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Enhancing Impedance Matching and Resonance Accuracy through Patch Size Tuning at 2.4 GHz

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Abstract

This study investigated the enhancement of impedance matching and resonance accuracy of a rectangular microstrip patch antenna operating at 2.4 GHz through systematic patch size tuning. The research was anchored on the transmission line model for initial antenna dimensioning, followed by parametric optimization using CST Microwave Studio Suite to refine patch width and length for improved performance. A simulation-based quantitative design approach was employed, using FR-4 substrate with a dielectric constant of 4.3 and thickness of 1.6 mm. The antenna geometry was analyzed under controlled variations of patch dimensions while maintaining constant feed and substrate parameters to isolate performance effects. Results show that the optimized antenna achieved a return loss of –18.06 dB, VSWR of 1.28, bandwidth of 85 MHz, and realized gain of 2.688 dBi at 2.4 GHz. These outcomes indicate strong impedance matching, stable resonance behavior, and acceptable radiation efficiency for wireless communication applications. The study confirms that patch width and length variations significantly influence resonance accuracy and overall antenna performance, particularly in correcting frequency shifts commonly observed in non-optimized transmission line designs. The findings highlight that precise dimensional tuning of the patch is essential for achieving reliable antenna performance in FR-4-based designs intended for Wi-Fi and IoT applications. The study concludes that parametric optimization is an effective and low-cost approach for improving microstrip antenna performance without requiring complex structural modifications. In relation to sustainability, the study supports SDG 9 (Industry, Innovation and Infrastructure) by contributing to the development of optimized and cost-efficient wireless communication components. It also aligns with SDG 11 (Sustainable Cities and Communities) through its relevance to IoT-enabled smart systems and connected environments. The sustainability impact is primarily technological and socio-economic, promoting efficient design practices that enhance wireless connectivity while reducing material and development costs.

Keywords: 2.4 GHz Antenna, FR-4 Substrate, Impedance Matching, Microstrip Patch Antenna, Parametric Optimization, Resonance Accuracy, Return Loss, CST Microwave Studio, VSWR

1. Introduction

The rapid development of wireless communication technologies has increased the demand for efficient antennas operating within the 2.4 GHz frequency band. The 2.4 GHz Industrial, Scientific, and Medical (ISM) band is widely used because of its reliable propagation characteristics and its support for systems such as Wi-Fi and Internet of Things (IoT) devices (Bhanarkar et al., 2014). Various wireless technologies, including Wi-Fi and IoT devices, operate within this frequency range (Qaddoori & Thaher, 2021). As these systems continue to expand, antenna designs must be compact, economical, and capable of maintaining stable performance under different operating conditions (Qaddoori & Thaher, 2021; Hakeem & Nahas, 2021). Microstrip patch antennas are commonly used in modern wireless communication because of their low profile, lightweight structure, ease of fabrication, and compatibility with printed circuit board technology (Hakeem & Nahas, 2021). These antennas provide acceptable gain and radiation performance while allowing integration into compact devices. For 2.4 GHz applications, microstrip patch antennas are practical options, particularly where cost efficiency and space limitations are important.

The performance of a microstrip patch antenna is affected by several design factors, including substrate material, feeding method, ground plane size, and patch shape. Among these factors, patch width and patch length are essential because they influence resonant frequency, impedance matching, bandwidth, gain, and radiation pattern (Wincza & Gruszczynski, 2011). Even small changes in these parameters can produce significant changes in antenna behavior, making dimensional optimization a critical step in antenna design.Previous antenna studies have commonly focused on feed length optimization (Noordin et al., 2025), slot configurations (Zainuddin et al., 2013), and substrate properties (Hany et al., 2024). These approaches have contributed to improved antenna performance by examining the effects of feeder length, ground plane modification, and dielectric variation. However, the direct effect of patch size variation has received less attention, even though patch dimensions are among the primary factors controlling resonance and radiation characteristics (Ai et al., 2020).

