The Academic
International Journal of Multidisciplinary Research

An Online Peer Reviewed / Refereed Journal
Volume 4 | Issue 5 | May 2026
ISSN: 2583-973X (Online), SJIF IF: 5.6
Website: www.theacademic.in

Design, Simulation, and Comparative Analysis of Single-Band and Multi-Band Slotted Microstrip Patch Antennas

Astha Anil Bokade[1], Ayush Narendra Phatangare[2*], Mrunal Rajendra Jadhav[3], Darshana Mukund Ashtekar[5], Dr. Kirti Vasant Thakur[4]

Department of Electronics and Telecommunication Engineering,
Government College of Engineering and Research, Awasari (Khurd),
Tal-Ambegaon, Dist-Pune 412405, Maharashtra, India
astha.bokade23131046@gcoeara.ac.in, ayush.phatangare23131023@gcoeara.ac.in *,
mrunal.jadhav23131058@gcoeara.ac.in, darshana.ashtekar23131016@gcoeara.ac.in, kirti79@gmail.com
(*Corresponding Author)

DOI : https://doi.org/10.5281/zenodo.20690278

ARTICLE DETAILS

Research Paper
Accepted: 24-05-2026
Published: 10-06-2026

Keywords:
CST Studio Suite, dual-band antenna, microstrip patch antenna, return loss, slot loading, VSWR

ABSTRACT

This paper presents the design, simulation, and comparative analysis of three microstrip patch antenna configurations: a single-band rectangular patch antenna, a dual-band single-slot patch antenna, and a dual-band dual-slot patch antenna. The conventional patch is first designed for a target resonant frequency, after which slot-loading techniques are applied to achieve multi-band operation by modifying the surface current distribution on the patch. All antenna models are developed and evaluated using CST Studio Suite, a full-wave electromagnetic simulation environment. Performance metrics including return loss (S11), voltage standing wave ratio (VSWR), bandwidth, and radiation behaviour are recorded and analysed for each configuration. Simulation results demonstrate that the dual-slot configuration achieves well-matched dual-band operation with S11 values of approximately –28.29 dB and –16.73 dB at 2.56 GHz and 5.81 GHz respectively. The study confirms that slot incorporation is an effective and compact technique for enabling multi-band functionality in microstrip patch antennas, making

them suitable for wireless applications including Wi-Fi, Bluetooth, and Internet of Things (IoT) systems.

1. Introduction

Microstrip patch antennas have become a fundamental component in modern wireless communication systems owing to their compact size, low profile, light weight, and ease of fabrication on printed circuit boards. These antennas find widespread application in Wi-Fi, Bluetooth, satellite communication, and Internet of Things (IoT) devices. A conventional microstrip patch antenna resonates at a single frequency, which constrains its utility in contemporary communication systems that increasingly demand multi-band or wideband operation.

With the rapid expansion of wireless technologies, there is a growing need for antennas capable of operating simultaneously at multiple frequency bands while maintaining compact physical dimensions and efficient radiation characteristics. Slot loading has emerged as one of the most practical techniques to address this requirement. By etching slots into the radiating patch, the surface current distribution is disturbed, additional resonant modes are excited, and dual-band or multi-band performance is achieved without a significant increase in antenna dimensions.

In this paper, three antenna configurations are investigated: a conventional single-band microstrip patch antenna, a dual-band antenna incorporating a single rectangular slot, and a dual-band antenna incorporating two rectangular slots. The objective is to study how the introduction and variation of slots influence key performance parameters such as return loss, bandwidth, VSWR, and radiation behaviour. A structured comparative analysis is conducted across all three designs to identify the trade-offs associated with each configuration and to validate the benefits of slot-loaded designs for modern wireless communication applications.

2. Literature Survey

2. Literature Survey

Microstrip patch antennas have attracted significant research interest due to their low profile, lightweight structure, ease of fabrication, and compatibility with printed circuit technology. These characteristics make them suitable for wireless communication systems, satellite communication, radar systems, Wi-Fi networks, Bluetooth devices, and Internet of Things (IoT) applications.

Balanis (2016) established the theoretical foundations of microstrip antenna design through transmission-line and cavity-model approaches. His work provides a comprehensive understanding of radiation mechanisms, resonant frequency calculations, impedance matching, and performance analysis and remains one of the most widely cited references in antenna engineering.

