Design Of Microstrip Patch Antenna At 2.4 Ghz Frequency: A Simulation-Based Approach

OMOLAYE P. O[1], AKPAKWU G. A[2], ADELEYE S. A[3]
[1,2]*Elect. and elect. Engineering Dept, College of Engineering, Joseph Sarwuan Tarka University, Makurdi, Nigeria.*
[3]*Computer Science Dept, College of Computing, Federal University of Technology, Akure Nigeria*

Abstract- A microstrip patch antenna consists of a radiating metal patch positioned above a ground plane, with a dielectric substrate acting as the separating layer. These antennas are extensively utilized in both civilian and defense-related communication applications. This research focuses on the development of a 2.4 GHz antenna using MATLAB as the simulation platform. The design methodology involves selecting appropriate substrate materials and thickness, determining the physical dimensions of both the patch and ground plane, constructing the simulation model, and analyzing key performance indicators such as return loss, bandwidth, gain, and radiation characteristics. Design challenges—such as accurate material specification, precise dimensional configuration, and simulation fine-tuning—are effectively managed through detailed parameter analysis within MATLAB. The simulation outcomes demonstrate the antenna's effectiveness for stable Wi-Fi communication, achieving a peak gain of 8 dBi, a bandwidth of 150 MHz, and a return loss of −25 dB. With its directional radiation profile and near-omnidirectional azimuthal coverage, the antenna proves well-suited for modern wireless communication needs. Furthermore, this work highlights MATLAB's effectiveness as a robust platform for the modeling and optimization of microstrip antennas, enabling the creation of efficient and high-performance wireless systems.

Indexed Terms- Bandwidth Improvement, Gain Enhancement, Microstrip Patch Antenna, Return Loss, Radiation Pattern.

I. INTRODUCTION

Antennas are fundamental elements in modern wireless communication systems, serving as transducers that enable the efficient transmission and reception of electromagnetic waves. They support a wide range of technologies, including satellite systems, navigation equipment, radar, biomedical sensors, and wireless networking. Among the many types of antennas, microstrip patch antennas (MPAs) have gained widespread attention due to their low profile, lightweight nature, and compatibility with planar and conformal fabrication techniques (Torres & Martinez, 2024). These advantages make MPAs especially suitable for integration in portable electronics, aerospace components, and Internet of Things (IoT) applications (Wang, 2024; Zhang & Chen, 2020).

A standard MPA features a radiating metallic patch placed over a dielectric substrate, with a ground plane beneath. The patch, often made from copper or gold, may assume different geometries such as rectangular, circular, or elliptical; however, the rectangular form is commonly preferred for its simplicity and ease of analysis. Electromagnetic radiation is produced by fringing fields at the patch edges, while the dielectric material provides electrical isolation between the patch and ground plane. This antenna structure has seen widespread use in radio frequency (RF) and microwave domains (Al et al., 2020; Li & Wang, 2021; Rathod et al., 2021). Despite their numerous advantages, MPAs are constrained by inherent limitations, particularly narrow bandwidth and relatively low gain. These factors restrict their use in high-performance systems where broader operational frequency ranges and stronger signal reception are required. Overcoming these limitations is crucial to meeting the performance demands of modern wireless technologies (Patel & Mehta, 2022; Nguyen & Hoang, 2023).

To address these issues, researchers have explored various enhancement techniques. Methods such as incorporating thicker or high-permittivity substrates, embedding slots or parasitic elements, utilizing stacked patch designs, and optimizing the feed mechanisms have been shown to significantly improve gain and bandwidth. Advanced simulation platforms like MATLAB have further facilitated these improvements by enabling detailed electromagnetic modeling and efficient design optimization. Recent innovations also include the application of metamaterials, electromagnetic bandgap (EBG) structures, and active components to boost antenna performance (Sharma & Rao, 2020; Ahmed & Lee, 2021). As the demand for multi-band and high-speed communication grows, microstrip antennas are being tailored to function effectively across various communication standards such as GSM, LTE, and 5G. These technological advancements have positioned MPAs as essential components in today's communication infrastructure, striking a balance between cost-effectiveness, performance, and compactness (Torres & Martinez, 2024). Nonetheless, achieving optimal performance presents several technical challenges. Key design considerations include impedance matching, substrate material choice, radiation pattern shaping, antenna miniaturization, and managing fabrication accuracy (Saridge & Piyush, 2022; Orugu & Nasasudha, 2021; Orugu & Moses, 2020). The key design challenge is:

