and Erginyurek (2024) proposed a wideband microstrip patch antenna that was implemented on an FR-4 substrate with $\epsilon_r = 4.3$ and a low-profile structure. The design achieved satisfactory bandwidth and directivity with moderate gain, making it suitable for general wireless communication applications.

The work of Aremu et al. (2025) developed a microstrip patch antenna array suitable for UAV and drone platforms. The design achieved a higher gain by incorporating a power divider, confirming its advantage over single-element patches for aerial communication links.

A meander-line antenna was developed on a Rogers RT-5880 substrate to achieve compact dimensions at 2.4 GHz. The geometry reduced the footprint while maintaining good impedance matching, making it highly attractive for IoT and portable device integration devices (Elabdi, Elayachi & Rahmoun, 2024).

Other works have focused on performance enhancement through structural modification. A rectangular microstrip patch antenna incorporating a ground-plane slot was introduced for WiFi at 2.4 GHz. The slotting technique enhanced impedance bandwidth and provided a stable radiation pattern, confirming its effectiveness for WLAN applications (Isra, Yuliana, & Indah, 2024).

A right-hand circularly polarized (RHCP) patch antenna was designed and fabricated to operate at 2.4 GHz. The single-feed geometry achieved polarization diversity and stable radiation, validating its use in WLAN and mobile communication systems. (Ahmad & Khalil, 2022).

In (Awan et al., 2024), a dual-band MIMO antenna was introduced for communication and wearable applications. By modifying a circular monopole with additional patches and stubs, and applying optimization techniques, the design achieved wide bandwidth, improved gain, and reduced mutual coupling. The antenna also met SAR standards, making it suitable for body-centric use while offering advantages in compactness and performance compared to earlier designs

The work of Hossain et al. (2025) proposed a 2.4 GHz microstrip patch antenna and a 1×2 array that was implemented on FR4 substrate. The array, optimized with a quarter-wave transformer, showed improved impedance matching, gain, and radiation characteristics compared to a single element, making it suitable for wireless communication systems. However, a notable limitation of this approach lies in its restricted bandwidth, which constrains the antenna's ability to support wider and more dynamic wireless services. Recent literature suggests that incorporating slot modifications, particularly U-slots, into antenna structures can significantly improve impedance bandwidth and overall performance.

While previous studies have examined U-slots, DGS techniques, and array- or series-fed architectures independently, none have combined a series-fed configuration with a U-slot ground-plane modification on an FR4 substrate at 2.4 GHz. This work focuses on improving the bandwidth by introducing a U-slot on the ground plane of a series-fed microstrip patch antenna array to enhance impedance bandwidth while maintaining structural compactness. This approach is expected to yield improved bandwidth and overall antenna performance, making the design more robust for modern ISM-band applications such as Wi-Fi and Bluetooth.

2. Materials and Method

All simulations utilized a time-domain transient solver. The substrate material was specified as FR-4 with a relative permittivity $\epsilon_r = 4.3$, a loss tangent of 0.025, and a thickness of 1.65 mm. Both the patch and feed were modeled as copper, assuming a conductivity of $\sigma = 5.8 \times 10^7$ S/m and a metal thickness of 30 μm . Spatial discretization was performed using a hexahedral mesh. Excitation was introduced via a waveguide port configured with a 50- Ω reference impedance. Far-field radiation parameters were extracted using a dedicated far-field monitor, and the quarter-wave transformer was represented using its characteristic impedance.

In this design, the process starts with selecting the substrate, as its dielectric constant and thickness play a crucial role in determining antenna performance. An FR-4 substrate is used, which has a thickness of 1.6 mm and a relative dielectric constant of 4.3. Copper serves as the conducting material for both the radiating patch and the ground plane because of its high electrical conductivity. The patch dimensions are then calculated using the transmission line model, following established design approaches (Zakariyya et al., 2016b; Balanis, 2005)

$$W = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

Here, W denotes the width of the designed patch, f_r is the resonant frequency, and ϵ_r refers to the dielectric constant of the chosen substrate. To consider the effect of fringing fields and the non-uniform distribution of the electric field around the patch edges, the effective dielectric constant is determined. It can be expressed as:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12h}{w}\right)^{-\frac{1}{2}} \quad (2)$$