James and Hall (1989) presented an extensive study on microstrip antenna structures, feeding techniques, substrate effects, and radiation characteristics. Their research highlighted the practical limitations of conventional microstrip antennas, particularly their narrow bandwidth and relatively low gain.

Pozar (1992) investigated microstrip antenna feeding methods and demonstrated how feed position and substrate properties affect impedance matching and radiation efficiency. The study provided valuable guidelines for optimizing antenna performance.

Wong (2002) introduced compact and broadband microstrip antenna designs and demonstrated that slot-loading techniques can generate additional resonant frequencies by modifying current paths on the radiating patch. This work significantly influenced later multiband antenna developments.

Gupta, Garg, Bahl, and Bhartia (2005) analyzed slot-loaded rectangular microstrip patch antennas and showed that slot dimensions and placement directly affect resonant frequencies, bandwidth, and impedance characteristics. Their findings confirmed slot loading as an effective approach for compact multiband operation.

Sharma (2015) investigated U-slot loaded microstrip patch antennas and reported significant improvements in bandwidth and frequency agility. The study demonstrated that carefully optimized slot geometries can produce dual-band and wideband characteristics while maintaining compact dimensions.

Borchardt (2019) proposed a detailed design methodology for U-slot patch antennas and explained the physical mechanism responsible for multiple resonant modes. The work provided systematic procedures for antenna optimization and practical implementation.

Prasad (2018) designed and implemented a multiband microstrip patch antenna using full-wave electromagnetic simulation tools. The study validated that introducing slots into the radiating patch effectively generates additional resonant modes suitable for wireless communication systems.

Kumar and Ray (2017) developed dual-band microstrip antennas for WLAN applications and reported that slot-based modifications improved return loss performance and enabled operation in both 2.4 GHz and 5 GHz frequency bands.

Patel et al. (2020) investigated E-shaped and H-shaped slot configurations for dual-band communication systems. Their results indicated that multiple slot geometries provide better control over resonant frequencies and enhance impedance matching compared with conventional designs.

Kashyap, Verma, and Kumar (2023) focused on gain and bandwidth enhancement of slotted microstrip patch antennas. Their work demonstrated that optimized slot structures improve radiation efficiency, bandwidth, and antenna gain while maintaining compact size.

Singh and Sharma (2023) presented a compact dual-band slotted antenna specifically designed for IoT devices. The antenna achieved stable performance across two communication bands while occupying minimal physical space, making it suitable for embedded wireless systems.

Nahas, Hamid, and Boudjemaa (2024) proposed a high-gain dual-band slotted microstrip patch antenna and reported excellent return loss, improved gain, and stable radiation characteristics. Their results confirmed the effectiveness of slot-loading techniques for modern wireless applications.

Zhang et al. (2024) developed a dual-band microstrip antenna for Wi-Fi and 5G applications using modified slot structures. Their design achieved improved bandwidth and impedance matching while maintaining a compact form factor.

Singh, Kumar, and Verma (2024) conducted a comparative analysis of single-slot and dual-slot microstrip patch antennas. Their results showed that dual-slot configurations provide superior impedance matching, lower VSWR, and more balanced dual-band operation than single-slot designs.