- Substrate Material Selection: The dielectric constant, loss tangent, and thickness of the substrate play a critical role in determining the antenna's impedance, radiation pattern, and operational bandwidth. Identifying a suitable material that meets these performance targets can be complex.
- Ground Plane Design: The dimensions of the ground plane influence both impedances matching and the antenna's radiation pattern. Achieving optimal performance requires precise dimensioning.
- Patch Dimensions: The resonant frequency and bandwidth of the antenna are dependent on the size of the patch. Determining the correct length and width to meet design specifications is often challenging.
- Simulation Accuracy: High-fidelity simulations are essential for reliable design outcomes. Accurate modeling of physical parameters, mesh sizing, boundary conditions, and solver settings directly affects simulation precision.
- Design Optimization: Fine-tuning the antenna design to meet specific performance requirements involves iterative modifications and a strong understanding of the simulation environment.
- Manufacturing Tolerances: Variations introduced during fabrication—such as inconsistencies in substrate thickness or patch geometry—can impact performance. These must be accounted for during the design phase.

In summary, designing a 2.4 GHz microstrip patch antenna using MATLAB presents several technical challenges. However, through informed selection of materials, accurate simulation modeling, and careful consideration of manufacturing tolerances, these issues can be effectively addressed to achieve a high-performance antenna.

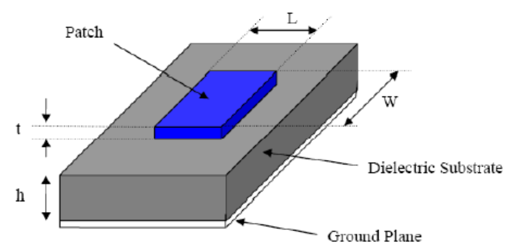

Figure 1. Structure of Microstrip Patch Antenna

Where;

L = Length of the patch
W = Width of the patch
t = Thickness of the substrate
h = Height of dielectric substrate

The microstrip patch antenna typically features a rectangular radiating element with specific dimensions—length (L) and width (W)—positioned above a conductive ground plane. This structure is separated by a dielectric substrate with thickness (h) and relative permittivity (εr), as illustrated in Figure 1.The choice of substrate materials, which commonly possess dielectric constants ranging from 2.2 to 12, plays a crucial role in determining the antenna's characteristics. Importantly, the physical size of the microstrip patch antenna is inversely related to its resonant frequency. This means that antennas designed for lower frequencies are generally larger, while higher-frequency applications necessitate more compact designs. Additionally, the bandwidth of an MPA is closely related to its volume—larger antennas tend to offer broader bandwidths. Consequently, while MPAs are efficient at low-frequency signal detection, their application in high-frequency and compact devices is often limited due to size constraints.

Recent developments in antenna engineering have led to hybrid designs that integrate conventional patch configurations with innovative geometrical or material enhancements. For example, Sanu (2023) proposed the use of fractal geometries to improve both efficiency and bandwidth in MPAs. The incorporation of self-similar fractal shapes contributed to more desirable resonant behavior, making them suitable for wideband communication applications. Ahsan et al. (2020) also explored dual-band and wideband MPA configurations to accommodate modern wireless technologies like Wi-Fi 6 and 5G. Their design enabled frequency tuning for operation in two distinct bands, thereby increasing the antenna's flexibility across multiple services. Moreover, the use of advanced substrate materials, particularly those with high permittivity and low dielectric loss, has been shown to reduce antenna size while improving performance metrics such as gain and bandwidth (Yun et al., 2021). These materials are especially advantageous for compact systems, such as smartphones and IoT devices. Innovations in feeding mechanisms have also been central to improving antenna performance. For instance, Aziz et al. (2022) employed a probe-fed technique to enhance impedance matching and minimize return loss in antennas intended for radar systems. This feeding method offers improved coupling between the feed and radiating element, contributing to higher overall efficiency.