Globally, the increasing use of Wi-Fi and IoT technologies has strengthened the need for antennas that can operate reliably within the 2.4 GHz ISM band (Bhanarkar et al., 2014; Qaddoori & Thaher, 2021). These systems support wireless connectivity in homes, institutions, industries, and smart environments. At the national and local level, compact and affordable antenna designs are relevant for wireless sensor networks, IoT-based devices, and communication systems that require stable operation, low cost, and practical integration into printed circuit boards. Since the study uses FR-4 substrate, which is affordable and widely available, the research supports practical antenna development for cost-sensitive wireless applications.

The study is grounded in the transmission line model for rectangular microstrip patch antenna design. This model provides initial calculations for the antenna dimensions required to achieve resonance at the target frequency. The design considers patch width, patch length, effective dielectric constant, effective length, and fringing effects. These theoretical calculations serve as the basis for simulation and optimization using CST Microwave Studio Suite. The conceptual focus of the study is that patch width and patch length directly affect resonant frequency, impedance matching, bandwidth, gain, and radiation pattern (Wincza & Gruszczynski, 2011). By varying these two parameters while keeping other design variables constant, the study isolates the effect of patch size variation on antenna performance. This approach allows a clearer evaluation of how dimensional tuning can correct frequency shifts and improve impedance characteristics.

Although patch geometry is essential in microstrip antenna design, limited systematic research has examined how changes in patch width and patch length affect antenna performance. Many existing designs use computed patch dimensions based on transmission line equations without further optimization, which may result in frequency shifts or poor impedance matching. This problem is especially relevant when using FR-4 substrates because their dielectric losses can affect antenna performance (Ai et al., 2020). The rationale of the study is to determine whether patch size tuning can improve resonance accuracy and impedance matching at 2.4 GHz. By varying the patch width and length while maintaining other design parameters constant, the study provides practical insight into how patch dimensions influence return loss, S11, Voltage Standing Wave Ratio, bandwidth, realized gain, and radiation pattern. The findings may guide antenna designers working with FR-4 substrates for Wi-Fi, IoT, and other low-power wireless systems.

The study aligns most directly with SDG 9 – Industry, Innovation and Infrastructure because it contributes to the development of compact, low-cost, and optimized antenna designs for wireless communication systems. By improving antenna performance through patch size tuning, the research supports innovation in communication infrastructure and IoT-based technologies. The study also relates to SDG 11 – Sustainable Cities and Communities because Wi-Fi and IoT systems are important components of connected homes, smart environments, and community-based digital systems. Reliable antenna performance supports stable wireless communication, which is necessary for devices used in monitoring, automation, and smart connectivity. The research may also support SDG 12 – Responsible Consumption and Production to the extent that it uses FR-4 substrate, a widely available and economical printed circuit board material. By optimizing antenna performance through dimensional tuning rather than relying on more costly materials or complex structures, the study supports practical and resource-conscious design approaches.

The study contributes to technological sustainability by improving the performance of microstrip patch antennas used in wireless communication systems. Accurate resonance at 2.4 GHz, good impedance matching, and stable radiation behavior are important for maintaining reliable connectivity in Wi-Fi and IoT applications. The research also supports socio-economic sustainability by focusing on a low-cost antenna design using FR-4 substrate. Since FR-4 is accessible and commonly used in printed circuit board fabrication, the proposed design approach may help reduce development costs for wireless devices while maintaining acceptable performance. In terms of innovation and digital sustainability, the study provides a practical method for improving antenna performance through patch size tuning. This can benefit wireless sensor networks, IoT devices, and compact communication systems that require dependable operation. The study is also relevant to community sustainability because stable wireless connectivity supports smart homes, monitoring systems, and localized digital infrastructure. Overall, the research demonstrates that careful tuning of patch width and patch length can improve the resonance accuracy and impedance matching of a 2.4 GHz rectangular microstrip patch antenna. This makes the study valuable for antenna design, wireless communication engineering, IoT development, and sustainable digital infrastructure.

2. Material and methods

2.1 Research Design

The research utilized a quantitative simulation-based design focused on parametric optimization. The study systematically varied the patch width (W) and patch length (L) while holding other antenna parameters constant to isolate their effects on antenna performance. Initial antenna dimensions were derived using the transmission line model, and full-wave electromagnetic simulation was conducted using CST Microwave Studio Suite to validate and optimize the design at the target frequency of 2.4 GHz.