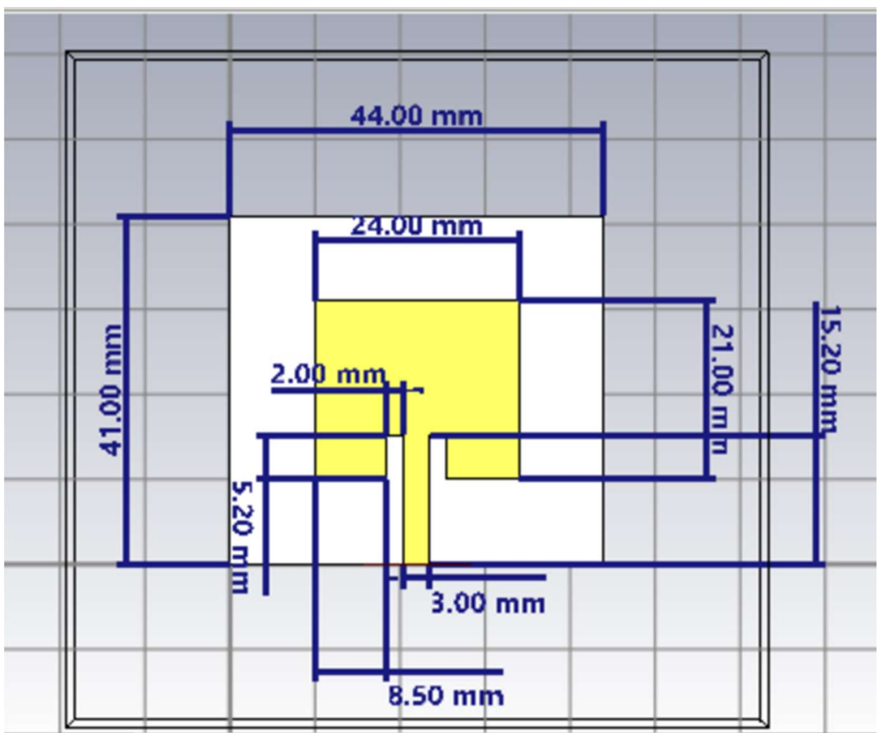
The reviewed literature demonstrates that slot loading remains one of the most effective and compact methods for achieving dual-band and multiband operation in microstrip patch antennas. Previous studies have largely focused on individual antenna configurations or specific slot geometries. However, direct comparative investigations involving conventional single-band antennas, single-slot dual-band antennas, and dual-slot dual-band antennas within a unified simulation environment are relatively limited. This research addresses that gap by designing, simulating, and comparing all three configurations using CST Studio Suite while evaluating their return loss, VSWR, resonant frequencies, and overall electromagnetic performance.

3. System Development And Operation

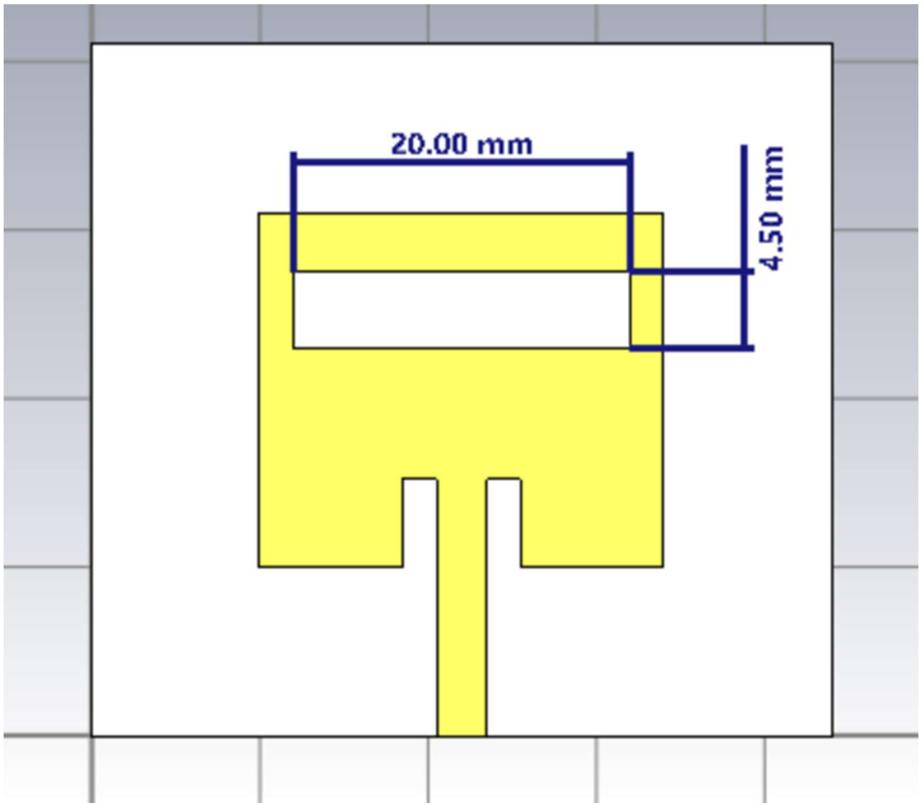
3.1 Design Approach

The development process begins with the design of a conventional single-band rectangular microstrip patch antenna. The patch dimensions are calculated using the standard transmission line model, which relates the physical geometry of the patch to the desired resonant frequency, the dielectric constant of the substrate, and the substrate thickness. Once the baseline antenna is established, slot-loading modifications are introduced sequentially to produce dual-band variants.