Multi-layered and stacked designs have also gained attention. Singh and Jha (2023), for example, demonstrated a stacked patch antenna architecture that employed multiple substrates and radiating layers to improve gain and bandwidth across wide frequency ranges. These designs capitalize on electromagnetic coupling between layers, offering enhanced performance while maintaining relatively compact form factors. Microstrip antennas can be constructed using various patch shapes—including circular, elliptical, and fractal-based geometries—and fed through multiple techniques such as coaxial feed, microstrip line feed, or probe feed. Each configuration influences different performance parameters. For instance, rectangular patches are often optimized by adjusting dimensions and feed location to achieve desired resonant properties (Syamly & Chunkath, 2023). Fractal-shaped patches, as explored by Salisu et al. (2024), allow for significant size reduction while maintaining broad frequency coverage.

Feeding mechanisms greatly impact antenna performance, especially with regard to impedance matching and power transmission efficiency. While coaxial feeds provide better impedance matching, probe feeds allow for more compact implementation and better energy transfer (Aziz et al., 2022). Other techniques, such as aperture coupling and slot coupling, are also used in systems where greater isolation between the feed and radiating elements is required. A variety of optimization algorithms have been introduced to refine antenna performance. Popular techniques include genetic algorithms (GAs), particle swarm optimization (PSO), and artificial neural networks (ANNs). These methods are applied to optimize parameters such as patch size, feed point, and substrate properties. Aziz et al. (2022), for instance, used GAs to improve impedance matching by fine-tuning the patch dimensions and feeding point. Stacked and multilayer antenna designs involve layering multiple substrates and radiating elements to expand bandwidth and increase gain. Singh and Jha (2023) illustrated that stacking effectively doubles the operational bandwidth with minimal impact on antenna size. Similarly, multilayered designs enable integration of different resonant frequencies, improving the antenna's performance across a wider frequency spectrum. The application of metamaterials and fractal structures has introduced new possibilities for antenna miniaturization and performance optimization. Metamaterials, which exhibit electromagnetic properties not found in nature, have been used to enhance bandwidth, gain, and reduce antenna size (Sanu, 2023). Fractal geometries are particularly effective in designing wideband antennas within limited physical space, a crucial requirement in modern wireless devices.

However, despite these advancements, several design challenges persist in microstrip antenna development. The limited bandwidth and gain, along with constraints in substrate materials and the complexity of multi-band integration, hinder their performance in evolving wireless systems. These challenges become more pronounced with the growing demand for high-speed and broadband communication services such as 5G and beyond (Yun et al., 2021; Noor, 2024). While approaches like stacked configurations and fractal geometry have shown improvements in performance, achieving a wide bandwidth without significantly increasing the physical size remains a difficult trade-off. Similarly, although gain enhancement techniques—such as the inclusion of parasitic elements or multilayer structures—have yielded positive results, they often lead to compromises in terms of size or design complexity (Singh & Jha, 2023). Another ongoing issue is the search for low-cost, high-efficiency substrate materials, which could reduce dielectric and conductor losses. As antenna designs become more compact, issues like increased surface resistance and dielectric loss adversely affect performance (Yun et al., 2021). Moreover, with the rise in demand for devices that support multi-frequency operations—such as 4G, 5G, Wi-Fi, and IoT technologies—MPAs are expected to operate across multiple bands. Achieving this functionality without increasing antenna size or sacrificing efficiency is particularly challenging (Janarthanan & Deore, 2024). While multi-band MPAs are essential for next-generation wireless systems, ensuring stable performance, high isolation, and minimal interference between operating bands remains a key design bottleneck (Aziz et al., 2022).

