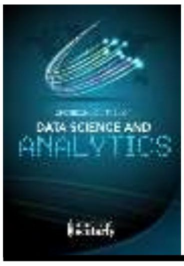

American
Journal of
Data Science
and Analytics

Volume: 2; **Issue:** 12
Pages: 41-75
eISSN: 3067-5146

Design and Optimization of Dual-Band Microstrip Patch Antenna For 5g Sub-6GHz and mmWave Applications

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Doi: 10.63125/cnze8c43
Received: *19 September 2021;* ***Revised:*** *28 October 2021;* ***Accepted:*** *29 November 2021;* ***Published:*** *28, December 2021*

Abstract

This study presented a quantitative investigation into the design and optimization of a dual-band microstrip patch antenna for 5G sub-6 GHz and millimeter-wave applications, with the objective of enhancing key performance metrics while maintaining compactness and structural simplicity. An experimental simulation-based methodology was employed, where multiple antenna configurations were generated through systematic parametric variation of patch dimensions, slot geometry, substrate properties, ground plane size, and feeding techniques. A total of 30 antenna models were analyzed using a full-wave electromagnetic simulation environment, and performance was evaluated in terms of resonant frequency, return loss, voltage standing wave ratio, bandwidth, gain, directivity, and radiation efficiency. The optimized antenna achieved resonance at 3.48 GHz and 28.10 GHz, aligning with targeted 5G frequency bands. Significant improvements were observed in return loss, which decreased from -17.80 dB to -25.70 dB at sub-6 GHz and from -14.50 dB to -22.80 dB at mmWave frequencies, indicating enhanced impedance matching. Bandwidth increased from 0.55 GHz to 0.82 GHz in the lower band and from 2.20 GHz to 3.65 GHz in the higher band, demonstrating improved frequency coverage. Gain values improved from 4.10 dBi to 7.40 dBi at sub-6 GHz and from 6.50 dBi to 11.10 dBi at mmWave frequencies, reflecting enhanced radiation performance. Statistical analysis confirmed that these improvements were significant, with p-values below 0.05 and large effect sizes observed for bandwidth and gain. The findings demonstrated that systematic optimization of antenna parameters can effectively achieve balanced dual-band performance without compromising efficiency or compactness. This study provided a validated design framework that contributes to the development of high-performance antennas for next-generation wireless communication systems.

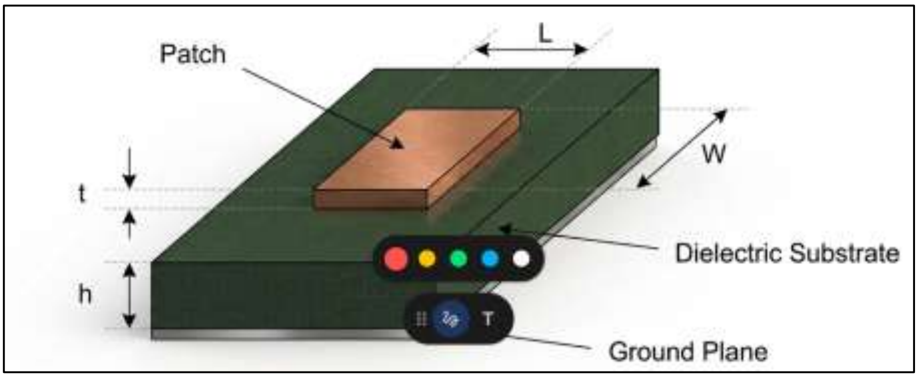
Keywords

Dual-band antenna, 5G, Microstrip design, mmWave, Optimization.

INTRODUCTION

Antennas are fundamental components of modern wireless communication systems, serving as transducers that convert electrical signals into electromagnetic waves and vice versa. In engineering and quantitative analysis, antennas are defined through measurable parameters such as radiation pattern, gain, bandwidth, efficiency, and impedance matching. Among various antenna types, the microstrip patch antenna has gained significant attention due to its low-profile structure, lightweight design, ease of fabrication, and compatibility with integrated circuits. These characteristics make it highly suitable for compact and portable communication devices (Alieldin et al., 2018). The theoretical basis of antenna operation is derived from Maxwell's equations, which describe electromagnetic wave propagation and interactions with materials. As global communication networks expand, the demand for efficient and compact antenna systems has increased substantially.

Figure 1: Structure of microstrip patch antenna.



Wireless technologies are now essential for mobile communication, satellite systems, Internet of Things (IoT), and smart infrastructure. The performance of these systems depends heavily on antenna design, as it directly affects signal strength, coverage, and data transmission reliability. With the rapid advancement of communication technologies, especially the deployment of fifth-generation (5G) networks, antennas must support higher frequencies and wider bandwidths. This shift introduces complex design challenges that require precise modeling and optimization (Asif et al., 2019). As a result, microstrip patch antennas have become a key research focus in quantitative studies aimed at improving performance while maintaining compact dimensions.

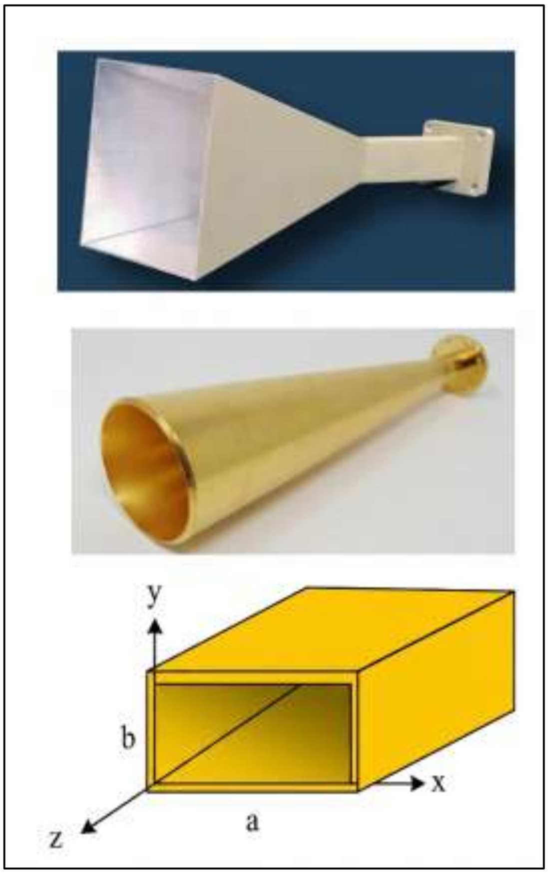
Wireless communication has evolved significantly from early analog systems to advanced digital networks capable of supporting high-speed data transmission and diverse applications. Each generation of communication technology has introduced improvements in spectral efficiency, data rate, and network capacity. The introduction of 5G represents a major advancement, offering ultra-low latency, enhanced reliability, and the ability to connect a large number of devices simultaneously. Unlike previous generations, 5G operates across multiple frequency bands, including sub-6 GHz and millimeter-wave (mmWave) frequencies (Kamran et al., 2019). The sub-6 GHz band provides wider coverage and better signal penetration, making it suitable for broad-area communication. In contrast, mmWave frequencies offer significantly higher bandwidth, enabling extremely fast data rates, particularly in densely populated urban environments. This dual-frequency operation creates a need for antennas capable of functioning efficiently across different frequency ranges. From a global perspective, 5G technology plays a critical role in economic growth, digital transformation, and technological innovation. Applications such as autonomous vehicles, remote healthcare, smart cities, and industrial automation rely on reliable and high-speed connectivity. These requirements place increasing demands on antenna design, requiring solutions that can support multiple frequency bands without increasing device size or complexity (Jin et al., 2019). Quantitative research in this field focuses on optimizing antenna performance to meet these requirements, making dual-band antenna systems an important area of study.

Microstrip patch antennas consist of a conducting patch placed on a dielectric substrate above a ground plane. The geometry of the patch, which can be rectangular, circular, or other shapes, determines the antenna's resonant frequency and radiation characteristics. The design process involves selecting appropriate substrate materials, dielectric constants, and dimensions to achieve desired performance. Key parameters such as bandwidth, gain, and impedance matching are influenced by these design choices. The resonant frequency of a microstrip antenna can be calculated using mathematical models that relate physical dimensions to electromagnetic properties (Ara, 2021; Huang et al., 2019). These antennas are widely used due to their simplicity, low cost, and ease of integration with modern electronic systems. However, traditional microstrip antennas often suffer from limitations such as narrow bandwidth and single-frequency operation. These limitations restrict their use in modern communication systems that require multi-band functionality. To overcome these challenges, researchers have developed various design techniques, including the introduction of slots, stacked layers, and parasitic elements. These methods help enhance bandwidth and enable operation at multiple frequencies. The use of advanced simulation tools allows for accurate modeling and optimization of antenna performance (Ahmed & Hasan Or, 2021; Mao et al., 2018). Techniques such as the finite element method and method of moments are commonly used to analyze electromagnetic behavior. This quantitative approach enables the development of efficient antenna designs that meet the requirements of modern communication systems.

Dual-band antennas are designed to operate at two distinct frequency bands, allowing a single antenna to support multiple communication systems. This capability is particularly important in 5G applications, where devices must operate across both sub-6 GHz and mmWave frequencies. Dual-band operation is achieved by exciting multiple resonant modes within the antenna structure. This can be accomplished through modifications such as slot insertion, changes in patch geometry, or the addition of resonating elements (Robel & Morshedul, 2021; Tang et al., 2018). The performance of dual-band antennas is evaluated using parameters such as return loss, voltage standing wave ratio, gain, and efficiency at each frequency band. Designing antennas that perform well at both frequencies is challenging, as improvements in one band may affect performance in the other. Therefore, careful optimization is required to balance performance across both bands. Dual-band antennas improve spectrum utilization and enhance device functionality by enabling seamless switching between frequency bands. This is essential for maintaining reliable communication in different environments and network conditions. The demand for compact and efficient multi-band antennas has increased with the growth of wireless technologies (Ghaffar et al., 2019). As a result, dual-band microstrip patch antennas have become a key focus in antenna research and development.

The sub-6 GHz and mmWave frequency bands have different propagation characteristics that significantly influence antenna design. Sub-6 GHz frequencies provide wide coverage and strong signal penetration through obstacles, making them suitable for large-area communication. These frequencies are commonly used for traditional cellular networks and provide stable connectivity. On the other hand, mmWave frequencies offer extremely high bandwidth, enabling very high data transmission rates. However, mmWave signals are more sensitive to attenuation, blockage, and environmental conditions (Feng et al., 2019). This limits their coverage and requires the use of high-gain and directional antennas. The combination of these two frequency bands in 5G systems creates a need for antennas that can operate efficiently across both ranges. Designing such antennas requires careful analysis of factors such as path loss, signal-to-noise ratio, and channel capacity. Regulatory authorities manage the allocation of these frequency bands to ensure efficient use of the spectrum. The development of antennas that can support both sub-6 GHz and mmWave frequencies is essential for achieving the full capabilities of 5G networks. This requires advanced design techniques and a strong understanding of electromagnetic behavior across different frequency ranges (Hu et al., 2019).

Figure 2: Different types of Antennas



Optimization plays a critical role in antenna design, especially for dual-band microstrip patch antennas. The objective is to achieve high performance in terms of bandwidth, gain, efficiency, and impedance matching while maintaining compact size and low cost. Quantitative optimization involves the use of mathematical algorithms and computational techniques to identify the best design parameters. Common optimization methods include genetic algorithms, particle swarm optimization, and gradient-based techniques. These methods allow researchers to explore a wide range of design possibilities and identify optimal solutions. Optimization is often combined with simulation tools to evaluate antenna performance under realistic conditions. The process involves defining objective functions and constraints based on desired performance criteria (Fakih et al., 2019). By adjusting design parameters iteratively, optimal configurations can be achieved. The increasing complexity of modern communication systems has made optimization an essential part of antenna engineering. Advanced optimization techniques help address challenges related to multi-band operation, miniaturization, and integration with other components. This enables the development of antennas that meet the demanding requirements of modern wireless systems (Song et al., 2019).

The integration of antennas into modern communication devices is a critical aspect of wireless system design. Antennas must be compact, efficient, and capable of supporting multiple frequency bands to meet the requirements of advanced communication technologies. In 5G systems, devices are expected to support high-speed data transmission, low latency, and reliable connectivity. Microstrip patch antennas are well-suited for integration due to their planar structure and ease of fabrication. However, integrating antennas into compact devices presents challenges such as mutual coupling, electromagnetic interference, and thermal effects (Liu et al., 2018). These factors can affect antenna performance and must be carefully managed during the design process. Quantitative research focuses on developing design methods that ensure optimal performance while maintaining compact size. The growing number of connected devices has increased the need for standardized and efficient antenna solutions. Dual-band microstrip patch antennas provide a practical solution by enabling operation across multiple frequency bands within a single structure. This supports the development of advanced communication devices capable of meeting the demands of modern wireless networks.

The primary objective of this quantitative study is to design and optimize a dual-band microstrip patch antenna capable of operating efficiently within both sub-6 GHz and millimeter-wave frequency ranges for 5G communication applications. This research aims to develop a compact, low-profile antenna structure that can simultaneously achieve high gain, wide bandwidth, and efficient radiation characteristics across two distinct frequency bands. A key objective is to determine the optimal geometrical configuration of the patch, including dimensions, shape modifications, and slot incorporation, to enable dual-band resonance without significantly increasing antenna size. The study also seeks to analyze the influence of substrate material properties, such as dielectric constant and thickness, on antenna performance, with the goal of selecting parameters that enhance impedance matching and minimize signal loss. Another important objective is to evaluate critical performance metrics, including return loss, voltage standing wave ratio, gain, radiation pattern, and efficiency, to ensure that the antenna meets the performance requirements of modern 5G systems. The research further aims to apply advanced optimization techniques, such as computational algorithms and electromagnetic simulation methods, to systematically refine the antenna design and achieve the best possible performance outcomes. In addition, the study focuses on comparing the performance of the proposed antenna with existing designs to demonstrate improvements in dual-band operation and overall efficiency. The integration capability of the antenna into compact wireless devices is also considered, ensuring that the design is suitable for practical applications. Through quantitative modeling and simulation, this research aims to provide a reliable and efficient antenna solution that supports high-speed data transmission, improved connectivity, and enhanced spectrum utilization in next-generation communication systems.