Due to the fringing fields at the edges of the patch, the effective electrical length of the antenna becomes slightly greater than its physical length. The additional length on each side, denoted as ΔL , is evaluated using:

$$\Delta L = \frac{(\epsilon_{eff} + 0.3)(w/h + 0.264)}{(\epsilon_{eff} - 0.258)(w/h + 0.8)} \quad (3)$$

By incorporating this adjustment, the patch's true length L_p can be calculated as:

$$L_p = L_{eff} - 2\Delta L \quad (4)$$

Where $L_{eff} = \frac{c}{2f_r \sqrt{\epsilon_{eff,p}}}$ is effective length of the antenna is structure and directly determines the resonant behavior of the antenna.

$$\text{The edge impedance } Z_{in} = 90 \frac{\epsilon_r^2}{\epsilon_r - 1} \left(\frac{L}{W}\right)^2 \quad (5)$$

The quarter-wave transformer impedance is evaluated as:

$$Z_T = \sqrt{Z_0 Z_{in}} \quad (6)$$

From the design equations, the patch dimensions were obtained, yielding a calculated length L_p of 29.7 mm and a width W of 38.3 mm. The single-element antenna was modeled and simulated in CST Microwave Studio (CST-MWS), as shown in Fig. 1(a). To improve performance, the design was extended into a 1×2 array by duplicating the patch element and connecting the two through a series feed line, effectively forming a dual-element configuration. The simulated structure of this array is illustrated in Fig. 1(b). Furthermore, a U-shaped slot was incorporated into the ground plane, which enhances radiation efficiency and increases gain, thereby improving the overall antenna performance as shown in Fig. 1(c).

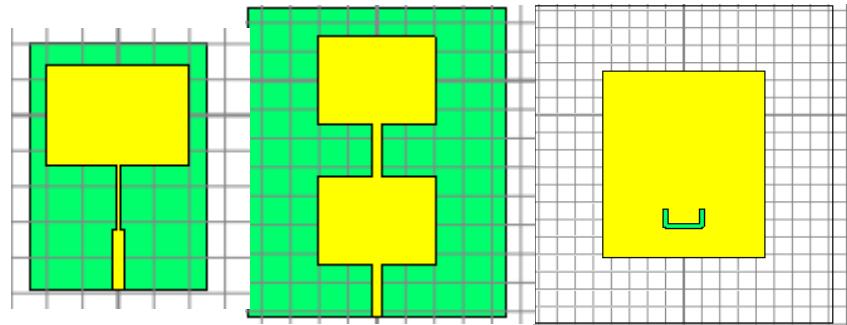


Fig. 1. Structural layouts of the proposed antenna configurations: (a) Single patch element, (b) Two-element array, (c) U slot ground plane

3. Results and Discussion

The simulation and performance analysis of the antenna, including metrics like return loss, VSWR, bandwidth, gain, and radiation pattern, were conducted using CST Microwave Studio.

3.1 SINGLE ELEMENT PATCH

As depicted in Fig. 2(a), the single-patch antenna resonates exactly at 2.4 GHz, attaining a return loss of -22.6 dB. This value of return loss signifies good impedance matching with little signal reflection at the resonant frequency. The resulting bandwidth is measured at 99.4 MHz, stretching from 2.346 GHz to 2.4409 GHz. Fig. 2(b) depicts in greater detail the Voltage Standing Wave Ratio (VSWR), which is observed at 1.15, confirming strong impedance matching and very low reflection losses. The radiation characteristics shown in Fig. 2(c) reveal a directive gain of 6.52 dB. Although this gain is satisfactory for many conventional wireless communication applications, it can be further enhanced by employing an antenna array configuration, which offers improved directivity and radiation efficiency.