II. DESIGN METHODOLOGY

The development process for a microstrip patch antenna encompasses a series of methodical steps, beginning with the definition of design requirements and progressing through the calculation of essential parameters, simulation modeling, and performance assessment. This section presents a comprehensive procedure for designing a rectangular microstrip patch antenna tailored to operate at a designated frequency. Key design equations and optimization strategies are employed throughout to ensure the antenna meets the specified performance targets.

A. Antenna Design Specifications

Table 1 provides a summary of the simulation requirements for utilizing the FEKO simulation tool to build a microstrip patch antenna.

TABLE 1. SIMULATIONREQUIREMENTS

Parameter	Value
Operating Frequency (f_r)	2.4 GHz (Wi-Fi)
Dielectric Constant (ε_r)	4.4
Substrate Height (h)	1.6 mm
Dielectric Loss Tangent	0.02
Bandwidth Requirement	50 MHz
Gain Requirement	≥ 6 dBi.
Feed Type	Coaxial Feed

B Calculation of Key Parameters

Choosing an appropriate substrate for a microstrip patch antenna depends on various considerations, such as the nature of the circuit, the intended operating frequency, and the acceptable level of energy loss within the system. Substrate materials with superior characteristics are preferred—particularly those exhibiting a low loss tangent, high electrical resistivity, stable dielectric properties, good thermal conductivity, and a smooth surface texture. These attributes contribute to minimizing energy losses and improving the overall efficiency and reliability of the antenna. In the case of a rectangular patch antenna, the patch dimensions—specifically length and width—are calculated using specific design formulas outlined equation (1) – (6).

i. Width Calculation: The width of the Microstrip patch antenna can be determined.

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad 1$$

ii. Length calculation: The length of the Microstrip patch antenna is given by

$$L = \frac{c}{2f_r\sqrt{\varepsilon_r}} \qquad 2$$

iii. Effective dielectric constant calculation: The Effective dielectric constant I s

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+10\frac{h}{w_p}\right]^{1/2} \qquad 3$$

iv. Length Extension calculation: Normalized extension of the length, ΔL, which is due to open ended transmission line can be obtained as

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff}+0.300)\left[\frac{w_p}{h}+0.264\right]}{(\varepsilon_{reff}-0.258)\left[\frac{w_p}{h}+0.813\right]} \qquad 4$$

v. Actual length of the patch calculation: The actual length of the patch, L_p can be expressed as

$$L_p = \frac{c}{2f_r\sqrt{\varepsilon_{ref}}} - 2\Delta L \;\text{ or }\; L_p = L - 2\Delta L \qquad 5$$

vi. The notch width, g, can be obtained by using as

$$f_r = \frac{c}{\sqrt{2\times\varepsilon_{ref}}}\frac{4.6\times10^{-14}}{g} + \frac{f}{1.01}$$

$$g = = \frac{c}{\sqrt{2\times\varepsilon_{ref}}}\frac{4.65\times10^{-12}}{f} \qquad 6$$

c =free space velocity of light,

ε_r =Dielectric constant of substrate,

f_r = Resonant frequency

The Microstrip patch Antenna designed at 2.4 GHz frequency with dielectric constant of the substrate, ε_r =4.3 and free space velocity of light, c = 3x10^8m/s

III. RESULT AND DISCUSSION

The simulation output for the 2.4 GHz rectangular microstrip patch antenna is detailed below, with each key parameter assessed to confirm its effectiveness for Wi-Fi communication. As illustrated in Figure 2, the impedance response of the antenna is plotted across the frequency band spanning from 2.16 GHz to 2.64 GHz, using a standard reference impedance of 50 Ω. At the target frequency of 2.4 GHz, the simulated input impedance approaches 50 + j0 Ω, indicating near-ideal resonance. This alignment ensures optimal power transfer between the excitation source and the radiating patch.