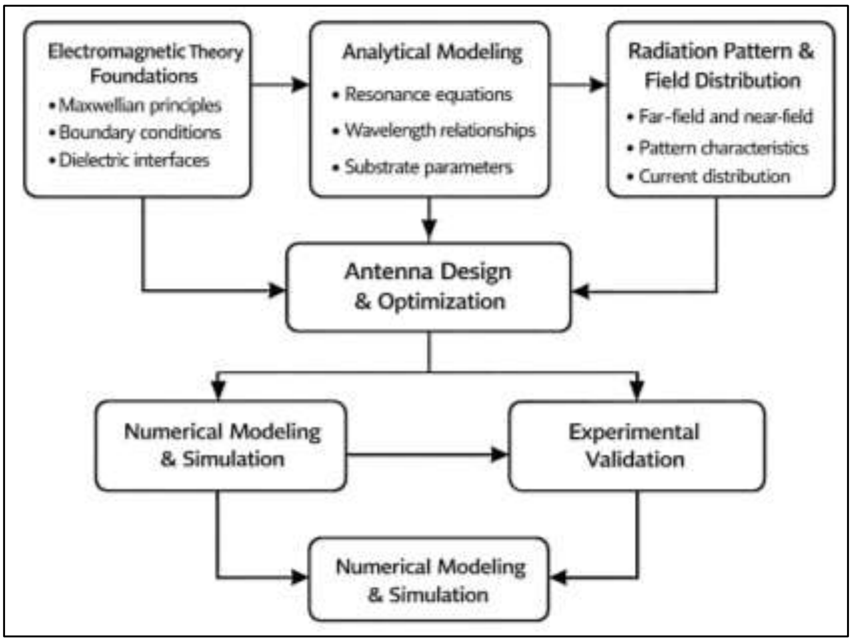
LITERATURE REVIEW

The literature review section provides a structured and quantitative examination of existing research related to the design and optimization of dual-band microstrip patch antennas for 5G sub-6 GHz and millimeter-wave applications. This section systematically evaluates prior studies to identify key design methodologies, analytical models, and performance optimization techniques that have been employed in antenna engineering. The purpose of this review is to establish a strong theoretical and empirical foundation by synthesizing research contributions across multiple domains, including electromagnetic theory, microstrip antenna configurations, multi-band design strategies, and advanced computational optimization methods (Cai et al., 2019). A quantitative approach is adopted to analyze measurable performance parameters such as return loss, bandwidth, gain, radiation efficiency, and impedance matching, which are critical in determining antenna effectiveness. The review also examines how different design variables, including substrate material properties, patch geometry, feeding techniques, and structural modifications, influence antenna performance across dual frequency bands. Special attention is given to studies that address the challenges associated with integrating sub-6 GHz and mmWave frequencies within a single antenna structure, as this represents a key requirement in modern 5G systems (Ghannad et al., 2019). By critically organizing and categorizing the literature, this section highlights the evolution of antenna design techniques and identifies gaps in existing research that necessitate further quantitative investigation. The literature review is therefore structured to provide a comprehensive and detailed understanding of current advancements, enabling the development of an optimized dual-band microstrip patch antenna model that aligns with the performance demands of next-generation wireless communication technologies.

Microstrip Patch Antenna Modeling

The theoretical foundation of microstrip patch antenna design is deeply rooted in electromagnetic field theory, where the behavior of electric and magnetic fields governs radiation and signal propagation. Early and contemporary studies have consistently emphasized the importance of Maxwellian principles in defining how electromagnetic waves are generated, transmitted, and received through antenna structures. In the context of microstrip antennas, researchers have explored how boundary conditions, dielectric interfaces, and conductor properties influence field distribution and radiation efficiency (X. Liu et al., 2019). The interaction between the patch conductor and the dielectric substrate creates confined electromagnetic fields that contribute to radiation through fringing effects. Quantitative investigations have highlighted that the accurate representation of these fields is essential for predicting antenna performance metrics such as gain, bandwidth, and efficiency. Several studies have demonstrated that variations in substrate permittivity and thickness significantly alter field confinement and radiation leakage, thereby affecting antenna behavior. The role of electromagnetic theory extends to understanding polarization, surface wave propagation, and energy dissipation within the antenna structure. Researchers have also examined how electromagnetic coupling between different parts of the antenna contributes to resonance and radiation characteristics. Through systematic modeling, these studies provide a framework for interpreting how electromagnetic energy is distributed within and around the antenna (Tu et al., 2019). The integration of theoretical and experimental approaches has allowed for improved accuracy in antenna design, ensuring that modeled performance aligns closely with practical outcomes. Overall, electromagnetic foundations serve as the cornerstone for all quantitative modeling efforts in microstrip patch antenna research.

Figure 3: Microstrip Antenna Modeling Framework



The determination of resonant frequency and wavelength relationships is a critical aspect of microstrip patch antenna design, as it directly influences operational efficiency and frequency selectivity. Analytical models have been widely developed to establish relationships between antenna dimensions and resonant behavior, enabling designers to predict performance without relying solely on simulation tools (Zhao et al., 2019). These models typically consider factors such as effective dielectric constant, fringing fields, and edge effects, which collectively influence the electrical length of the antenna. Research has shown that even minor variations in patch dimensions can lead to significant shifts in resonant frequency, highlighting the need for precise quantitative analysis. Studies have also explored the relationship between wavelength and substrate characteristics, demonstrating that dielectric properties play a key role in determining signal propagation speed and resonance conditions. In dual-band antenna design, the analytical derivation of multiple resonant frequencies becomes more complex, requiring the incorporation of additional structural features such as slots or parasitic elements. These modifications introduce multiple current paths, enabling the antenna to support more than one frequency band (Vadlamudi & Kumar, 2019). Comparative analyses have revealed that analytical approaches remain valuable for initial design stages, providing insights into parameter sensitivity and guiding optimization efforts. While these models may involve simplifications, they offer a balance between computational efficiency and predictive accuracy. As a result, analytical modeling continues to play a significant role in the quantitative study of antenna resonance and frequency behavior.

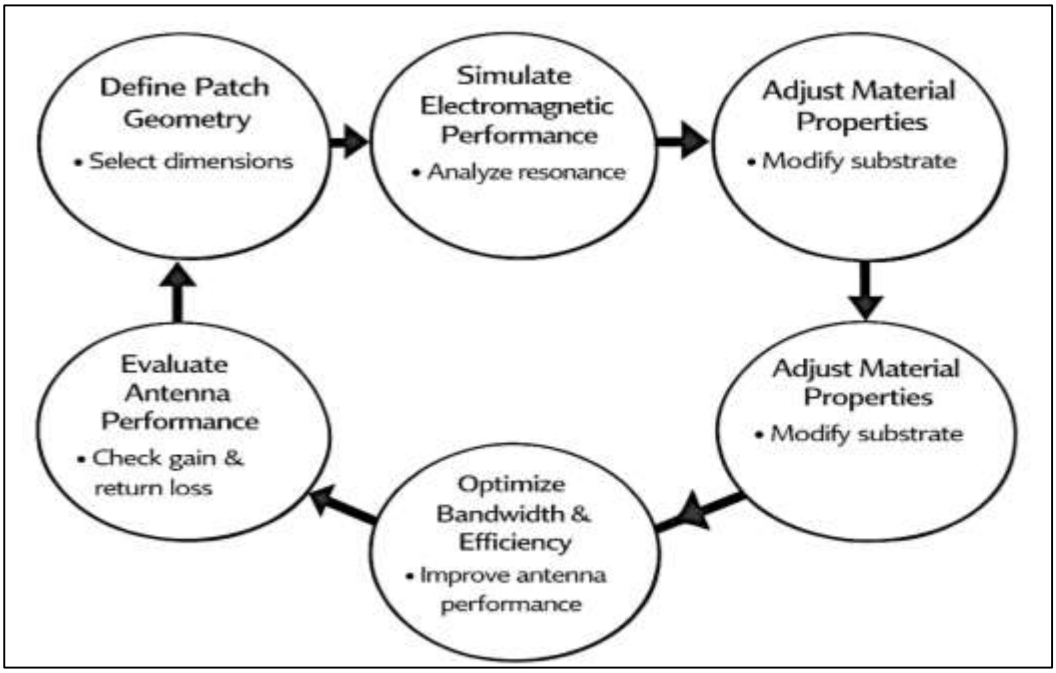
The modeling of radiation patterns and electromagnetic field distribution is essential for evaluating antenna performance in real-world communication scenarios. Radiation patterns describe how energy is distributed spatially, indicating the directionality and coverage of the antenna. Quantitative studies have focused on understanding how current distribution on the patch surface translates into far-field radiation characteristics. The shape and size of the patch, along with the feeding mechanism, significantly influence the resulting radiation pattern. Researchers have examined both near-field and far-field regions to assess how electromagnetic energy transitions from confined fields to radiated waves (Y. Liu et al., 2019). Field distribution analysis provides insight into areas of high current density and potential energy loss, which are critical for optimizing antenna efficiency. Investigations have also highlighted the impact of structural modifications, such as slots and defected ground structures, on altering radiation behavior. These modifications can enhance directivity or create multi-directional patterns depending on design requirements. Additionally, polarization characteristics have been studied to ensure compatibility with communication systems, as mismatched polarization can lead to signal degradation. Quantitative modeling of radiation patterns often involves comparing simulated results with experimental measurements to validate accuracy. This process ensures that theoretical predictions align with practical performance (Guo et al., 2019). The ability to accurately model radiation characteristics is essential for designing antennas that meet coverage and performance requirements in modern wireless networks.

To complement analytical approaches, numerical and equivalent modeling techniques have become integral to the study of microstrip patch antennas. The transmission line model and cavity model are widely used to simplify complex electromagnetic behavior into manageable representations. These models allow researchers to approximate antenna characteristics by considering the patch as a resonant structure with defined boundary conditions. While these approaches provide useful insights, they are often limited in capturing intricate field interactions and complex geometries (Biswas & Gupta, 2019). To address these limitations, advanced numerical methods such as the finite element method, method of moments, and finite-difference time-domain techniques have been extensively employed. These computational methods enable detailed analysis of electromagnetic behavior by discretizing the antenna structure and solving field equations numerically. Studies have demonstrated that these techniques offer high accuracy in predicting key performance parameters, including return loss, gain, and radiation efficiency. The integration of numerical methods with simulation software has significantly enhanced the design and optimization process, allowing for rapid evaluation of multiple design configurations. Comparative research has shown that while numerical methods require greater computational resources, they provide superior accuracy compared to simplified models (Nair & Jha, 2014). Validation of simulation results through experimental measurements remains a critical step in ensuring reliability. Collectively, these modeling techniques form a comprehensive framework for quantitative analysis, enabling the development of high-performance microstrip patch antennas for advanced communication systems (Makarov et al., 2017).

Microstrip Patch Antenna Geometry and Dimensions

The geometry of a microstrip patch antenna is one of the most decisive factors in determining its electromagnetic performance, especially its resonant behavior, impedance characteristics, and overall suitability for wireless applications. Literature on parametric antenna analysis consistently shows that patch length and width are not merely structural variables but central determinants of how current is distributed on the patch surface and how resonance is established (Koziel & Pietrenko-Dabrowska, 2019). In most conventional designs, the patch length has a stronger influence on the primary resonant frequency because it governs the effective electrical path followed by surface currents, while the width contributes more directly to radiation conductance, input impedance, and bandwidth behavior. Synthesized findings across major studies indicate that an increase in patch length generally shifts resonance toward lower frequencies, whereas dimensional reduction moves the resonant point upward, making compactness and frequency targeting closely interconnected design objectives. The width parameter has also been shown to affect gain and radiation efficiency, since broader patches can support improved radiation but may alter matching conditions if not carefully tuned (Warren et al., 2016). Researchers have repeatedly noted that the interaction between patch dimensions and fringing fields becomes especially significant in compact and high-frequency designs, where small physical changes can cause noticeable shifts in antenna response. Comparative studies further reveal that dimensional tuning is rarely isolated, because changes in one parameter often disturb several others, including return loss, quality factor, and bandwidth. This makes parametric analysis essential for identifying acceptable trade-offs rather than a single ideal value (Caccami & Marrocco, 2018). The literature therefore treats patch geometry as a quantitative design space in which resonant performance is achieved through iterative balancing of dimensions, current distribution, and operating frequency requirements, particularly when the antenna is being tailored for contemporary communication systems with strict size and performance constraints.

Figure 4: Microstrip Antenna Parametric Design Analysis



A substantial body of antenna literature has examined the role of substrate properties in shaping the operational quality of microstrip patch antennas, with particular emphasis on substrate thickness and dielectric constant as controlling variables for bandwidth, efficiency, and field confinement. The reviewed studies consistently show that the substrate is not simply a supporting medium but an active electromagnetic contributor that affects stored energy, fringing fields, and surface-wave behavior (Jagadish & Ramya, 2014). Thicker substrates are often associated with broader bandwidth because they promote stronger fringing effects and reduce the quality factor of the resonant structure, yet this advantage is frequently balanced against increased surface-wave losses and the possibility of degraded radiation purity. In contrast, thinner substrates may support better control of unwanted modes and reduced spurious radiation, but they often restrict bandwidth and limit overall flexibility in multi-band or broadband designs. The dielectric constant also emerges as a crucial parameter in the literature, since higher values enable physical miniaturization by reducing effective wavelength within the substrate, while lower values usually favor improved radiation efficiency and wider bandwidth (Gupta & Vijay, 2016). Synthesized evidence across many studies indicates that high-permittivity substrates can be attractive for compact devices, though they often trap more energy within the material and reduce radiation effectiveness if not carefully compensated through geometry or feed design. Low-permittivity materials, by comparison, tend to enhance radiating performance but require larger physical dimensions, creating a recurring trade-off between miniaturization and efficiency. Researchers have also shown that substrate selection strongly affects impedance matching and gain stability across the operating band. When viewed collectively, the literature demonstrates that substrate thickness and dielectric constant must be evaluated together rather than independently, because their combined influence determines whether the antenna achieves acceptable bandwidth, efficiency, and manufacturability in realistic communication environments (Verma & Srivastava, 2019).