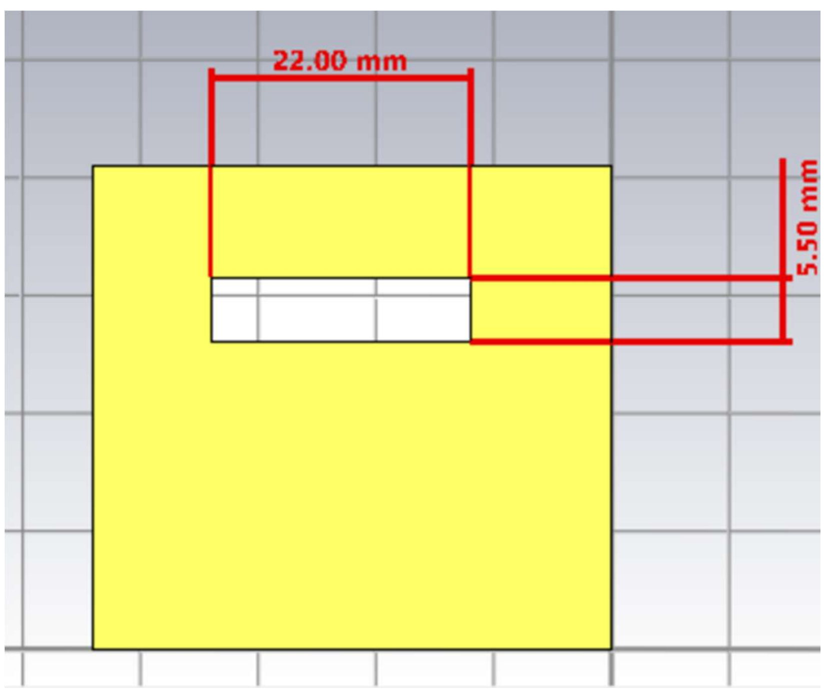
For the single-slot antenna, one rectangular slot is etched at a selected location on the patch surface to disturb the dominant current distribution and introduce a secondary resonant mode. For the dual-slot antenna, two rectangular slots are incorporated to provide further control over the current paths, enabling improved frequency selectivity and more balanced impedance matching at both resonant bands.



Img-1: Single band patch antenna



Img-2: Dual band single slot patch antenna



Img-3: Dual band dual slot patch antenna

3.2 Simulation Setup In CST Studio Suite

All three antenna models are designed, simulated, and analysed within CST Studio Suite using a full-wave time-domain solver. The simulation workflow follows the sequence described below.

A new microwave studio project is created, and the substrate material is defined with appropriate dielectric properties. The ground plane, patch, and microstrip feed line are modelled as copper conductors. Slot structures are implemented with precise geometric dimensions determined through iterative parametric studies. Open boundary conditions with added space are assigned to simulate free-space radiation. A waveguide port is placed at the feed line input to provide 50-ohm excitation. The frequency domain post-processing module is used to extract S-parameter data, from which return loss and VSWR are computed over the range of 1 GHz to 7 GHz.

3.3 Material Specifications

The ground plane and the radiating patch, along with the feed line, are modelled using annealed copper. The substrate is FR-4 (lossy), a widely used dielectric material in printed circuit board fabrication. FR-4 has a relative permittivity of approximately 4.3 and a loss tangent of 0.025. These material properties directly influence the resonant frequency, bandwidth, and radiation efficiency of each antenna design.

3.4 Operation Of The System

The system operates on the fundamental principle of electromagnetic radiation from a microstrip patch antenna. An RF signal is applied through the simulation port, which serves as the excitation reference with a characteristic impedance of 50 ohms. The signal propagates through the microstrip feed line to the radiating patch. At the resonant frequency, standing waves are established across the patch and fringing fields at the patch edges produce the radiated electromagnetic wave.

The introduction of slots modifies this operation in the following ways. A single slot increases the effective current path on the patch surface, thereby introducing a secondary resonant frequency in addition to the dominant mode determined by the patch dimensions. A dual-slot configuration creates multiple modified current paths, enabling better control over both resonant frequencies and achieving more uniform impedance matching across the two operating bands.

Three distinct modes of operation are thus observed across the antenna configurations.