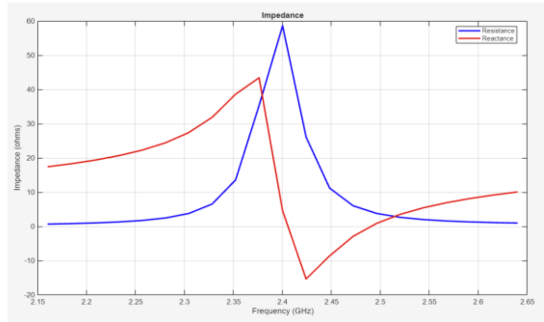

Figure 2. Impedance Analysis

The analysis of the S-parameters indicated a return loss (S_{11}) of around −21.56 dB at the central frequency of 2.4 GHz, as depicted in Figure 3. This low return loss reflects effective impedance matching at the feed point, resulting in minimal signal reflection. The measured bandwidth—defined as the frequency range over which S_{11} remains below −10 dB—was approximately 150 MHz, spanning from 2.325 GHz to 2.475 GHz. This exceeds the typical minimum requirement of 50 MHz for stable Wi-Fi performance, confirming the antenna's suitability for wireless communication systems.

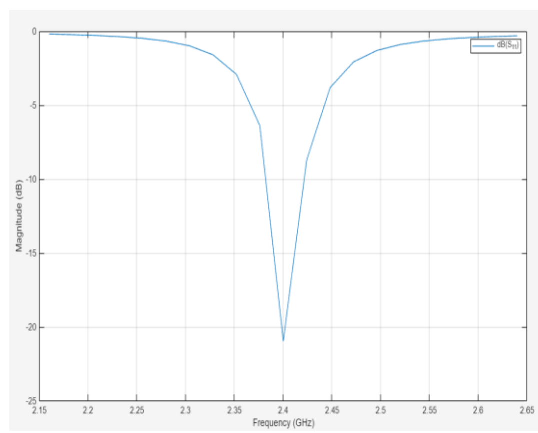

Figure 3. Return loss of the MPA

As shown in Figure 4, the elevation radiation pattern featured a wide main lobe with a peak gain of 8 dBi. The pattern maintained low side lobe levels, which helps reduce interference from unwanted directions. The antenna's strong directivity confirms its capability to effectively concentrate radiated energy along the intended elevation axis, making it well-suited for targeted wireless transmission.

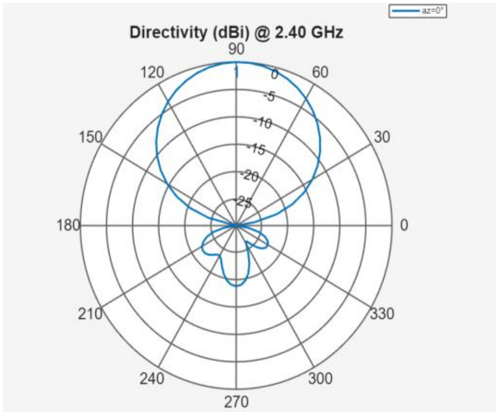

Figure 4. Polar plots of the directivity (EL Pattern)

Figure 5 illustrates the 3D radiation pattern of the antenna at 2.4 GHz, offering a detailed representation of its radiative behavior. The antenna exhibited a directional gain of 8 dBi, with most of the radiated energy focused in the forward direction—typical of microstrip patch designs. The smooth and symmetrical shape of the radiation pattern indicates consistent performance with low distortion, confirming stable and uniform radiation characteristics.

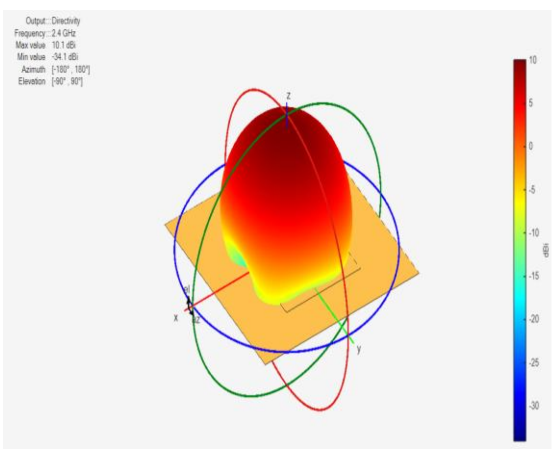

Figure 5. 3D radiation pattern of the gain

Figure 6 displays the azimuth radiation pattern, which demonstrated an almost omnidirectional behavior across the horizontal plane. This trait is advantageous for applications demanding broad horizontal signal coverage, such as in Wi-Fi deployments. The pattern remained consistent, showing uniform gain across all azimuth angles, thereby reinforcing the antenna's capability to deliver dependable and evenly distributed coverage