2.2 Locale of the Study

The study was conducted within a virtual simulation environment at the Electronics Engineering Department of Quezon City University. All design iterations, modeling, and performance evaluations were carried out using CST Microwave Studio Suite, eliminating the need for physical fabrication during the initial analysis phase.

2.3 Respondents of the Study

The study did not involve human respondents. The subject of analysis was a rectangular microstrip patch antenna model, and all evaluations were performed through electromagnetic simulation. The antenna structure served as the primary system under investigation, with performance assessed under controlled simulated conditions.

2.4 Sample and Sampling Procedure

The "sample" in this study refers to the set of antenna geometrical configurations generated through parametric variation. Specifically, the patch width ranged from 32 mm to 41 mm, and the patch length ranged from 24 mm to 31 mm, with an optimized configuration identified through simulation. A controlled parametric sweep was used to evaluate each configuration while maintaining constant feed and substrate parameters, allowing isolation of the effects of W and L variations on antenna behavior.

2.5 Research Instrument

The primary research instrument was CST Microwave Studio Suite, a full-wave electromagnetic simulation software used for modeling, analyzing, and optimizing the microstrip patch antenna. The transmission line model was also used as a theoretical tool for initial dimension calculation. The antenna was modeled on an FR-4 substrate with dielectric constant 4.3 and thickness 1.6 mm, incorporating standard PCB parameters including copper thickness and loss tangent for realistic simulation conditions.

2.6 Data Gathering Procedure

Data were gathered through iterative electromagnetic simulations. Initial antenna dimensions were computed using the transmission line model, after which the antenna geometry was built in CST Microwave Studio Suite. The patch width and length were then systematically varied to observe changes in resonance behavior and impedance matching. Each configuration was evaluated based on simulated return loss (S11), VSWR, bandwidth, gain, and radiation pattern. The optimized design was selected based on achieving resonance closest to 2.4 GHz with improved impedance matching and minimal reflection loss.

2.7 Data Analysis Techniques

Data analysis was performed using comparative evaluation of simulated antenna performance metrics. Return loss (S11) was used to assess impedance matching, VSWR to evaluate transmission efficiency, bandwidth to determine operational frequency range, gain to measure radiation effectiveness, and radiation pattern to assess directionality. Results from different patch size configurations were compared to identify the optimal geometry that produced the best overall performance at 2.4 GHz. The final optimized antenna performance was validated based on standard antenna design thresholds such as S11 below −10 dB and VSWR below 2.0.

3. Results and Discussion

3.1 Impedance Matching and Return Loss Performance

3.1.1 Return Loss (S11) at Resonance

The simulation results show that the optimized antenna achieved a return loss of –18.06 dB at 2.4 GHz, which is significantly below the –10 dB reference threshold for acceptable antenna performance. This indicates that most of the input power is effectively radiated, with minimal reflection occurring at the feed point. The result demonstrates that proper tuning of patch dimensions improves impedance matching between the feed line and the radiating patch. The strong return loss performance confirms that patch size variation effectively corrects frequency shift issues commonly observed in standard transmission-line-based antenna designs, as reported in earlier studies where dimensional inaccuracies often degrade impedance behavior (Kumar, 2019).

3.2 Bandwidth Performance

3.2.1 Operational Bandwidth around 2.4 GHz

The antenna exhibits an operational bandwidth of 85 MHz (0.085 GHz), covering approximately 2.357 GHz to 2.442 GHz. This range satisfies the required coverage for narrowband systems operating within the 2.4 GHz ISM band. The result indicates that despite using FR-4 substrate, which typically introduces higher dielectric losses, the antenna still maintains sufficient bandwidth for Wi-Fi and IoT applications. The narrow bandwidth is consistent with known behavior of FR-4-based microstrip antennas, where losses limit bandwidth expansion compared to low-loss substrates. However, this bandwidth remains suitable for standard 20 MHz Wi-Fi channel spacing, ensuring compatibility with practical communication systems (Latha & Anand, 2016; Noordin et al., 2024).