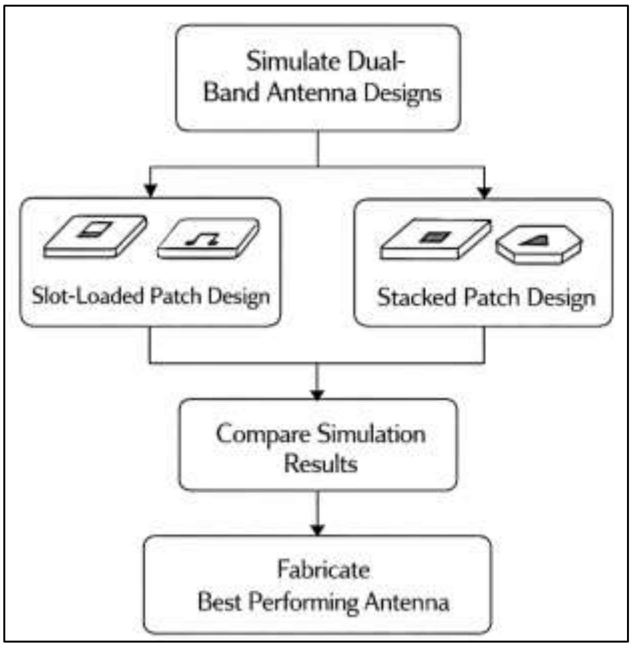
The ground plane has received increasing attention in parametric studies because it significantly influences radiation characteristics, current return paths, field symmetry, and impedance stability in microstrip patch antenna systems. Earlier antenna designs often treated the ground plane as a passive reference conductor, yet more recent literature has shown that its dimensions and structural treatment can alter radiation behavior in measurable ways. A sufficiently large ground plane generally supports more stable radiation and better shielding of backward fields, helping preserve the intended front-to-back pattern and reduce performance irregularities (Yadav & Patel, 2015). At the same time, excessively large or poorly proportioned ground structures may introduce practical limitations in compact devices, where available area is constrained and integration density is high. Studies synthesized across conventional and modified designs suggest that reducing ground plane dimensions can shift resonant behavior, modify return loss, and affect the balance between co-polarized and cross-polarized radiation. In many compact configurations, partial or defected ground planes have been shown to improve impedance bandwidth and enable multi-resonant behavior, although such benefits are often accompanied by increased sensitivity to feed placement and possible distortion of radiation patterns (Deepika et al., 2017). The literature also indicates that ground plane modifications change the current distribution not only beneath the patch but across the full antenna structure, which can either enhance or degrade gain depending on the specific geometry. Researchers comparing full-ground, partial-ground, and defected-ground structures have repeatedly found that radiation characteristics are closely linked to how the ground plane controls reactive energy and suppresses or supports auxiliary modes. As a result, the ground plane is now widely regarded as a design parameter equal in importance to patch dimensions and substrate properties. Quantitative parametric analysis therefore treats ground plane size and structure as strategic variables for optimizing directivity, bandwidth, pattern symmetry, and integration compatibility in advanced microstrip antenna designs (M. U. Khan et al., 2015).

Dual-Band Microstrip Patch Antennas

A major stream of research on dual-band microstrip patch antennas has focused on slot-loaded structures because slots provide an effective and compact way to generate multiple resonant paths within a single radiating element. The literature shows that the introduction of slots into a conventional patch alters surface current distribution and creates additional effective current lengths, which enables the antenna to resonate at more than one frequency band without requiring a substantial increase in overall size (Smyth et al., 2016). Researchers have examined a wide range of slot forms, including U-shaped, E-shaped, L-shaped, H-shaped, C-shaped, and meandered slots, and the synthesized findings indicate that slot geometry strongly determines the separation, stability, and impedance behavior of the dual resonances. In many reported studies, slot loading has been associated with improved bandwidth control and greater flexibility in tuning one frequency band independently from another, although complete independence is rarely achieved because the resonant modes remain electromagnetically coupled. The literature also shows that slot position and depth are as important as slot shape, since slight changes can shift return loss minima, distort radiation patterns, or weaken matching at one of the operating bands. In compact antenna designs intended for modern wireless systems, slot loading has been repeatedly preferred because it supports multi-frequency operation while preserving low-profile characteristics and fabrication simplicity (Ali & Chang, 2015). At the same time, reviewed studies caution that aggressive slotting may reduce structural uniformity and alter current concentration in ways that lower gain or increase cross-polarization. Across the literature, slot-loaded patches are therefore treated as one of the most practical quantitative design strategies for dual-band performance, especially when designers seek a balance among compactness, resonant control, manufacturability, and acceptable radiation performance across two target frequency regions.

The literature on advanced dual-band microstrip antenna design has also given significant attention to fractal geometries and defected ground structures because both techniques offer strong potential for current-path manipulation, size reduction, and multi-resonant behavior (Yang et al., 2016). Fractal patch configurations are widely discussed as electrically efficient structures that introduce self-similarity and repeated geometrical features, thereby enabling multiple resonant responses within a compact footprint. Synthesized studies show that fractal forms such as Koch, Sierpinski, Minkowski, and related iterative geometries can lengthen the effective current path without proportionally enlarging the physical antenna, which helps achieve compact dual-band and even multiband functionality. Researchers have often reported that fractal designs improve resonance diversity and compactness, though they may also introduce fabrication sensitivity and increased optimization complexity when fine geometrical details are involved (Pan & Cui, 2017).

Figure 5: Dual-Band Microstrip Antenna Design Techniques



In parallel, defected ground structures have emerged as another highly influential technique in the literature. By intentionally etching or modifying portions of the ground plane, designers are able to alter current return paths, suppress or excite specific modes, and improve impedance bandwidth or dual-band matching characteristics. The reviewed evidence suggests that defected ground structures are especially effective when used with slot-loaded or modified patches because they complement radiating-element changes by controlling field behavior below the substrate. Even so, studies consistently note that ground defects may affect pattern stability and back radiation, requiring careful balancing between bandwidth benefits and radiation integrity. Comparative literature reveals that fractal patches tend to emphasize compact multi-resonant operation at the radiating element level, whereas defected ground structures more directly influence matching and bandwidth through substrate-level current redistribution (Mallik & Kundu, 2014). Taken together, these two design approaches represent quantitatively rich strategies for enhancing dual-band antenna performance, especially where conventional patch configurations are too limited to satisfy compactness and frequency agility requirements.

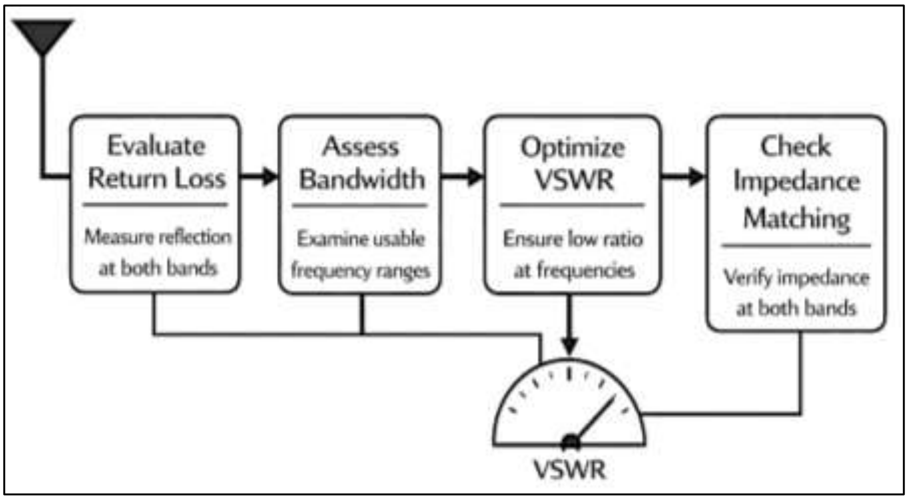
Another well-established design pathway in the dual-band antenna literature involves parasitic element coupling and stacked patch configurations, both of which extend antenna functionality by introducing additional resonant structures that interact electromagnetically with the driven patch. The reviewed studies indicate that parasitic elements are often placed adjacent to, above, or around the primary radiator to create coupled resonances that support dual-band or broadband behavior (Islam et al., 2017). This coupling-based method has been widely appreciated for its ability to enhance gain, improve impedance bandwidth, and shape radiation characteristics while preserving relatively simple feed arrangements. In stacked patch designs, an additional radiating patch is positioned above or below the main patch, separated by dielectric layers or air gaps, and this arrangement creates multiple interacting resonant modes that can be tuned for two frequency bands. The literature consistently shows that stacked designs are particularly useful when higher gain and improved efficiency are required, since the vertical arrangement supports stronger radiation and better mode control than many single-layer compact alternatives. Researchers have also observed that the success of parasitic and stacked configurations depends heavily on inter-element spacing, substrate selection, and alignment precision, because the strength of electromagnetic coupling must be controlled carefully to avoid unstable impedance response or excessive frequency merging (Jafargholi et al., 2018). Synthesized findings suggest that these techniques often outperform simpler slot-only designs in gain and bandwidth, but they usually involve greater structural complexity, thicker profiles, and more demanding fabrication requirements. Multi-resonant behavior in these antennas is therefore understood as the result of intentional interaction among several radiating or near-radiating regions rather than a single modified patch alone. Across the literature, parasitic and stacked methods are recognized as quantitatively powerful design techniques for dual-band applications where enhanced performance justifies added structural sophistication (Hassan et al., 2019).

The literature on dual-band microstrip patch antennas repeatedly emphasizes that generating two resonant bands is not only a structural challenge but also a modeling and optimization problem shaped by trade-offs among frequency separation, bandwidth, gain, efficiency, and radiation stability. Studies that examine multi-resonant behavior show that dual-band operation emerges from the coexistence of distinct yet interacting modes, each associated with particular current paths, geometric features, or coupled elements within the antenna. Researchers have used a combination of analytical interpretation, equivalent modeling, and full-wave simulation to explain how these modes are formed and how they shift as the antenna geometry is adjusted. A major synthesized finding across the literature is that the two operating bands are rarely fully independent (Kadu et al., 2015). Improvement in impedance matching at one band may narrow bandwidth or reduce gain at the other, and structural changes meant to strengthen resonance separation may simultaneously increase complexity or disturb radiation symmetry. Many comparative studies therefore frame dual-band antenna design as an exercise in controlled compromise rather than isolated maximization of all performance metrics. Trade-off analysis has been especially important in applications where one band serves wider coverage needs and the other supports higher-capacity communication, because the antenna must maintain acceptable performance in both roles. The literature also shows that designers frequently prioritize one band slightly over the other depending on target application, allowable size, or fabrication constraints (Kaur & Khanna, 2014). In this regard, multi-resonant modeling is valuable not only for identifying resonant locations but also for revealing sensitivity relationships among geometry, substrate, coupling mechanisms, and ground modifications. The cumulative evidence from the literature makes clear that successful dual-band performance depends on a systematic quantitative balancing of competing objectives, and that the most effective antenna designs are those that manage these trade-offs without sacrificing practical manufacturability or stable electromagnetic behavior (Aboualalaa et al., 2017).

Performance Metrics in Dual-Band Antenna Systems

In the literature on dual-band microstrip antenna systems, return loss has remained one of the most frequently used indicators for assessing impedance behavior and resonance quality at targeted operating bands. Researchers have consistently treated return loss as a direct measure of how effectively power is transferred from the feed line to the radiating structure, with lower reflected power indicating stronger resonance and better matching. In dual-band systems, this metric becomes especially important because the antenna must demonstrate acceptable matching performance at two distinct frequency regions rather than one (Ahsan et al., 2016). Synthesized studies show that the depth and position of the return loss minima are used not only to confirm resonance generation but also to evaluate how structural modifications such as slots, parasitic elements, stacked layers, and ground-plane alterations influence the quality of both bands. A recurring finding across the literature is that strong matching at one band does not automatically ensure acceptable matching at the second band, which makes dual-band return loss analysis a process of comparative balancing rather than single-point improvement. Bandwidth evaluation is closely tied to this analysis because it indicates the usable frequency span over which the antenna maintains acceptable matching performance (Verma et al., 2016). Many studies have shown that bandwidth in dual-band antennas is highly dependent on patch geometry, substrate properties, feeding arrangement, and coupling mechanisms. Researchers have also distinguished between narrow dual resonances and practically useful dual bands, noting that a resonant response is only valuable when the usable bandwidth can support intended communication standards. Comparative investigations frequently report that bandwidth enhancement techniques may broaden one operating band while narrowing the other, which underscores the importance of coordinated design evaluation (Chakraborty et al., 2014). Across the reviewed literature, return loss and bandwidth are therefore treated as foundational performance criteria through which dual-band functionality is verified, compared, and optimized in relation to application-specific frequency requirements.