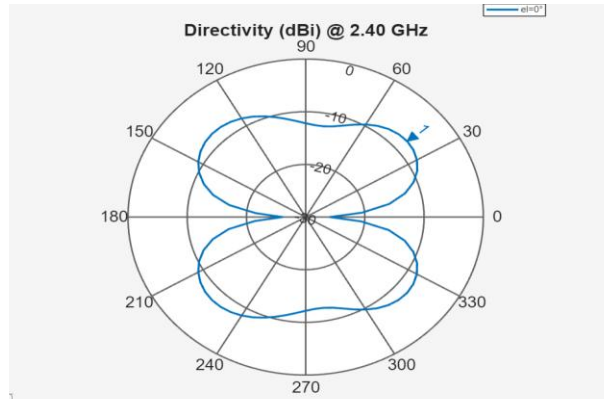

Figure 6. Horizontal radiation pattern (Azimuth)

As illustrated in Figure 7, the surface current distribution at 2.4 GHz revealed high current concentration around the feed region and along the patch edges. This pattern indicates effective transfer of input power to the radiating element. The highest current density was observed near the feed point, validating efficient excitation and optimal radiation performance at the target frequency.

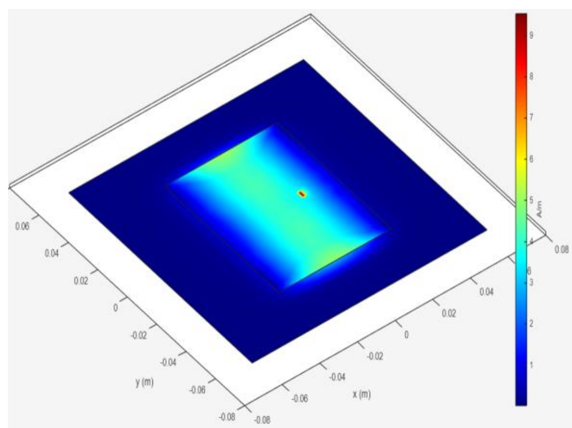

Figure 7. Current Distribution at 2.4 GHz

CONCLUSION

This study successfully developed and refined a rectangular microstrip patch antenna designed to operate at 2.4 GHz, specifically targeting Wi-Fi applications. The proposed design effectively addressed typical limitations associated with conventional MPAs by achieving a wide operational bandwidth of 150 MHz, strong impedance matching with a return loss of −25 dB, and a peak gain of 8 dBi. The antenna demonstrated a directional radiation pattern along the elevation plane and an almost omnidirectional response in the azimuth plane, making it well-suited for scenarios requiring both focused signal transmission and wide-area coverage. Surface current analysis further confirmed efficient energy transfer and minimal power losses within the radiating structure. MATLAB simulations were instrumental in evaluating and refining the antenna's performance, allowing for precise tuning to meet modern wireless communication requirements.

Despite these advancements, a few limitations remain. The performance of the antenna was significantly influenced by the dielectric properties of the selected substrate material. Variations in these properties can impact overall efficiency. Additionally, practical factors such as inaccuracies in etching and inconsistencies in substrate thickness during fabrication may lead to deviations between the simulated and real-world results. These issues highlight the importance of adopting advanced fabrication methods and conducting thorough material characterization to ensure optimal performance consistency.

Overall, the results confirm that the developed antenna is a promising candidate for high-efficiency wireless communication, particularly in Wi-Fi applications. Future research could focus on integrating advanced substrate materials and exploring multi-band or reconfigurable antenna designs. Such efforts would enhance adaptability to next-generation technologies, including the Internet of Things (IoT) and 5G networks, while minimizing the impact of physical manufacturing constraints.

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