In the single-band patch antenna, the RF energy excites the dominant TM10 mode, producing radiation at a single resonant frequency. The current distribution is uniform and the impedance matching is stable, resulting in good return loss and low VSWR at the design frequency.

In the dual-band single-slot antenna, the slot disturbs the TM10 mode and introduces a higher-order resonance. The antenna radiates at two frequencies; however, because only one slot is present, control over the secondary mode is limited, and the impedance matching at the lower resonant frequency may be weaker than at the higher one.

In the dual-band dual-slot antenna, two slots produce two additional current path modifications that interact to provide stable excitation of two resonant modes. The result is improved impedance matching and more consistent return loss values at both operating frequencies, making this configuration the most suitable for practical dual-band applications.

4. Results

The three antenna configurations were simulated using CST Studio Suite, and the following results were obtained for the key performance parameters.

4.1 Single-Band Microstrip Patch Antenna

The conventional rectangular patch antenna exhibits a single resonance at approximately 3.36 GHz. The return loss at this frequency is approximately –18.67 dB, and the VSWR is approximately 1.25. The S11 curve shows a well-defined dip below −10 dB, confirming proper impedance matching at the designed frequency. The VSWR value close to unity indicates minimal signal reflection and efficient power radiation. As expected for a basic patch design, the antenna operates within a single, relatively narrow frequency band.

4.2 Dual-Band Single-Slot Patch Antenna

The introduction of a single rectangular slot into the patch modifies the surface current distribution and produces dual resonance. The two resonant frequencies are observed at approximately 2.32 GHz and 5.77 GHz. The return loss values are approximately −7.00 dB and −18.38 dB at the respective frequencies, and the VSWR values are approximately 2.60 and 1.27.

The higher-frequency band at 5.77 GHz demonstrates strong impedance matching, with S11 well below −10 dB and VSWR close to unity. At the lower frequency of 2.32 GHz, however, the return loss does not meet the commonly accepted threshold of −10 dB, and the VSWR exceeds 2.0, indicating partial resonance and sub-optimal power transfer. This asymmetric performance is attributable to the limited control over current redistribution afforded by a single slot.

4.3 Dual-Band Dual-Slot Patch Antenna

The dual-slot configuration introduces two modified current paths and achieves well-balanced dual-band operation. Resonances are observed at approximately 2.56 GHz and 5.81 GHz. The return loss values at these frequencies are approximately −28.29 dB and −16.73 dB respectively, and the VSWR values are approximately 1.10 and 1.36.

Both resonant frequencies exhibit S11 well below −10 dB, confirming excellent impedance matching at both bands. VSWR values close to unity indicate efficient power transfer and very low signal reflection. Compared to the single-slot design, the lower band shows a substantial improvement in return loss (from −7.00 dB to −28.29 dB), and the higher band maintains strong performance. The dual-slot structure thus demonstrates superior frequency tuning capability and more optimised electromagnetic coupling across both operating bands.

4.4 Comparative Summary

Table 1 summarises the simulated performance metrics for all three antenna configurations.

Parameter	**Single-Band**	**Single-Slot Dual-Band**	**Dual-Slot Dual-Band (Lower Band)**	**Dual-Slot Dual-Band (Upper Band)**
Resonant Freq. (GHz)	3.36	2.32 / 5.77	2.56	5.81
Return Loss (dB)	−18.67	−7.00 / −18.38	−28.29	−16.73
VSWR	1.25	2.60 / 1.27	1.10	1.36

Table 1: Comparative Performance Summary Of The Three Antenna Designs

From the comparative data it is evident that slot loading successfully enables dual-band operation. The single-slot design introduces a second resonant frequency but produces uneven performance across the two bands. The dual-slot design corrects this imbalance, providing strong return loss and low VSWR at both resonant frequencies. Increasing the number of slots thus improves both impedance matching and frequency control, validating the effectiveness of multi-slot antenna design for multi-band wireless applications.

5. Conclusion

This paper presented the design, simulation, and comparative analysis of three microstrip patch antenna configurations: a single-band patch, a dual-band single-slot patch, and a dual-band dual-slot patch. All designs were modelled and simulated using CST Studio Suite with FR-4 substrate and copper conductors.