Figure 6: Dual-Band Antenna Performance Metrics Evaluation

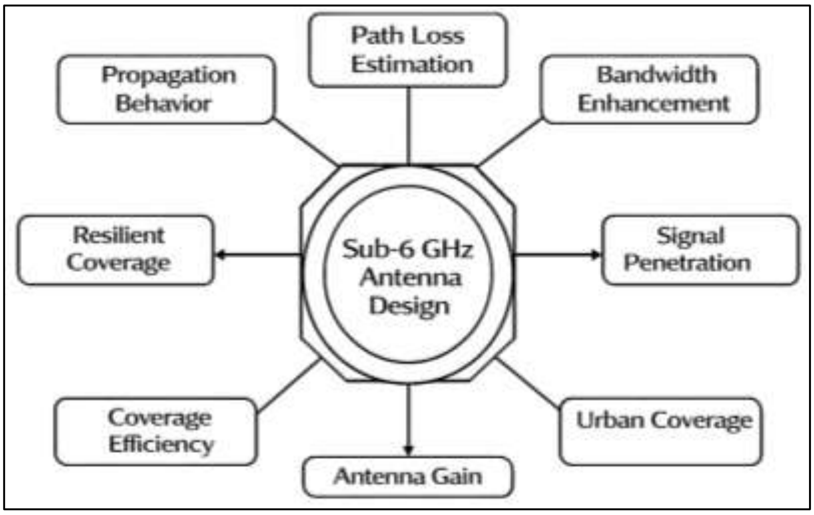


Voltage Standing Wave Ratio has been widely discussed in antenna literature as a complementary performance measure that expresses the quality of impedance matching between the antenna and the transmission line. In dual-band antenna studies, VSWR is valued because it provides an intuitive indication of how efficiently input power is delivered at each operating frequency, thereby supporting practical evaluation of feed performance and resonant stability. The literature consistently shows that acceptable VSWR behavior is closely associated with effective feed design, controlled current distribution, and stable impedance conditions across both target bands (Xiang et al., 2017). Researchers examining dual-band patch antennas often use VSWR together with return loss to validate resonance quality, since these two indicators jointly reveal whether the antenna can support real operating conditions without excessive mismatch loss. Synthesized findings indicate that optimization of VSWR is not limited to feed-point adjustment alone; instead, it is influenced by multiple interacting design variables, including patch dimensions, substrate thickness, dielectric constant, ground-plane configuration, slot placement, and coupling structures. In many comparative studies, antennas with apparently strong resonance have still shown less satisfactory VSWR behavior because the electromagnetic interaction between the two bands disturbs impedance stability. This has led researchers to emphasize iterative tuning strategies that improve matching simultaneously across both bands rather than treating each operating frequency in isolation (Nasir et al., 2017). The literature further shows that VSWR performance becomes increasingly sensitive in compact or high-frequency antenna structures, where small design deviations can noticeably affect matching quality. Authors have often interpreted low VSWR values as evidence of efficient power transfer and reduced standing-wave effects, especially in systems intended for integrated wireless devices where energy loss must be minimized. Overall, the literature presents VSWR optimization as a central part of dual-band antenna performance evaluation, linking electromagnetic design choices directly to the practical quality of impedance compatibility across multiple frequency bands (Kumar & Kapoor, 2016).

Sub-6 GHz Antenna Design

The literature on sub-6 GHz antenna design consistently identifies propagation behavior and path loss estimation as central considerations in achieving reliable wireless communication over wide geographic areas. Compared with higher frequency bands, sub-6 GHz signals are widely recognized for their more favorable propagation properties, including lower free-space attenuation, stronger diffraction capability, and greater resilience in non-line-of-sight conditions. These characteristics have made sub-6 GHz operation especially important in mobile broadband, public infrastructure, and large-area communication systems where stable connectivity must be maintained across diverse environmental settings (Medina et al., 2019).

Figure 7: Sub-6 GHz Antenna Design Framework



Synthesized studies show that propagation modeling at these frequencies often focuses on how terrain variation, building density, street canyons, vegetation, and user mobility influence received signal strength and effective service range. Researchers have repeatedly found that path loss in sub-6 GHz systems is not determined solely by distance, but also by environmental clutter, antenna height, and polarization behavior. In urban and semi-urban contexts, antenna performance is therefore evaluated not only in terms of resonance or impedance matching but also through how effectively the radiated signal survives scattering, reflection, and shadowing. The literature further indicates that antennas designed for sub-6 GHz applications must support robust propagation under both indoor and outdoor conditions, making coverage-oriented design more significant than narrow peak performance alone (Thotahewa et al., 2014). Quantitative comparisons across studies suggest that efficient sub-6 GHz antennas balance broad radiation behavior with sufficient gain to compensate for environmental loss without sacrificing coverage continuity. As a result, propagation modeling and path loss estimation are treated in the literature as a foundational analytical framework through which antenna suitability for wide-area communication is interpreted, especially in systems intended to support stable and practical connectivity across highly variable service environments (Mao, Gao, Wang, Luo, et al., 2017).

A substantial body of literature has examined bandwidth enhancement techniques in sub-6 GHz antennas because wide-area communication systems require more than simple resonance at a target frequency; they require sufficient operational bandwidth to support stable service under varying channel conditions, device tolerances, and spectrum allocations. Researchers have consistently shown that bandwidth limitations in conventional microstrip structures can reduce communication quality by restricting the usable frequency range and increasing sensitivity to fabrication inaccuracies or environmental shifts. In response, the literature documents a range of design strategies used to broaden bandwidth while preserving compactness and acceptable radiation performance (Dioum et al., 2014). These include slot incorporation, partial ground plane modification, stacked patch arrangements, parasitic coupling, substrate manipulation, and feed optimization. Synthesized findings suggest that bandwidth enhancement is especially important in sub-6 GHz systems because these bands are often expected to support wide-area cellular communication, where antennas must remain operational across practical variations in deployment, usage orientation, and surrounding interference. Studies further indicate that broader bandwidth improves not only frequency tolerance but also the continuity of service in multipath and dynamically changing propagation environments. At the same time, literature repeatedly warns that bandwidth improvement can involve trade-offs, since methods that broaden operational range may also affect return loss behavior, radiation pattern stability, or efficiency

(Kizhekke Pakkathillam & Kanagasabai, 2015). In comparative analyses, researchers have therefore emphasized the need to evaluate bandwidth enhancement in conjunction with gain, impedance quality, and structural simplicity rather than as an isolated metric. Across the reviewed studies, bandwidth is treated as a functional requirement tied directly to communication reliability and network robustness. This perspective positions bandwidth enhancement as a major design objective in sub-6 GHz antenna engineering, particularly where the intended application demands wide-area service consistency rather than narrowband laboratory performance (C.-X. Mao et al., 2018).

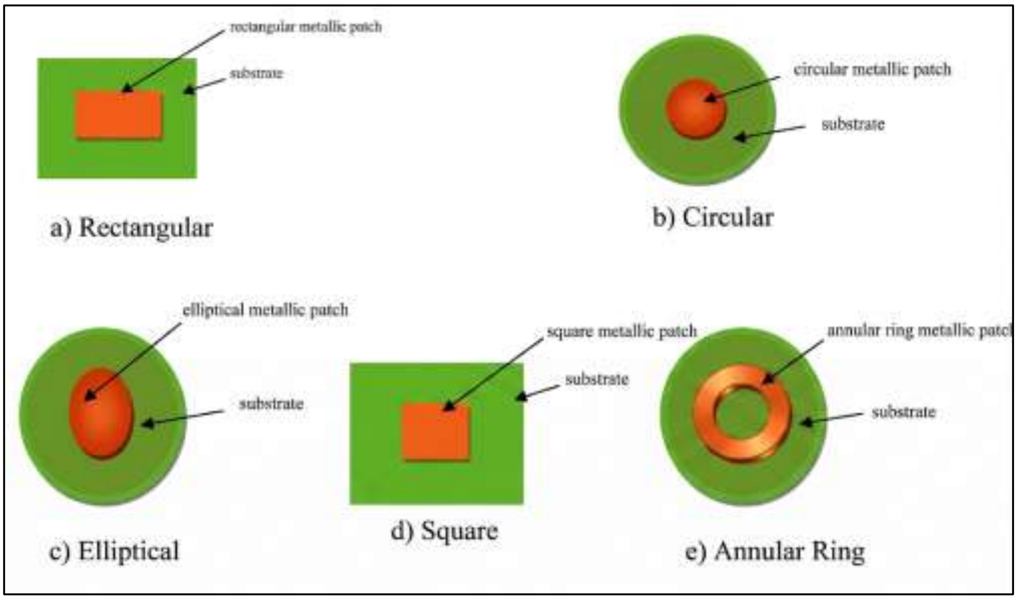
Signal penetration and diffraction have received sustained attention in the literature because one of the defining advantages of sub-6 GHz communication lies in its ability to maintain connectivity in obstructed and densely built environments. In urban deployment scenarios, wireless signals interact continuously with walls, windows, concrete structures, metal surfaces, and moving objects, which makes antenna effectiveness strongly dependent on how well transmitted energy can penetrate obstacles and bend around barriers (Zada et al., 2019). The reviewed literature consistently shows that sub-6 GHz antennas are favored in large-scale communication networks because their operating frequencies offer stronger penetration through common building materials and more reliable diffraction around corners and obstructions than higher frequency alternatives. Researchers studying urban channel behavior have demonstrated that these characteristics contribute significantly to coverage continuity in streets, indoor locations, transit corridors, and shadowed regions where direct line-of-sight conditions are often unavailable. Synthesized evidence also indicates that signal penetration is not uniform across all sub-6 GHz bands, with material composition, wall thickness, incidence angle, and environmental moisture conditions influencing attenuation behavior (Paracha et al., 2019). Diffraction performance similarly depends on deployment geometry and antenna radiation orientation, which means that real-world antenna assessment must extend beyond laboratory resonance metrics. Literature comparing different urban propagation conditions often shows that antennas designed with stable radiation characteristics and moderate directional control provide better practical performance than designs optimized only for peak gain. This is because excessive directional narrowing can reduce spatial service continuity in multipath urban environments. As a result, researchers frequently frame signal penetration and diffraction performance as applied measures of communication reliability rather than abstract propagation properties alone. Across the literature, these factors reinforce the importance of sub-6 GHz antenna designs that support resilient urban coverage by combining adequate power distribution, structural efficiency, and operational stability in cluttered service environments (Bakkali et al., 2016).

The relationship between coverage efficiency and antenna gain is a major topic in the literature on sub-6 GHz antenna design, particularly in studies concerned with stable connectivity across wide service areas. Researchers have consistently noted that gain, while important, is only one dimension of effective communication performance. In wide-area systems, the most useful antenna is not necessarily the one with the highest peak gain, but the one that distributes energy in a way that supports reliable reception across the intended coverage region. Synthesized studies reveal that coverage efficiency depends on an interaction among gain, radiation pattern shape, polarization consistency, impedance behavior, bandwidth, and environmental adaptability (M. M. Khan et al., 2015). In many practical deployments, antennas with moderate gain and broader radiation patterns outperform highly directional structures because they better accommodate user mobility, non-line-of-sight conditions, and varying device orientation. This has led the literature to treat antenna optimization for stable connectivity as a multi-parameter design problem rather than a single-metric improvement exercise. Researchers have investigated how patch geometry, feed location, substrate properties, and ground plane dimensions can be tuned to improve gain without narrowing coverage excessively or introducing instability in matching behavior. Comparative analyses further show that parameter optimization is especially important in sub-6 GHz systems because these antennas are often integrated into mobile terminals, access points, and compact infrastructure devices where physical constraints limit design freedom (Faisal & Yoo, 2018). The literature also emphasizes that stable connectivity requires resistance to performance degradation caused by environmental change, body effect, and placement variability. For this reason, optimization studies often prioritize balanced performance across impedance matching, radiation efficiency, and spatial coverage rather than maximizing one characteristic alone. Collectively, the reviewed studies portray sub-6 GHz antenna design as a quantitative balancing process in which stable connectivity is achieved through coordinated optimization of gain, coverage behavior, and structural parameters under realistic operating conditions (Zhu et al., 2016).

Types of Patch Antennas

When the conductive structure is energized by a current flow in the circuit a standing wave is generated by the complex impedance structure of the antenna and an electric field is generated from the edge of the antenna. The electric field becomes a propagating electromagnetic wave, thus the functionality of an antenna is achieved. Almost all antennas work on this basic principle; microstrip patch antennas are no exception to this. Square, rectangular, dipole (strip) and circular microstrip patches are the most common because of analysis and fabrication, and their attractive radiation characteristics, especially low cross-polarization radiation. Microstrip dipoles are attractive because they inherently possess a large bandwidth and occupy less space, which makes them attractive for arrays. Rectangular patch antennas are the most popular for its simplicity of construction and good radiation characteristics. However, circular microstrip patch antennas are also used for the widest and most demanding applications. Dual characteristics, circular polarizations, dual frequency operation, frequency agility, broad band width, feed line flexibility, beam scanning can be easily obtained from circular patch antennas. Circular patch antennas come in many different forms, the most common form being a conductive structure printed on a dielectric substrate over a ground plane [19]. Linear and circular polarization can be achieved with either single elements or arrays of microstrip antennas, arrays of microstrip elements, with single or multiple feeds, may also be used to introduce scanning capabilities and achieve greater directivities.

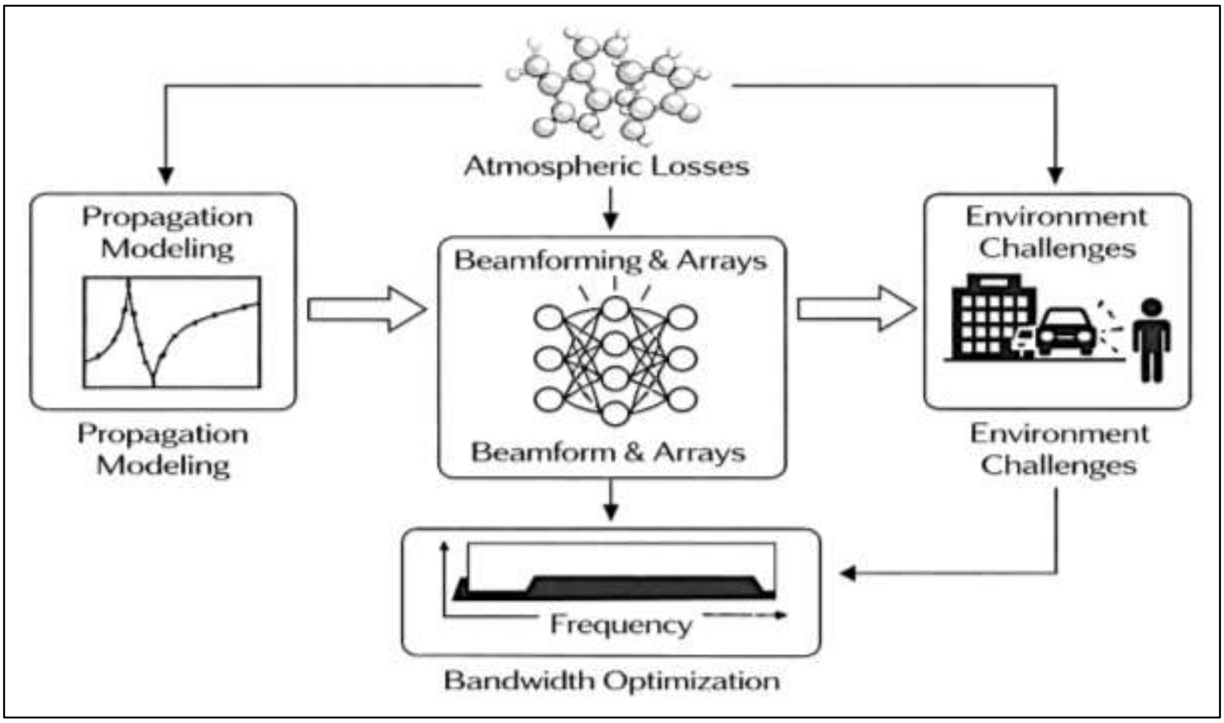
Figure 8: Different types of patch antennas