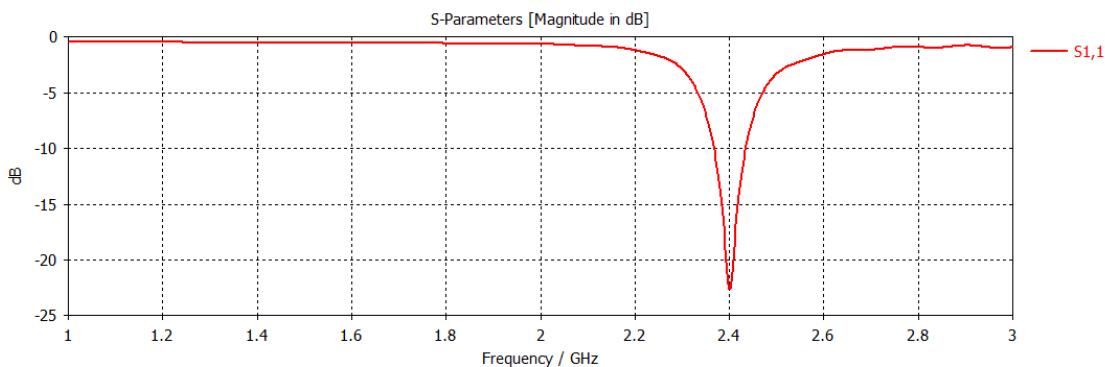


Fig. 2(a). Reflection coefficient (S_{11}) plot for the single patch antenna

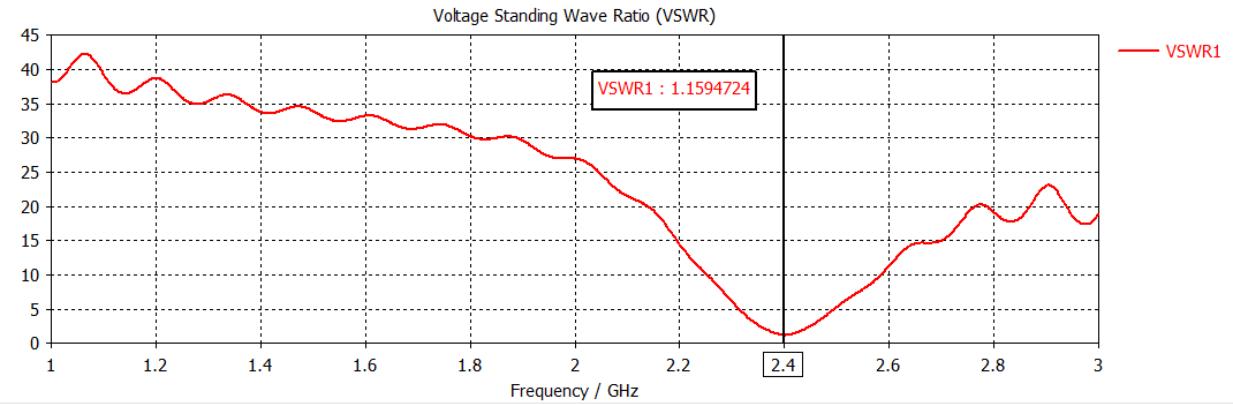


Fig. 2(b). Simulated VSWR plot for the single patch antenna element

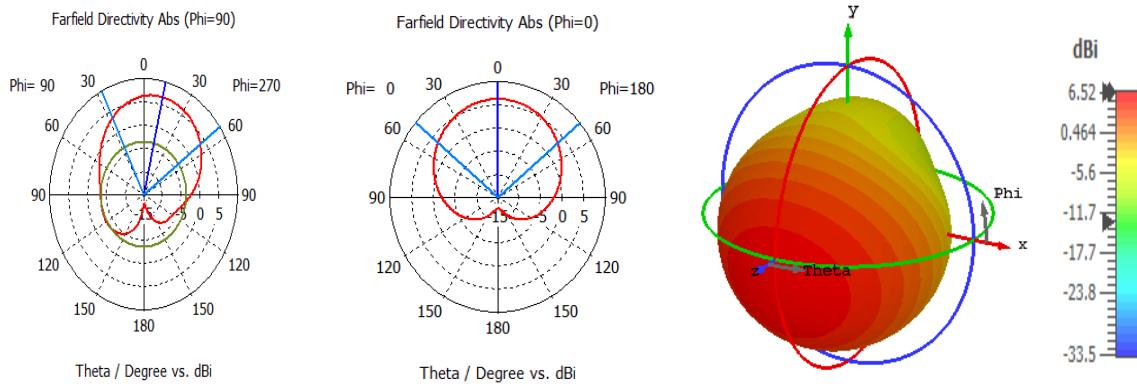


Fig. 2(c). Radiation pattern characteristic of single-element patch antenna

3.2 TWO ELEMENT PATCH

By adopting a two-element linear series-fed arrangement, the antenna demonstrates significant performance improvements. As presented in Fig. 3(a), it achieves a return loss of -42.3 dB along with an expanded bandwidth of 202 MHz, spanning from 2.3646 GHz to 2.5667 GHz. Such wideband operation is highly advantageous for 2.4 GHz ISM band applications, enabling reliable support for high data throughput and multi-service operations. Fig. 3(b) further indicates a stable VSWR of 1.01 across the operating band, confirming efficient and consistent impedance matching. Moreover, the directivity increases to 7.4 dBi, as illustrated in Fig. 3(c), underscoring the array's strong gain performance. The combination of enhanced gain, broader bandwidth, and low VSWR establishes the proposed antenna as a highly effective design for modern wireless communication systems, ensuring improved coverage, higher data capacity, and robust connectivity.