3.3 Voltage Standing Wave Ratio (VSWR) Performance

3.3.1 Impedance Stability and Matching Efficiency

The simulated VSWR value at resonance is 1.28, which is well below the commonly accepted limit of 2.0 for efficient antenna operation. This result indicates excellent impedance matching and low power reflection in the antenna system. The stable VSWR response across the resonant region further shows that the antenna maintains consistent impedance behavior, even with minor environmental or material variations. Such stability enhances reliability for IoT and wireless communication systems, where consistent signal transmission is essential (Deepika et al., 2017).

3.4 Radiation Pattern Characteristics

3.4.1 Directional Radiation Behavior

The simulated radiation pattern shows a directional radiation profile typical of rectangular microstrip patch antennas, with the main lobe oriented perpendicular to the patch surface. This directional behavior improves signal concentration in the desired coverage area while reducing radiation in undesired directions. As a result, interference with nearby systems operating in the same frequency band is minimized. This characteristic is particularly beneficial for Wi-Fi routers, IoT gateways, and access points where controlled coverage is required for stable network performance (Sudhakar, 2020).

3.5 Gain Performance

3.5.1 Realized Gain at 2.4 GHz

The antenna achieves a realized gain of 2.688 dBi at 2.4 GHz, which is consistent with expectations for FR-4-based microstrip patch antennas. Although the gain is moderate compared to antennas built on low-loss substrates, it remains sufficient for short-range wireless communication applications. The result confirms that the antenna provides an appropriate balance between compact size, low cost, and acceptable radiation efficiency. This makes it suitable for IoT sensors, smart home systems, and other embedded wireless devices requiring energy-efficient communication.

3.6 Effect of Patch Size Variation on Overall Performance

3.6.1 Relationship Between Geometry and Antenna Behavior

The results collectively demonstrate that variations in patch width and length have a direct impact on resonance accuracy, impedance matching, and overall antenna performance. The optimized configuration successfully corrects frequency shifts commonly encountered in initial transmission line model designs by compensating for fringing effects and substrate losses. The findings confirm that even small dimensional adjustments significantly influence antenna behavior, reinforcing the importance of parametric optimization in microstrip antenna design. This is particularly relevant when using FR-4 substrates, where dielectric losses and fabrication tolerances can easily shift resonant frequency and degrade performance if not properly compensated.

3.7 Summary of Performance Outcomes

3.7.1 Integrated Performance Evaluation

Overall, the antenna demonstrates strong impedance matching, stable radiation characteristics, and adequate operational bandwidth for 2.4 GHz ISM band applications. The combination of low return loss, acceptable VSWR, moderate gain, and sufficient bandwidth confirms the effectiveness of patch size tuning as an optimization strategy for microstrip patch antennas. These results validate the design approach and confirm that parametric variation of patch geometry is a practical method for improving antenna performance in low-cost wireless communication systems

4. Conclusion & Recommendations

The study concluded that patch size variation significantly improves the impedance matching and resonance accuracy of a rectangular microstrip patch antenna operating at 2.4 GHz. By applying transmission line model calculations and CST Microwave Studio Suite optimization, the final design achieved a return loss of –18.06 dB, VSWR of 1.28, bandwidth of 85 MHz, and realized gain of 2.688 dBi. These results confirm that precise tuning of patch width and length effectively corrects frequency shifts and enhances overall antenna performance for Wi-Fi and IoT applications using FR-4 substrate.

It is recommended that further studies explore additional optimization of patch geometry and substrate selection to improve bandwidth performance while maintaining low-cost design constraints. Future work may also consider advanced parametric tuning methods to further enhance impedance matching and radiation efficiency for broader wireless communication applications while maintaining the same design framework used in this study.

Compliance with ethical standards

The authors declare that there are no conflicts of interest regarding the publication of this study. The research involved only simulation-based analysis of a microstrip patch antenna and did not include human participants, animals, or identifiable personal data. Therefore, ethical approval and informed consent were not required.

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