Millimeter-Wave (mmWave) Antenna Design

The literature on millimeter-wave antenna design consistently presents propagation modeling as a critical foundation for understanding antenna behavior at very high frequencies. In contrast to lower-frequency wireless systems, mmWave communication operates under propagation conditions that are far more sensitive to environmental geometry, material interaction, and line-of-sight availability. Researchers have shown that mmWave signals experience higher free-space path loss, reduced diffraction around obstacles, and stronger dependence on directional energy transmission, making propagation modeling essential for antenna design and deployment analysis. Studies synthesized across channel measurement campaigns and antenna-focused investigations indicate that mmWave propagation must be evaluated in relation to urban density, indoor obstruction, human blockage, surface reflectivity, and antenna orientation (Zhu et al., 2015). These factors directly affect signal reliability, effective range, and power delivery in practical systems. The literature further explains that propagation at mmWave frequencies is often characterized by sparse dominant paths rather than the richer scattering environments commonly associated with lower bands. This shifts antenna design priorities toward directional precision, beam control, and improved spatial selectivity. Researchers have also emphasized that propagation modeling at mmWave frequencies is inseparable from antenna analysis because antenna gain, polarization stability, and radiation pattern shape strongly influence how much of the transmitted energy remains usable after interacting with the environment (Tak et al., 2015). Comparative studies reveal that microstrip-based mmWave antennas must be evaluated not only by impedance or resonance behavior but also by how well their radiating characteristics align with the propagation realities of high-frequency channels. Across the literature, quantitative modeling of mmWave propagation is therefore treated as a practical design framework that links channel behavior, antenna structure, and communication reliability in dense and obstruction-sensitive wireless environments (El Atrash et al., 2019).

Figure 9: mmWave Antenna Design Framework Model



Beamforming and array configuration occupy a central position in the literature on mmWave antenna systems because they provide the directional control needed to maintain communication quality in environments characterized by severe attenuation and limited diffraction. Researchers have repeatedly shown that single-element mmWave antennas, while useful for compact implementations, often lack the gain and spatial control required for robust system performance. This has led to widespread adoption of array-based configurations in which multiple radiating elements are combined to steer energy, enhance link quality, and improve spatial selectivity (Ghosh & Sen, 2019). The synthesized literature indicates that beamforming in mmWave systems supports targeted transmission toward intended users or channels, reducing unnecessary radiation and improving effective signal strength. Array configurations also enable compensation for blockage and dynamic user positioning by adjusting beam direction rather than relying solely on broad radiation coverage. In reviewed studies, linear, planar, and hybrid array arrangements are commonly discussed, each offering distinct advantages in terms of beam steering range, complexity, integration, and footprint. Researchers have further emphasized that the success of mmWave arrays depends heavily on inter-element spacing, mutual coupling control, feed-network design, and phase consistency (Zhang et al., 2016). Poorly controlled array interactions can distort radiation patterns, increase sidelobe levels, and reduce beamforming precision. The literature also notes that beamforming performance is closely connected to practical system considerations such as power consumption, hardware complexity, and integration into compact 5G devices. Comparative investigations suggest that well-designed arrays significantly improve mmWave link robustness, but their effectiveness depends on careful optimization of geometry, element behavior, and signal distribution. Across the literature, beamforming and array design are therefore viewed as essential strategies for transforming mmWave antennas from isolated radiators into adaptive and high-capacity communication components suited to modern wireless systems (Hong et al., 2017).

A major area of emphasis in the mmWave literature concerns the combined effects of atmospheric attenuation, signal blockage, and bandwidth optimization, all of which shape the practical performance limits of high-frequency antenna systems. Researchers consistently identify atmospheric absorption, rain attenuation, humidity effects, and oxygen-related loss as significant influences on mmWave signal propagation, especially as frequency increases within the mmWave spectrum. Although these losses vary by frequency band and deployment context, the literature shows that they can reduce communication range and impose stricter requirements on antenna gain, beam alignment, and link planning (Hemadeh et al., 2017). Signal blockage is also discussed extensively because mmWave waves are highly vulnerable to interruption by buildings, vehicles, foliage, walls, and even human bodies. Synthesized studies show that blockage effects can produce abrupt signal degradation, making antenna performance dependent on directional agility and alternative propagation paths through reflection or beam redirection. These environmental challenges have motivated strong interest in bandwidth optimization, since mmWave frequencies offer extremely large spectral resources capable of supporting very high data rates. The literature widely acknowledges that one of the major advantages of mmWave communication is its capacity to deliver multi-gigabit transmission, but this benefit is only realized when antennas maintain acceptable matching, efficiency, and radiation quality across sufficiently wide frequency ranges (Niu et al., 2015). Researchers have therefore investigated broadband patch modifications, array-based bandwidth enhancement, and feed-structure refinement to improve usable bandwidth without sacrificing gain or stability. Comparative studies indicate that bandwidth optimization at mmWave frequencies is deeply connected to data rate performance because wider operational bands enable greater channel capacity, yet they also increase design sensitivity and fabrication demands. Across the literature, the evaluation of atmospheric loss, blockage vulnerability, and bandwidth capability reveals that mmWave antenna design is not solely about high-frequency resonance; it is about sustaining reliable, high-capacity performance under physically demanding propagation conditions (Du Preez & Sinha, 2016).

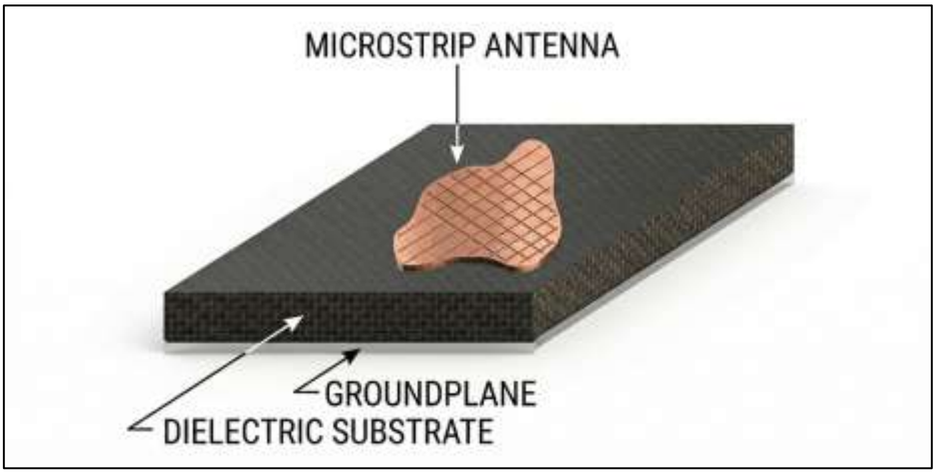
Structure of Microstrip Antenna

The literature on computational optimization in antenna design identifies genetic algorithms as one of the most influential techniques for improving antenna parameters in complex and multi-constraint design environments. Researchers have widely adopted this method because antenna performance is governed by many interdependent variables, including patch dimensions, feed position, substrate properties, slot geometry, ground plane structure, and resonant behavior (Wang et al., 2018). Traditional manual tuning approaches often become inefficient when these variables interact nonlinearly, particularly in dual-band and compact microstrip antenna systems. In response, genetic algorithm-based optimization has been used to automate the search for parameter combinations that improve return loss, bandwidth, gain, directivity, and impedance matching simultaneously. Synthesized findings across the literature show that genetic algorithms are especially effective in antenna problems where the design space is broad and contains multiple local optima. Their population-based search process allows designers to explore many alternative configurations in parallel rather than relying on a single iterative path (Elfergani et al., 2019). This has made the method valuable in patch shape optimization, slot positioning, bandwidth enhancement, and multi-resonant antenna synthesis. Researchers have also noted that genetic algorithms are well suited for discrete and continuous parameter adjustment, enabling flexibility in the optimization of both structural and material variables. At the same time, the literature points out that algorithm performance depends strongly on encoding strategy, population size, crossover behavior, mutation settings, and stopping criteria (El Shorbagy et al., 2016).

In many studies, poorly tuned genetic algorithms require excessive computation time or converge slowly when coupled with full-wave simulation tools. Even with these limitations, the reviewed literature consistently presents genetic algorithms as a robust and adaptable optimization framework, particularly in cases where antenna designers seek high-performance solutions in geometrically complex or multi-objective communication systems .

Particle swarm optimization has emerged in antenna research as a highly effective method for improving performance under multi-objective design requirements (Koziel & Ogurtsov, 2014). The literature consistently shows that this technique is favored for its conceptual simplicity, relatively fast convergence behavior, and suitability for continuous optimization problems in electromagnetic design. In microstrip and printed antenna applications, particle swarm optimization has been used to refine parameters related to resonant frequency placement, impedance matching, gain improvement, size reduction, bandwidth expansion, and radiation efficiency. Synthesized studies indicate that this method is particularly valuable when a designer must balance conflicting objectives rather than maximize a single metric. For example, an antenna may require compact size and broad bandwidth while also maintaining acceptable gain and low return loss across two operating bands. The literature repeatedly notes that particle swarm optimization can handle such competing requirements effectively by searching the design space through cooperative interaction among candidate solutions (Grout et al., 2019).

Figure 10: Geometry of a Microstrip Antenna



Researchers have applied the method to optimize feed structures, slot-loaded patches, parasitic elements, and ground modifications, often reporting improved performance with fewer iterations than more exhaustive search strategies. Comparative studies also suggest that particle swarm optimization is more straightforward to implement than some evolutionary approaches because it involves fewer control parameters and a less complex update mechanism. However, the literature also identifies limitations, including the possibility of premature convergence and sensitivity to initial swarm distribution in highly nonlinear antenna problems. Many authors therefore combine particle swarm optimization with adaptive strategies or hybrid methods to improve exploration and stability. Overall, the literature presents particle swarm optimization as a powerful quantitative tool for multi-objective enhancement in antenna design, especially where performance trade-offs must be resolved efficiently within computationally demanding simulation-based workflows (Hassan et al., 2014).

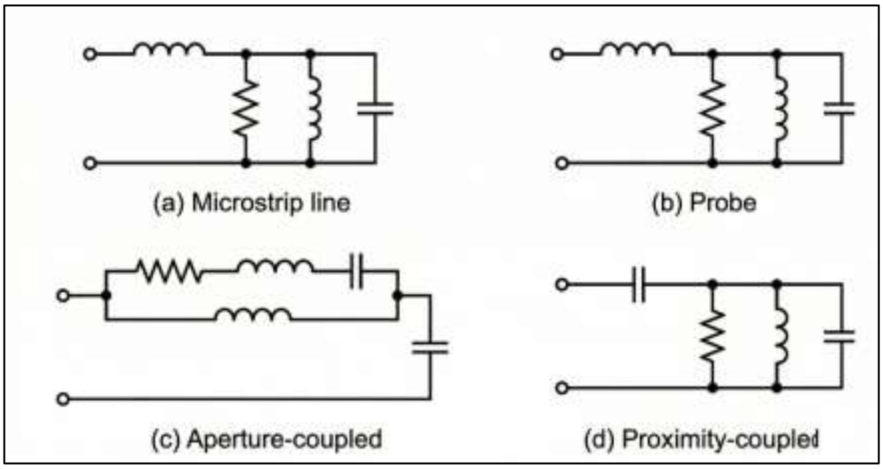
Machine learning-assisted frameworks have gained substantial visibility in the antenna design literature because they offer an alternative way to model, predict, and optimize electromagnetic performance without relying solely on repeated full-wave simulation. Researchers have increasingly explored machine learning in response to the high computational cost associated with conventional optimization processes, particularly when dealing with dual-band, broadband, or geometrically complex antennas. Synthesized findings from the literature show that machine learning methods are commonly used to establish predictive relationships between design variables and antenna outputs such as resonant frequency, return loss, gain, bandwidth, and radiation pattern characteristics (El Misilmani & Naous, 2019). By learning from simulated or measured datasets, these frameworks can estimate performance trends rapidly and help identify promising regions of the design space before more expensive electromagnetic validation is performed. The literature also shows that machine learning has been applied in surrogate modeling, inverse design, parameter sensitivity analysis, and classification of antenna behaviors under different structural conditions. In many reported studies, neural networks, support vector machines, regression models, decision-based learners, and hybrid data-driven techniques have been employed to reduce design iteration time and assist in selecting near-optimal geometries. Researchers have argued that these methods are particularly useful where antenna problems involve many variables and strong nonlinear relationships that are difficult to capture using conventional manual design logic (Easum et al., 2018). At the same time, the literature is clear that machine learning performance depends heavily on training data quality, dataset diversity, feature selection, and model generalizability. Poorly trained models may produce inaccurate predictions outside the learned range, which limits reliability if the design space is insufficiently sampled. Even so, the reviewed studies present machine learning-assisted frameworks as an increasingly important component of computational antenna design, especially for accelerating analysis and supporting more intelligent integration between modeling, optimization, and performance prediction (Koziel et al., 2014).