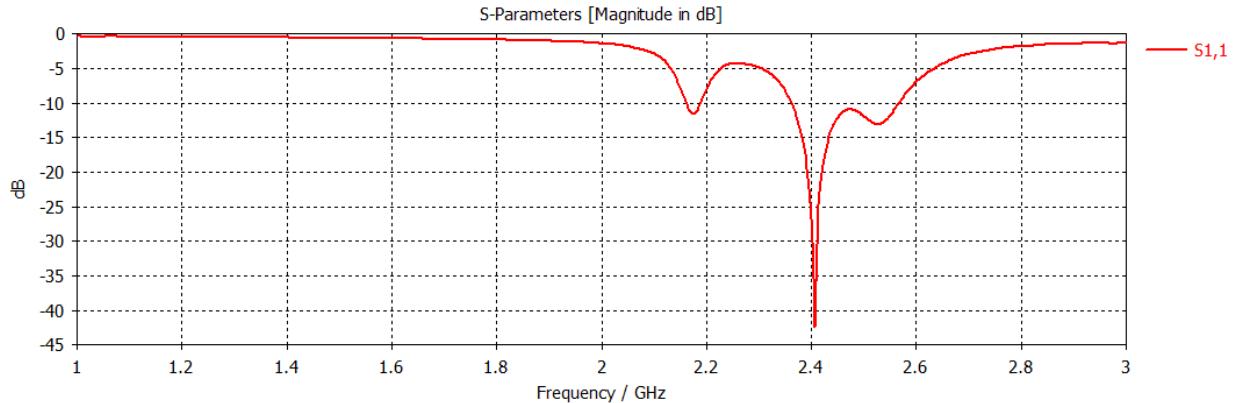


Fig. 3(a): Reflection coefficient (S_{11}) plot for the two element patch antenna