The single-band patch antenna demonstrated stable and well-matched operation at a single resonant frequency of 3.36 GHz, with a return loss of −18.67 dB and a VSWR of 1.25. The single-slot variant successfully introduced dual-band functionality at 2.32 GHz and 5.77 GHz; however, impedance matching at the lower band was insufficient, with a return loss of only −7.00 dB.

The dual-slot patch antenna achieved the best overall performance, exhibiting return loss values of −28.29 dB and −16.73 dB at 2.56 GHz and 5.81 GHz respectively, with VSWR values of 1.10 and 1.36. These results confirm that increasing the number of slots enhances control over the surface current distribution, leading to improved impedance matching, lower VSWR, and more balanced dual-band operation.

The study validates slot loading as a reliable and compact technique for achieving multi-band microstrip patch antenna designs. The dual-slot configuration is particularly well suited for modern wireless communication applications such as Wi-Fi (2.4 GHz and 5 GHz bands), Bluetooth, and IoT systems.

Future Scope

Several avenues exist for extending and improving upon the present work. The application of defected ground structures (DGS), parasitic patch elements, or substrate stacking can be investigated to enhance the bandwidth at each resonant frequency. Reconfigurable antenna designs employing PIN diodes or RF MEMS switches may be explored to enable dynamic frequency tuning. The use of low-loss substrates such as Rogers RT/Duroid materials can improve radiation efficiency and gain. Further miniaturisation may be achieved through fractal-based patch geometries or the incorporation of metamaterial loading. The integration of these antenna designs into practical platforms such as IoT sensor nodes, unmanned aerial vehicle (UAV) communication systems, and wearable electronics represents a natural progression.

Fabrication and over-the-air measurement are recommended to validate the simulation results experimentally and to identify any fabrication-induced deviations.

Acknowledgements

The authors gratefully acknowledge the guidance and support of Dr. M. S. Nagmode (Head of Department, Electronics and Telecommunication Engineering), and Dr. N. S. Nehe (Principal) at the Government College of Engineering and Research, Awasari (Khurd). The authors also thank the college management for providing access to the library and laboratory facilities that facilitated this work.

References

Balanis, C. A. (2016). Antenna Theory: Analysis and Design (4th Ed.). Wiley.

James, J. R., & Hall, P. S. (1989). Handbook of Microstrip Antennas. Peter Peregrinus Ltd.

Pozar, D. M. (1992). Microstrip antennas. Proceedings of the IEEE, 80(1), 79–91.

Wong, K. L. (2002). Compact and Broadband Microstrip Antennas. Wiley-Interscience.

Gupta, K. C., Garg, R., Bahl, I., & Bhartia, P. (2005). Analysis of Slot-Loaded Rectangular Microstrip Patch Antenna. Indian Journal of Radio & Space Physics, 34(6), 424–430.

Sharma, S. (2015). Design and Analysis of U-Slot Loaded Microstrip Patch Antenna.

Prasad, L. (2018). Design and Implementation of Multiband Microstrip Patch Antenna. Advanced Electromagnetics, 7(4).

Kumar, A., & Ray, K. P. (2017). Dual-Band Microstrip Antenna for WLAN Applications. IEEE Antennas and Wireless Propagation Letters.

Patel, H., Shah, V., & Mehta, D. (2020). Comparative Analysis of E-Shaped and H-Shaped Slot Patch Antennas. International Journal of RF and Microwave Computer-Aided Engineering.

Borchardt, J. J. (2019). U-Slot Patch Antenna Principle and Design Methodology. arXiv Preprint.

Kashyap, P., Verma, S., & Kumar, R. (2023). Gain and Bandwidth Enhancement of Slotted Microstrip Patch Antenna. Alexandria Engineering Journal.

Singh, R., & Sharma, P. (2023). Compact Dual-Band Slotted Microstrip Antenna for IoT Applications. Progress in Electromagnetics Research.

Nahas, M., Hamid, M., & Boudjemaa, A. (2024). A High-Gain Dual-Band Slotted Microstrip Patch Antenna. Engineering, Technology & Applied Science Research, 14(1).

Zhang, Y., Liu, X., & Wang, H. (2024). Dual-Band Slotted Microstrip Antenna for Wi-Fi and 5G Communication Systems. IEEE Access.

Singh, A., Kumar, N., & Verma, S. (2024). Comparative Performance Analysis of Single-Slot and Dual-Slot Patch Antennas for Wireless Applications. International Journal of Microwave and Wireless Technologies.