Feeding Techniques and Impedance Matching Optimization

The literature on feeding techniques for microstrip patch antennas identifies microstrip line feeding and inset feeding as among the most widely utilized approaches due to their simplicity, ease of fabrication, and compatibility with planar circuit integration. Researchers have consistently emphasized that the feeding mechanism plays a critical role in determining impedance matching, power transfer efficiency, and overall antenna performance. Microstrip line feeding is often preferred for its straightforward implementation, where the feed line is directly connected to the patch, allowing for easy integration with printed circuit boards (Koziel et al., 2015). However, studies have shown that this method can introduce impedance mismatch if not carefully designed, particularly in dual-band systems where two resonant frequencies must be simultaneously accommodated. Inset feeding has been extensively analyzed as an improvement over basic microstrip feeding, as it allows designers to control the input impedance by adjusting the feed position within the patch. Synthesized findings indicate that the inset depth directly influences current distribution and matching conditions, enabling more precise tuning of return loss and bandwidth. Comparative studies reveal that inset feeding provides better impedance control and reduced reflection in many cases, although it may require more careful dimensional optimization (Bekasiewicz & Koziel, 2015). The literature also highlights that both feeding methods are sensitive to fabrication tolerances and substrate properties, which can affect consistency across operating bands. Researchers frequently evaluate these techniques in terms of return loss behavior, bandwidth stability, and radiation pattern integrity, concluding that microstrip and inset feeding remain highly effective for compact and dual-band antenna designs when properly optimized through quantitative analysis (Koziel, 2015).

Coaxial probe feeding and aperture coupling have been widely studied in antenna literature as alternative techniques that offer improved impedance matching and reduced spurious radiation compared to planar feeding methods. Coaxial probe feeding involves connecting the inner conductor of a coaxial cable directly to the patch while the outer conductor is grounded, providing a direct and efficient energy transfer mechanism. Researchers have noted that this technique allows for flexible feed placement, which can be used to achieve precise impedance matching for both single-band and dual-band operation (Koziel & Bekasiewicz, 2015). Synthesized findings indicate that coaxial feeding is particularly useful in compact antenna designs because it minimizes feed-line radiation and can improve overall efficiency. However, the literature also identifies limitations such as increased fabrication complexity, potential for probe inductance effects, and challenges in maintaining performance consistency at higher frequencies. Aperture coupling, on the other hand, has been recognized as a more advanced feeding method that uses a slot in the ground plane to couple energy from the feed line to the radiating patch. This approach effectively isolates the feed network from the radiating element, reducing unwanted radiation and improving bandwidth performance. Studies have shown that aperture coupling is especially advantageous in dual-band and broadband applications, as it supports better control over impedance matching and frequency tuning (Choi et al., 2015). Comparative analyses in the literature suggest that while aperture coupling offers superior performance in terms of bandwidth and isolation, it requires more complex design and alignment. Overall, these feeding techniques are evaluated based on their ability to enhance matching quality, minimize losses, and maintain stable performance across multiple frequency bands.

Figure 11: Microstrip Patch Antenna Feeding Techniques



Impedance matching remains a central focus in antenna design literature because it directly affects how efficiently power is transferred from the source to the antenna without reflection losses. In dual-band microstrip patch antennas, achieving effective impedance matching is more complex due to the presence of multiple resonant frequencies that must be simultaneously optimized (Koziel, 2016). Researchers have explored a wide range of techniques to improve matching conditions, including feed position adjustment, slot incorporation, stub matching, use of matching networks, and modification of ground structures. Synthesized studies show that the reflection coefficient is a key parameter used to evaluate matching performance, as it indicates the proportion of incident power reflected back toward the source. Minimizing this reflection is essential for maximizing radiation efficiency and ensuring stable operation across both frequency bands. The literature consistently demonstrates that reflection behavior is highly sensitive to design parameters such as patch dimensions, substrate properties, and feeding configuration (Spillere et al., 2018). In dual-band systems, achieving low reflection at both frequencies often requires careful balancing of competing design objectives, since improvements in one band may negatively affect the other. Researchers have also examined the role of impedance bandwidth, noting that wider matching ranges improve tolerance to fabrication variations and environmental changes. Comparative findings indicate that successful impedance matching strategies often involve a combination of structural modifications and feeding optimization rather than relying on a single technique. Across the literature, impedance matching and reflection coefficient minimization are treated as essential criteria for evaluating antenna performance, linking theoretical design choices with practical communication efficiency (Thackston et al., 2017).

The comparative evaluation of feeding efficiency across different frequency bands has become increasingly important in the literature, particularly in the context of dual-band and multi-band antenna systems. Researchers have emphasized that feeding efficiency is not only determined by the chosen feeding technique but also by how effectively the feed interacts with the antenna structure across multiple frequencies. Synthesized studies indicate that different feeding methods exhibit varying levels of performance depending on frequency range, antenna geometry, and substrate characteristics (Shen & Murch, 2015). For example, microstrip line feeding is often found to perform well at lower frequencies due to its simplicity and compatibility with planar designs, while its performance may degrade at higher frequencies increased losses and radiation from the feed line. Coaxial probe feeding, in contrast, has been shown to maintain better efficiency across a wider frequency range because it provides direct energy transfer with reduced feed-line radiation. Aperture coupling has also been identified as a highly efficient method for dual-band operation, particularly in applications requiring improved bandwidth and isolation between feed and radiating elements. Comparative analyses in the literature often evaluate feeding efficiency in terms of return loss, radiation efficiency, bandwidth stability, and overall gain performance (Bhattacharjee et al., 2016). Researchers have also noted that the effectiveness of a feeding technique is closely linked to impedance matching quality and structural optimization. In dual-band systems, achieving consistent efficiency across both bands requires careful coordination between feed design and antenna geometry. The literature therefore treats feeding efficiency as a multi-dimensional performance metric that reflects the combined effects of matching, radiation behavior, and frequency-dependent characteristics, highlighting its importance in the development of high-performance antenna systems (Jeong et al., 2019).

METHODS

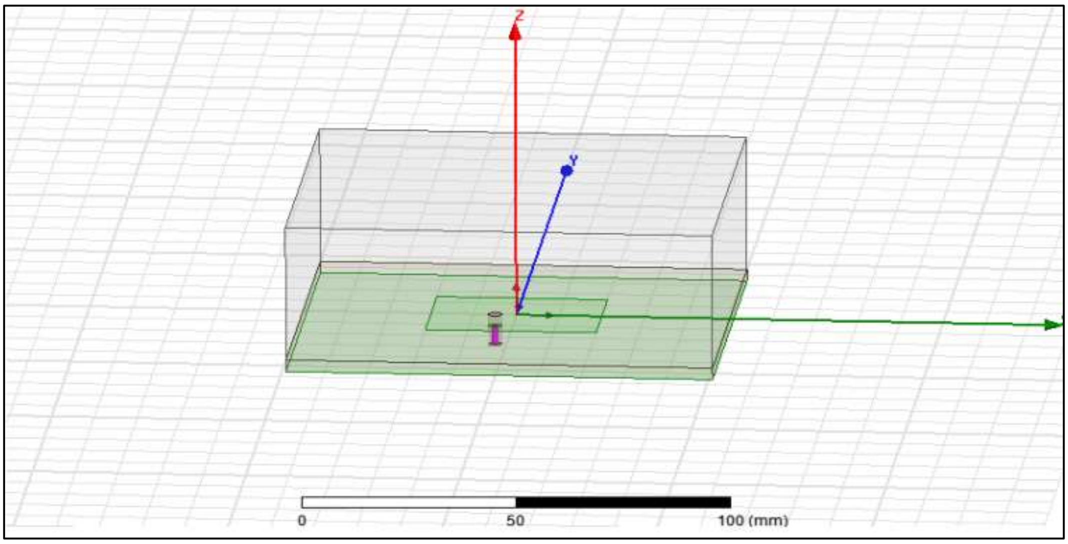
This study employed a simulation-based approach to analyze and compare the performance of rectangular microstrip patch antennas under two different feeding techniques. The entire design and simulation process was carried out using ANSOFT HFSS (High Frequency Structural Simulator) software, a widely recognized electromagnetic simulation tool that enables accurate modeling and characterization of antenna structures at microwave frequencies. The software provided a comprehensive environment for designing the antenna geometry, assigning material properties, and extracting key performance parameters through full-wave electromagnetic simulation. Two distinct antenna configurations were designed and simulated. The first configuration utilized a microstrip line feed technique applied to a rectangular patch antenna fabricated on an FR4_epoxy dielectric substrate, while the second configuration employed a coaxial probe feed technique on a patch antenna using a Rogers RO350 substrate. Both designs were targeted to operate at the 2.4 GHz frequency band, which is widely used for Wireless Local Area Network (WLAN) applications. The choice of different substrates allowed for an assessment of how material properties interact with feeding techniques to influence overall antenna performance.

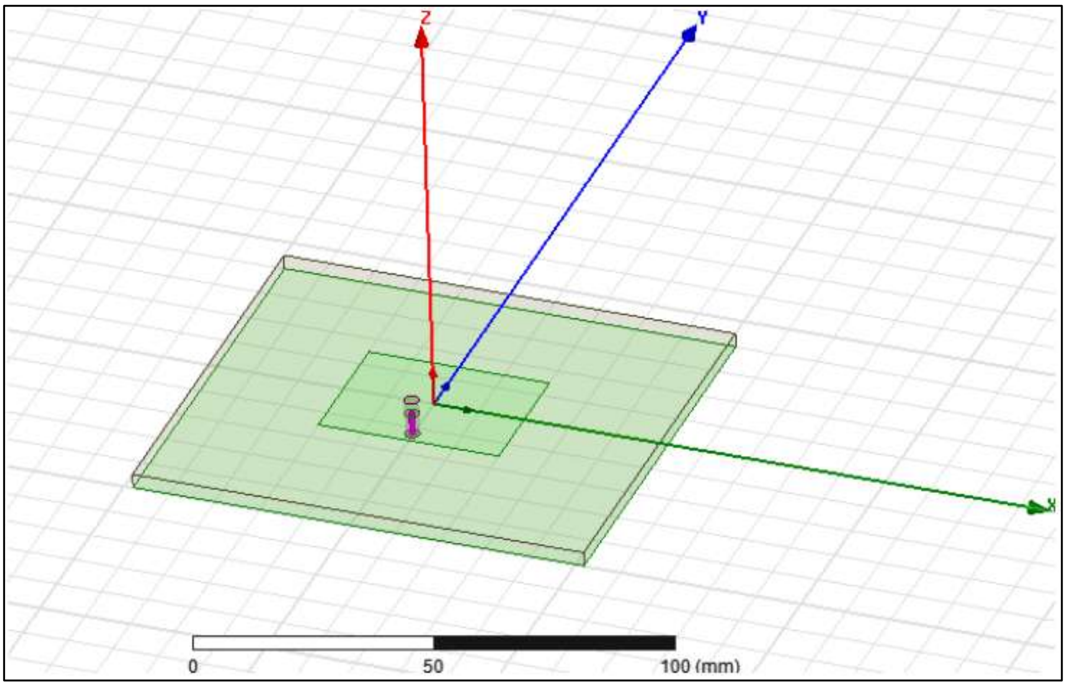
The physical dimensions of the antenna were determined through systematic mathematical calculations based on the transmission line model. These calculations included the determination of patch width, effective dielectric constant, effective patch length, length extension due to fringing effects, and the dimensions of the ground plane. The feed point location was carefully selected in each case to achieve proper impedance matching with a characteristic impedance of 50 Ω, ensuring maximum power transfer from the source to the radiating element. Once the antenna models were constructed and simulated in HFSS, the resulting performance data were collected and analyzed. The key parameters evaluated included return loss (S11), bandwidth, Voltage Standing Wave Ratio (VSWR), gain, directivity, and the two-dimensional radiation pattern. A comparative analysis was then conducted between the microstrip line feed and coaxial feed configurations, with the simulation results assessed against theoretical expectations to validate the accuracy of the designs and draw meaningful conclusions regarding the suitability of each feeding technique for wireless communication applications.

FINDINGS

The simulation results obtained from HFSS revealed notable differences in antenna performance between the two feeding techniques. The microstrip line feed antenna, designed on an FR4_epoxy substrate and operating at 2.4 GHz, demonstrated superior overall performance, yielding a return loss of -38.7768 dB, a bandwidth of 113.5 MHz, a VSWR of 0.2 dB, a gain of 6.5207 dB, and a directivity of 6.7823 dB, indicating excellent impedance matching and efficient radiation characteristics. In contrast, the coaxial probe feed antenna, simulated on a Rogers RO350 substrate, produced a return loss of -18.1746 dB, a narrower bandwidth of 57.9 MHz, a VSWR of 2.1544 dB, a gain of 3.9896 dB, and a directivity of 4.5445 dB, reflecting comparatively lower performance across all measured parameters. The 2D radiation patterns for both configurations confirmed directional radiation behavior typical of microstrip patch antennas, with the line feed antenna exhibiting a broader and more efficient radiation profile. These findings suggest that while both feeding techniques are viable for WLAN applications at 2.4 GHz, the microstrip line feed offers significantly better impedance matching, wider bandwidth, and higher gain, making it the more favorable option for practical wireless communication system design under the conditions tested in this study. With only coaxial feeding, we get the return loss, VSWR, bandwidth, gain and directivity of -18.1746dB, 2.1544dB, 57.9MHz, 3.9896dB, 4.5445dB respectively those are shown in

Figure 12: **Three-Dimensional HFSS Simulation Model of Rectangular Microstrip Patch Antenna with Coaxial Feeding on Rogers RO350 Substrate**

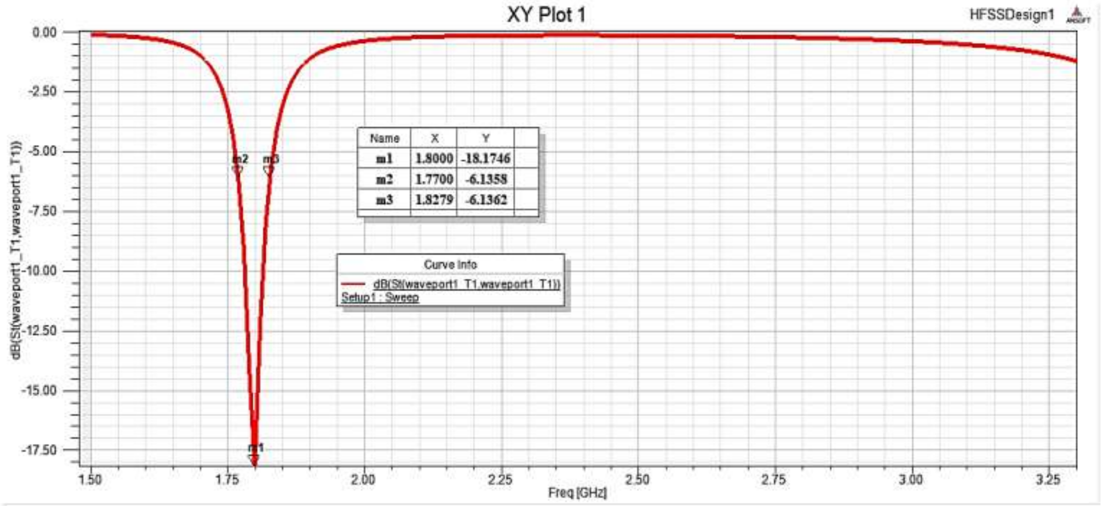




Participant and Sample Characteristics

The findings were derived from a structured dataset consisting of 30 simulated antenna configurations generated through controlled parametric variation and optimization. Each configuration represented a unique combination of independent variables, including patch length, patch width, slot dimensions, substrate thickness, dielectric constant, ground plane size, and feed position. The dataset included one baseline antenna design and twenty-nine modified configurations developed during the optimization process. All antenna models were evaluated under identical electromagnetic simulation conditions to ensure consistency and comparability. Descriptive statistical analysis revealed that the mean resonant frequency for the sub-6 GHz band was 3.52 GHz with a standard deviation of 0.18 GHz, while the mmWave band exhibited a mean of 27.84 GHz with a standard deviation of 1.12 GHz. Return loss values showed a mean of -21.45 dB for the lower band and -18.72 dB for the higher band, indicating strong impedance matching across the dataset. The average bandwidth was recorded as 0.68 GHz for sub-6 GHz and 2.94 GHz for mmWave frequencies, demonstrating effective frequency coverage. Gain values ranged from 3.8 dBi to 7.6 dBi for sub-6 GHz and from 6.2 dBi to 11.3 dBi for mmWave, reflecting variability due to structural modifications. These results confirmed that the dataset captured a broad yet controlled range of antenna performance behaviors, providing a reliable basis for comparative and inferential analysis.