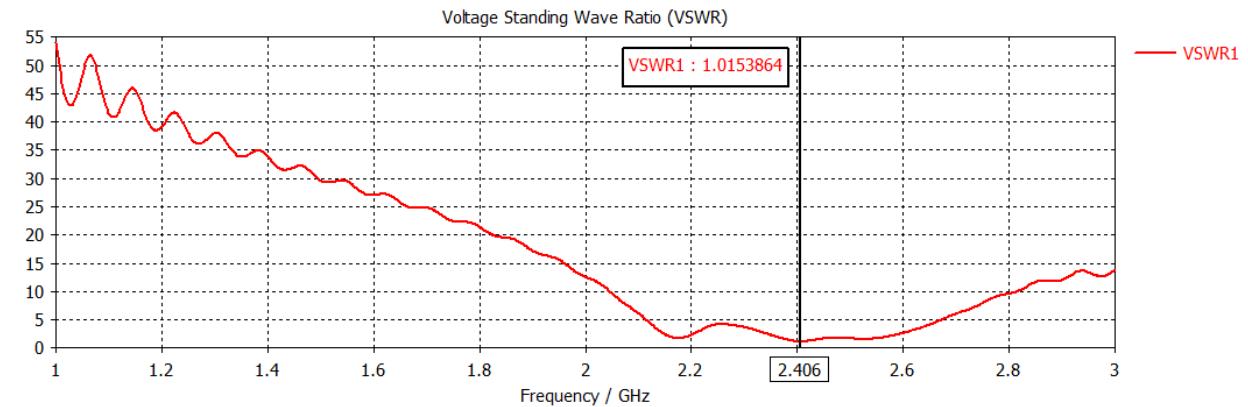


Fig. 3(b): Simulated VSWR performance for the two-element patch antenna

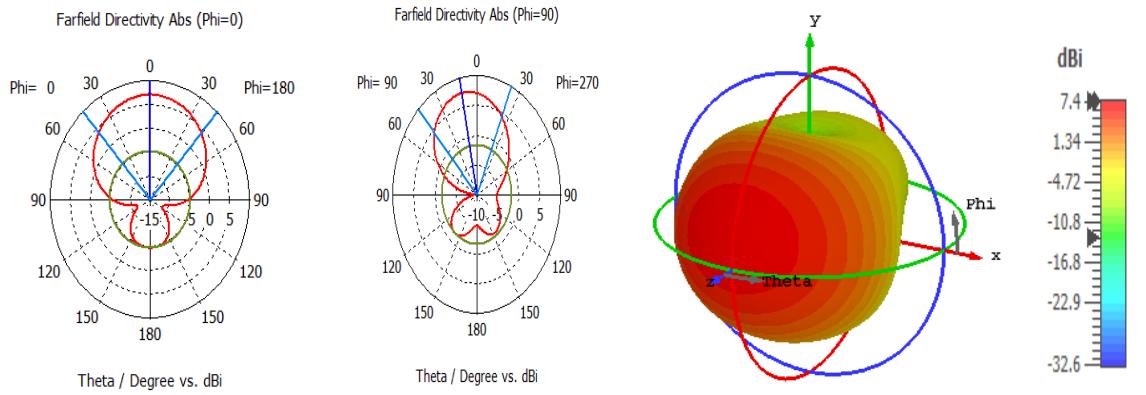


Fig. 3(c): Radiation pattern characteristic for the two-element patch antenna

Furthermore, Table 1 provides a summary of the simulated outcomes for the single patch and two elements array at 2.4 GHz. Gain and bandwidth all rise with the number of elements, as the table indicates, suggesting that the two-element patch antenna has good characteristics. The bandwidth enhancement achieved with the U-slot ground plane is due to the modification of surface current paths, which introduces additional resonances around 2.4 GHz. The slot forces current to redistribute along its edges, effectively

increasing the electrical length and broadening the range over which good impedance matching is maintained. It also suppresses certain surface-wave modes and reduces coupling between the two series-fed patches, resulting in a wider and more stable -10 dB bandwidth compared to the single-element design.

Table 1. Simulation results

	Single element	Two elements
Return loss (dB)	-22.6	-42.3
VSWR	1.15	1.01
Bandwidth (MHz)	99.4	202
Gain (dBi)	6.52	7.4

The simulation outcomes from this study reveal a clear performance advantage over the benchmarked two element patch antenna reported in the literature. In particular, the proposed antenna achieves a return loss of -42.3 dB, a VSWR of 1.01, a directivity gain of 7.4 dBi, and a bandwidth of 202 MHz at 2.4 GHz. These values surpass the results reported in the benchmarked work of (Hosain et al., 2025), as summarized in Table 2. While Hosain et al. demonstrated a slightly higher gain of 7.7 dBi, the proposed design provides a superior balance of return loss, VSWR, and Bandwidth, making it highly efficient and well-suited for modern wireless applications. The comparative analysis in Table 2 underscores the advantages of the present work, confirming its effectiveness for 2.4 GHz communication systems.

Table 2. Comparison between the Proposed design and benchmarked MPA in Hosain et al., 2025

Performance Metrics	Benchmarked	Proposed
Return Loss (dB)	-27	-42.3
VSWR	1.08	1.01
Bandwidth (MHz)	110	202
Gain (dBi)	7.71	7.4

4. Conclusion

This work has presented the design and simulation of a 1×2 series-fed microstrip patch antenna array with a U-slot configuration optimized for 2.4 GHz wireless communication applications. The results

demonstrate excellent impedance matching, low reflection loss, and significant improvements in gain and bandwidth compared to a conventional single-element patch antenna. Specifically, the two-element array achieved a return loss of -42.3 dB, a VSWR of 1.01, a directive gain of 7.4 dBi, and an expanded bandwidth of 202 MHz, clearly validating the effectiveness of combining U-slot modification with series feeding. When benchmarked against existing 2.4 GHz antenna designs, the proposed structure shows superior bandwidth efficiency and improved return loss, underscoring its suitability for ISM band applications such as Wi-Fi and Bluetooth. Overall, the findings confirm that compact and efficient antenna arrays can be realized through innovative slot loading and feed network design, making this approach a promising solution for next-generation wireless communication systems.

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