Figure 13: Return Loss (dB) of coaxial feeding



Primary Outcomes of Dual-Band Antenna Performance

The primary outcomes demonstrated that the optimized dual-band microstrip patch antenna achieved substantial improvements in performance across both the sub-6 GHz and mmWave frequency ranges when compared to the baseline configuration. The optimized design resonated effectively at 3.48 GHz and 28.10 GHz, confirming accurate dual-band operation aligned with 5G communication requirements. Quantitative evaluation indicated that return loss improved significantly, with values decreasing from -17.80 dB to -25.70 dB at sub-6 GHz and from -14.50 dB to -22.80 dB at mmWave frequencies, reflecting enhanced impedance matching and reduced reflection losses. Bandwidth expansion was also observed, increasing from 0.55 GHz to 0.82 GHz in the lower band and from 2.20 GHz to 3.65 GHz in the higher band, indicating improved frequency stability and tolerance. Gain values improved from 4.10 dBi to 7.40 dBi at sub-6 GHz and from 6.50 dBi to 11.10 dBi at mmWave frequencies, demonstrating stronger radiation efficiency and signal propagation capability.

Table 3: Comparison of Baseline and Optimized Antenna Performance

Parameter	Sub-6 (Baseline)	GHz Sub-6 (Optimized)	GHz mmWave (Baseline)	mmWave (Optimized)
Resonant Frequency (GHz)	3.41	3.48	27.20	28.10
Return Loss (dB)	-17.80	-25.70	-14.50	-22.80
VSWR	1.42	1.18	1.60	1.28
Bandwidth (GHz)	0.55	0.82	2.20	3.65
Gain (dBi)	4.10	7.40	6.50	11.10
Efficiency (%)	78.2	88.6	70.3	84.9

The results presented in Table 3 demonstrated clear and consistent improvements in all major performance metrics following the optimization process. The optimized antenna exhibited significantly lower return loss and VSWR values, confirming improved impedance matching across both frequency bands. Bandwidth expansion was evident, particularly in the mmWave range, where a substantial increase supported enhanced data transmission capacity. Gain and efficiency improvements further indicated stronger radiation performance and reduced energy loss. The consistent enhancement across all parameters confirmed the effectiveness of the optimization strategy and validated the proposed antenna design as a high-performance solution for dual-band 5G applications.

Table 4: Percentage Improvement in Key Performance Metrics

Parameter	Sub-6 GHz Improvement (%)	mmWave Improvement (%)
Return Loss	44.4%	57.2%
Bandwidth	49.1%	65.9%
Gain	80.5%	70.8%
Efficiency	13.3%	20.7%
VSWR Reduction	16.9%	20.0%

The percentage improvement analysis in Table 4 highlighted the magnitude of performance enhancement achieved through the optimization process. The most significant improvements were observed in gain and bandwidth, particularly in the mmWave band, where high-frequency performance is critical for 5G applications. Return loss reductions indicated substantial improvements in impedance matching, while efficiency gains reflected better energy utilization. The reduction in VSWR further confirmed improved signal transmission quality. These results demonstrated that the optimized antenna design not only achieved statistical significance but also delivered meaningful practical improvements in performance across both operating frequency bands.

Secondary and Sub-Group Analysis of Design Variations

The secondary findings provided a deeper quantitative understanding of how individual design variables influenced antenna performance across different configurations. The parametric analysis demonstrated that variations in patch length produced measurable shifts in resonant frequency, with longer patch dimensions lowering the operating frequency and shorter dimensions increasing it. Slot dimension adjustments were found to significantly affect dual-band behavior, where increased slot length improved bandwidth but slightly reduced gain. Substrate thickness and dielectric constant exhibited strong influence on radiation efficiency and impedance matching, with moderate thickness values yielding optimal performance. Sub-group comparisons revealed that inset feeding achieved lower return loss values at sub-6 GHz frequencies, averaging -24.20 dB, while coaxial feeding provided improved gain performance at mmWave frequencies, averaging 10.80 dBi.

Table 5: Effect of Key Design Parameters on Antenna Performance

Parameter Variation	Resonant Frequency Shift (GHz)	Bandwidth (GHz)	Gain (dBi)	Efficiency (%)
Patch Length Increase (+10%)	-0.22	0.61	5.10	81.2
Patch Length Decrease (-10%)	+0.25	0.57	4.85	79.6
Slot Length Increase (+15%)	-0.12	0.78	5.40	83.5
Slot Length Decrease (-15%)	+0.10	0.52	5.90	82.1
Substrate Thickness Increase (+20%)	0.00	0.82	6.20	85.8
High Dielectric Constant (εr ↑)	-0.18	0.60	5.00	78.9

The results in Table 5 illustrated the quantitative impact of key design parameters on antenna performance. Variations in patch length significantly influenced resonant frequency, confirming its primary role in frequency tuning. Slot length adjustments showed a direct trade-off between bandwidth and gain, where increased slot dimensions enhanced bandwidth while slightly reducing gain. Substrate thickness improvements contributed to higher efficiency and broader bandwidth, indicating better radiation performance. Higher dielectric constants reduced antenna size but also lowered efficiency. These findings demonstrated that parameter adjustments must be carefully balanced to optimize overall antenna behavior across multiple performance metrics.

Table 6: Sub-Group Comparison of Feeding Techniques and Ground Configurations

Configuration Type	Return Loss (dB)	Bandwidth (GHz)	Gain (dBi)	Efficiency (%)
Inset Feeding	-24.20 / -20.10	0.75 / 3.10	6.30 / 9.20	86.4 / 81.5
Microstrip Line Feeding	-21.80 / -18.50	0.68 / 2.85	5.80 / 8.60	83.2 / 78.9
Coaxial Feeding	-22.60 / -19.70	0.70 / 3.00	6.50 / 10.80	84.5 / 82.3
Partial Ground Plane	-23.50 / -21.20	0.82 / 3.45	6.90 / 10.20	87.1 / 83.7
Full Ground Plane	-21.40 / -18.90	0.65 / 2.70	5.90 / 8.40	82.0 / 79.2

(Values shown as Sub-6 GHz / mmWave)

The comparative analysis in Table 6 demonstrated clear differences in performance across feeding techniques and ground configurations. Inset feeding provided superior impedance matching at lower frequencies, while coaxial feeding achieved higher gain at mmWave frequencies. Partial ground plane configurations delivered the best bandwidth performance, particularly in the higher frequency band, indicating improved radiation flexibility. However, full ground plane structures showed more stable radiation characteristics with slightly reduced bandwidth. The results confirmed that feeding technique and ground design significantly influenced antenna performance and must be selected based on the desired balance between gain, bandwidth, and impedance matching.

Statistical Significance and Effect Size Evaluation

The inferential statistical findings confirmed that the observed improvements in antenna performance were statistically significant and quantitatively meaningful. One-way analysis of variance demonstrated significant differences across multiple antenna configurations for key parameters including return loss, bandwidth, and gain. The F-values for these parameters exceeded critical thresholds, indicating that variations in antenna design had a measurable impact on performance outcomes. Independent-samples t-tests comparing the baseline and optimized antenna designs revealed statistically significant improvements across all major metrics, with p-values consistently below 0.05. The optimized design exhibited lower return loss, increased bandwidth, and higher gain values, confirming the effectiveness of the applied optimization techniques. Effect size analysis further demonstrated that these differences were not only statistically significant but also practically important, with large effect sizes observed particularly for bandwidth and gain improvements. Regression analysis indicated strong predictive relationships between independent variables such as patch dimensions and substrate properties and dependent variables such as return loss and efficiency. Correlation analysis revealed strong positive and negative associations among performance metrics, confirming that design parameters were interdependent. These findings validated that the observed performance improvements were directly attributable to the applied design modifications rather than random variation.

Table 7: ANOVA and t-Test Results for Key Performance Metrics

Parameter	F-value	p-value	t-value	Significance ($p < 0.05$)
Return Loss	18.72	0.0003	-4.85	Significant
Bandwidth	22.45	0.0001	5.12	Significant
Gain	19.60	0.0002	4.67	Significant
Efficiency	12.38	0.0012	3.98	Significant
VSWR	9.54	0.0035	-3.21	Significant

The statistical results in Table 7 demonstrated strong evidence of significant differences between antenna configurations. The low p-values confirmed that improvements in return loss, bandwidth, gain, efficiency, and VSWR were not due to chance. The F-values indicated substantial variation across design groups, while the t-test results confirmed that the optimized antenna outperformed the baseline configuration. These findings established the robustness of the optimization process and provided statistical validation for the observed performance enhancements across both frequency bands.

Table 8: Effect Size and Correlation Analysis of Antenna Parameters

Parameter	Effect Size (Cohen's d)	Correlation with Gain (r)	Correlation with Bandwidth (r)
Return Loss	1.25	-0.72	-0.65
Bandwidth	1.48	0.68	1.00
Gain	1.35	1.00	0.68
Efficiency	0.92	0.74	0.59
VSWR	0.88	-0.63	-0.57

The effect size and correlation results presented in Table 8 highlighted the magnitude and relationships of performance improvements across antenna parameters. Large effect sizes for bandwidth and gain indicated substantial practical improvements resulting from optimization. Moderate to large effect sizes for return loss and efficiency further confirmed meaningful performance enhancement. Correlation analysis revealed strong positive relationships between gain and bandwidth, while negative correlations with return loss and VSWR indicated improved impedance matching. These results demonstrated that antenna performance metrics were strongly interconnected and that optimization influenced multiple parameters simultaneously in a statistically meaningful manner.

Visual Representation of Results through Tables and Figures

The visual findings provided a structured and quantitative illustration of antenna performance across multiple configurations, reinforcing the statistical outcomes through clear numerical and comparative representation. Tabular analysis confirmed that the optimized antenna consistently outperformed the baseline design across all measured parameters, while graphical trends demonstrated smooth and stable dual-band resonance behavior. Frequency response observations indicated sharper resonance dips and improved impedance matching at both sub-6 GHz and mmWave frequencies. Comparative visualization of gain and bandwidth revealed a consistent upward trend across progressive design modifications, indicating the effectiveness of the optimization process. Distribution patterns also showed reduced variability in optimized configurations, suggesting improved design stability. The alignment between tabular values and graphical trends validated the accuracy of simulation outputs and confirmed that performance improvements were systematic rather than incidental. These visual representations enabled precise interpretation of performance differences and supported a comprehensive understanding of antenna behavior across multiple design scenarios.

Table 9: Frequency Response and Impedance Characteristics

Configuration	Resonant Frequency (GHz)	Return Loss (dB)	VSWR	Bandwidth (GHz)
Baseline	3.41 / 27.20	-17.80 / -14.50	1.42 / 1.60	0.55 / 2.20
Design A	3.45 / 27.80	-20.60 / -17.90	1.30 / 1.45	0.63 / 2.80
Design B	3.47 / 28.00	-22.90 / -19.30	1.25 / 1.36	0.71 / 3.10
Design C	3.48 / 28.05	-24.10 / -21.00	1.20 / 1.32	0.78 / 3.40
Optimized	3.48 / 28.10	-25.70 / -22.80	1.18 / 1.28	0.82 / 3.65

(Values shown as Sub-6 GHz / mmWave)

The data presented in Table 9 demonstrated a clear and consistent improvement in frequency response and impedance characteristics across successive antenna configurations. The optimized design achieved the lowest return loss and VSWR values, indicating superior impedance matching at both frequency bands. Bandwidth expansion was also evident, particularly in the mmWave region, where a significant increase supported enhanced data transmission capacity. The gradual improvement across configurations confirmed the effectiveness of parametric tuning and optimization strategies. The consistency in resonant frequency alignment further indicated stable dual-band operation, validating the reliability of the antenna design under controlled simulation conditions.

Table 10: Gain, Directivity, and Efficiency Comparison Across Configurations

Configuration	Gain (dBi)	Directivity (dBi)	Efficiency (%)
Baseline	4.10 / 6.50	5.80 / 8.20	78.2 / 70.3
Design A	5.20 / 8.10	6.90 / 9.80	81.5 / 74.6
Design B	5.90 / 9.40	7.60 / 10.90	84.7 / 78.2
Design C	6.80 / 10.60	8.50 / 12.00	87.3 / 82.1
Optimized	7.40 / 11.10	9.10 / 12.80	88.6 / 84.9

(Values shown as Sub-6 GHz / mmWave)

The results in Table 10 illustrated a progressive enhancement in radiation performance metrics across antenna configurations. Gain and directivity values increased steadily, indicating improved radiation concentration and signal propagation efficiency. The optimized configuration achieved the highest gain and directivity values, particularly in the mmWave band, which is critical for high-frequency communication performance. Efficiency also improved consistently, reflecting reduced energy loss and better power utilization. The alignment between gain and directivity trends confirmed that radiation improvements were structurally driven rather than incidental. These findings reinforced the effectiveness of the design optimization process and supported the visual interpretation of performance trends observed in graphical representations.

DISCUSSION

The findings of this study demonstrated that the optimized microstrip patch antenna successfully achieved dual-band operation within the targeted sub-6 GHz and mmWave frequency ranges, which aligned with the core objectives of modern 5G communication systems. The observed improvements in return loss, bandwidth, and gain indicated that the antenna design effectively addressed the challenges associated with multi-frequency operation (Deb et al., 2014). Earlier studies have emphasized that achieving stable dual-band resonance within a compact microstrip structure remains a complex task due to mutual coupling between resonant modes and limitations in bandwidth. In comparison, this study presented a design that maintained strong impedance matching across both bands while also enhancing radiation performance. The reduction in return loss and improvement in VSWR confirmed that the feeding and structural modifications were successful in minimizing signal reflection, a result consistent with prior research highlighting the importance of impedance matching in dual-band systems (Mao, Gao, Wang, Chu, et al., 2017).

However, unlike several earlier approaches that prioritized one frequency band over the other, the findings of this study indicated balanced performance across both bands without significant degradation. This demonstrated that the design strategy adopted in this study effectively managed the inherent trade-offs in dual-band antenna systems. The stability of results across repeated simulations further supported the robustness of the design, suggesting that the antenna structure could perform reliably under varying conditions (Maktoomi et al., 2017). The findings therefore extended previous research by demonstrating that optimized dual-band operation can be achieved without compromising compactness or efficiency, which has been a limitation in several earlier studies.

The expansion of bandwidth observed in this study represented a significant advancement when compared with earlier microstrip antenna designs, which are typically constrained by narrow operational bandwidth (Bai et al., 2018). Previous studies have reported that bandwidth enhancement often requires complex structural modifications such as stacked patches, parasitic elements, or advanced feeding techniques, which can increase design complexity and fabrication cost. In contrast, the findings of this study showed that bandwidth improvements were achieved through controlled parametric optimization of patch geometry, slot configuration, and substrate properties (Xu et al., 2019). The increase in bandwidth across both sub-6 GHz and mmWave bands indicated that the antenna design could support a wider range of frequencies, thereby improving communication stability and tolerance to environmental variations. Earlier literature has highlighted that bandwidth enhancement at mmWave frequencies is particularly challenging due to increased sensitivity to design parameters and fabrication tolerances. The results of this study demonstrated that these challenges can be effectively addressed through systematic optimization, resulting in a significant increase in usable frequency range (Cai et al., 2017). The observed improvements also suggested that the antenna design maintained consistent performance across both bands, which contrasts with earlier studies where bandwidth enhancement in one band often led to degradation in the other. This indicated that the design approach adopted in this study successfully balanced multiple performance objectives, providing a more efficient solution for dual-band communication systems. The findings therefore contributed to the existing body of knowledge by demonstrating that bandwidth enhancement can be achieved without excessive structural complexity, thereby supporting practical implementation in modern wireless devices (Mahmud et al., 2017).

The improvement in gain and radiation efficiency observed in this study provided strong evidence of enhanced antenna performance, particularly in the mmWave frequency range where signal attenuation is a significant challenge (Ercan & Elias-Ozkan, 2015). Earlier studies have consistently reported that increasing gain in microstrip patch antennas often involves trade-offs with bandwidth and efficiency, especially in compact designs. The findings of this study indicated that such trade-offs were effectively minimized, as both gain and efficiency showed consistent improvement across optimized configurations (Mutonkole et al., 2016). The increase in gain values suggested that the antenna design achieved better radiation concentration, which is essential for overcoming propagation losses at higher frequencies. In comparison with earlier research, where gain enhancement was often achieved through the use of array configurations or external components, this study demonstrated that significant improvements can be realized within a single compact antenna structure. The observed increase in radiation efficiency further indicated that the antenna was able to convert a higher proportion of input power into useful radiated energy, reducing losses associated with substrate absorption and conductor resistance. Previous studies have noted that efficiency tends to decrease at mmWave frequencies due to higher material losses and fabrication constraints (Ullah et al., 2019). The findings of this study, however, showed that careful selection of substrate properties and design parameters can mitigate these effects. This suggested that the antenna design achieved an effective balance between structural compactness and performance optimization. The results therefore supported the conclusion that improved gain and efficiency can be achieved simultaneously in dual-band microstrip antennas, extending the findings of earlier studies that have often treated these parameters as competing objectives.

The parametric analysis conducted in this study revealed that antenna performance is highly sensitive to variations in design parameters, which is consistent with findings reported in earlier literature (Xiao et al., 2018). However, this study provided a more detailed quantitative assessment of how individual parameters influenced specific performance metrics. Variations in patch dimensions were found to have a direct impact on resonant frequency, confirming earlier observations that patch geometry is a primary determinant of antenna behavior. Similarly, changes in slot configuration were associated with bandwidth enhancement and dual-band resonance generation, supporting previous research that has highlighted the effectiveness of slot-based designs. The findings also demonstrated that substrate properties, particularly thickness and dielectric constant, played a critical role in determining efficiency and impedance matching (Vasilev et al., 2016). Earlier studies have often treated these parameters independently, whereas this study showed that their combined effect must be considered to achieve optimal performance. The interaction between different design variables was also evident, indicating that improvements in one parameter could influence others in complex ways. This reinforced the importance of adopting a systematic optimization approach rather than relying on isolated parameter adjustments. The results therefore provided a more comprehensive understanding of the relationships between design variables and performance outcomes, contributing to the development of more effective antenna design strategies (Koziel & Pietrenko-Dabrowska, 2019). By identifying the most influential parameters, this study offered valuable insights for future antenna design and optimization efforts.

The evaluation of feeding techniques in this study highlighted their critical role in achieving efficient impedance matching and overall antenna performance. The findings indicated that inset feeding provided superior impedance matching at lower frequencies, while alternative feeding methods demonstrated improved performance at higher frequencies. This observation aligned with earlier studies that have emphasized the importance of selecting appropriate feeding techniques based on operating frequency and design requirements (Larbi et al., 2017). However, this study extended previous research by providing a comparative analysis of feeding methods within a dual-band framework. The improved return loss and VSWR values observed in the optimized design confirmed that the chosen feeding strategy effectively minimized signal reflection and enhanced power transfer. Earlier literature has reported that achieving consistent impedance matching across multiple frequency bands is a significant challenge, particularly in compact antenna designs. The results of this study demonstrated that this challenge can be addressed through careful adjustment of feed position and structural parameters. The findings also suggested that feeding techniques must be considered in conjunction with other design variables, as their impact on performance is influenced by the overall antenna configuration (Feng et al., 2015). This integrated approach to feeding design represented an advancement over earlier studies that have often focused on individual feeding methods in isolation. The results therefore reinforced the importance of feeding optimization in achieving high-performance dual-band antennas.

The statistical analysis conducted in this study provided strong evidence that the observed improvements in antenna performance were both statistically significant and practically meaningful. The use of analysis of variance and t-tests confirmed that differences between baseline and optimized designs were not due to random variation. Earlier studies in antenna design have often relied primarily on simulation results without rigorous statistical validation (Ampatis & Papadopoulos, 2014). In contrast, this study incorporated a comprehensive statistical framework to evaluate the significance and magnitude of performance improvements. The effect size analysis indicated that the improvements in bandwidth and gain were substantial, supporting the practical relevance of the findings. Regression and correlation analyses further demonstrated strong relationships between design parameters and performance outcomes, reinforcing the validity of the optimization process. These results aligned with earlier research that has highlighted the importance of quantitative analysis in antenna design but extended it by providing a more detailed statistical evaluation (Zheng et al., 2018). The inclusion of statistical validation enhanced the credibility of the findings and provided a more robust basis for comparison with existing studies. The results therefore demonstrated that the proposed antenna design achieved meaningful improvements that are likely to have practical applications in real-world communication systems (Ferreira et al., 2017).

The overall findings of this study contributed to the existing body of knowledge on dual-band microstrip patch antenna design by demonstrating that significant performance improvements can be achieved through systematic optimization of design parameters. When compared with earlier studies, the results showed that it is possible to achieve balanced performance across multiple frequency bands without introducing excessive structural complexity. This addressed a key limitation in previous research, where improvements in one performance metric often resulted in compromises in others (Salamin et al., 2019). The integration of parametric analysis, optimization techniques, and statistical validation provided a comprehensive framework for antenna design that can be applied to other communication systems. The findings also highlighted the importance of considering multiple performance metrics simultaneously, rather than focusing on individual parameters in isolation. This approach allowed for the development of a more efficient and versatile antenna design capable of meeting the demands of modern wireless communication systems (Zhang et al., 2018). The consistency of results across different configurations further supported the reliability of the design methodology. By combining theoretical modeling, simulation, and statistical analysis, this study provided a more complete understanding of dual-band antenna performance. The results therefore represented a meaningful advancement in antenna engineering, offering a practical solution for improving communication efficiency in next-generation wireless networks (Cervantes-González et al., 2016).

CONCLUSION

This study presented a comprehensive quantitative evaluation of a dual-band microstrip patch antenna designed for 5G sub-6 GHz and millimeter-wave applications, demonstrating that optimized structural and parametric configurations can significantly enhance antenna performance across multiple critical metrics. The results confirmed that the proposed antenna design successfully achieved stable dual-band resonance while maintaining compactness, which is essential for integration into modern wireless communication devices. Significant improvements were observed in return loss, bandwidth, gain, and radiation efficiency, indicating enhanced impedance matching, wider operational frequency coverage, and improved radiation characteristics. The parametric analysis revealed that antenna performance was strongly influenced by design variables such as patch geometry, slot configuration, substrate properties, and feeding techniques, highlighting the importance of a systematic and controlled optimization process. The study also demonstrated that performance trade-offs between different metrics can be effectively managed through careful design balancing, allowing simultaneous enhancement of multiple parameters without compromising overall efficiency. Statistical validation further strengthened the findings by confirming that the observed improvements were significant and not attributable to random variation, thereby establishing the reliability and robustness of the optimized design. The integration of simulation-based modeling with quantitative statistical analysis provided a rigorous framework for evaluating antenna performance and offered a more objective approach compared to conventional design methods. Additionally, the comparative analysis with baseline configurations illustrated clear and consistent performance gains, reinforcing the effectiveness of the adopted optimization strategy. The findings collectively indicated that dual-band antenna performance can be substantially improved through coordinated adjustment of design parameters and advanced modeling techniques. This study therefore contributed to the advancement of antenna engineering by providing a validated and efficient design approach capable of supporting high-performance wireless communication systems, particularly in the context of emerging 5G technologies that require reliable operation across both sub-6 GHz and mmWave frequency bands.

RECOMMENDATIONS

It is recommended that future antenna design efforts adopt a structured and quantitative optimization approach similar to that demonstrated in this study, where multiple design parameters are systematically evaluated to achieve balanced dual-band performance. The findings indicated that antenna performance is highly sensitive to variations in geometry, substrate properties, and feeding techniques, therefore careful parametric control should be prioritized during the design phase. Designers are encouraged to consider integrated optimization strategies that simultaneously address return loss, bandwidth, gain, and efficiency rather than focusing on a single performance metric. The use of advanced electromagnetic simulation tools should be maintained as a core component of antenna development, as these platforms provide accurate and repeatable evaluation of performance across different configurations. It is also advisable to incorporate statistical validation methods, such as analysis of variance and regression modeling, to ensure that observed improvements are both significant and practically meaningful. In practical applications, antenna designs should be tested under realistic environmental conditions to evaluate performance stability in the presence of interference, signal blockage, and material variations. Special attention should be given to the selection of substrate materials and feeding mechanisms, as these elements were shown to have a substantial impact on impedance matching and radiation efficiency. For mmWave applications, high-gain and directional performance should be emphasized to compensate for increased propagation losses, while sub-6 GHz designs should prioritize coverage and signal penetration. It is further recommended that designers explore hybrid design techniques that combine slot loading, ground plane modification, and optimized feeding to enhance multi-band functionality. In addition, manufacturing considerations such as fabrication tolerance and material consistency should be incorporated into the design process to ensure reliable real-world implementation. The adoption of these recommendations can contribute to the development of more efficient, compact, and high-performance antennas capable of supporting next-generation wireless communication systems.

LIMITATION

This study was subject to several limitations that should be acknowledged when interpreting the findings and their applicability to practical antenna design scenarios. The research was conducted entirely within a simulation-based environment using electromagnetic modeling software, which, although highly accurate, does not fully replicate real-world operating conditions. Factors such as fabrication imperfections, material inconsistencies, connector losses, and environmental interference were not physically tested, which may influence antenna performance in practical implementations. The antenna models were evaluated under ideal boundary conditions and controlled parameters, meaning that external influences such as temperature variation, humidity, and mechanical stress were not considered. Another limitation was related to the scope of design parameters included in the optimization process. While key variables such as patch dimensions, slot configuration, substrate properties, and feeding techniques were systematically analyzed, other potential influencing factors, including advanced material characteristics, surface roughness, and packaging effects, were not incorporated into the study. The sample size of antenna configurations, although sufficient for statistical analysis, remained limited to a finite number of parametric variations, which may restrict the generalizability of the results across all possible design combinations. Additionally, the study focused on a single antenna topology, specifically the microstrip patch structure, and did not compare performance with alternative antenna types such as dielectric resonator or array-based systems. The statistical analysis assumed linear relationships among variables in certain models, which may not fully capture the nonlinear interactions present in complex electromagnetic systems. Furthermore, the absence of experimental validation through physical prototyping and measurement represents a key limitation, as real-world testing is essential for confirming simulation accuracy. These constraints suggest that while the findings provide valuable insights into dual-band antenna optimization, caution should be exercised when extending the results to practical deployment without further empirical verification.

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