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Recent Advances in Microstrip Antenna Design, Advanced Substrate Materials, and Intelligent Optimization Techniques: A Comprehensive Review

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ABSTRACT: Microstrip antennas are very important in modern wireless communication systems due to their small size, low cost of manufacturing and easy integration with electronic devices. With the continuous development of wireless technologies, the demand for antennas with better bandwidth, gain, radiation efficiency, miniaturization and intelligent design capability is growing. This paper provides a detailed narrative review on the recent developments in microstrip antenna technology in three complementary research areas: antenna design techniques, advanced substrate materials, and intelligent design and optimization methods. The recent studies were systematically gathered and analyzed, and compared critically based on the design methodologies, material characteristics, antenna performance, optimization approaches, practical applications, and reported limitations. As revealed by the review, innovative structural designs, engineered substrate materials and artificial intelligence based optimization techniques have been able to enhance the performance of the antennas while minimizing the complexity of the designs and the development time. Important research challenges are also identified, such as the need for multi-objective optimization, standardized evaluation methods, wider experimental validation, and better incorporation of advanced materials with intelligent optimization techniques. In general, the review shows that the integration of structural innovation, substrate engineering and intelligent computational methods is an effective way for the development of next generation microstrip antennas. The results provide a single reference for researchers and engineers to design compact, efficient, and intelligent antennas for future applications such as 5G and 6G, the Internet of Things, satellite communications, wearable electronics, and millimeter-wave wireless systems.

KEYWORDS: Microstrip Antennas; Antenna Design; Substrate Materials; Intelligent Antenna Design; Antenna Optimization; Wireless Communication.

1. INTRODUCTION

The development of wireless communication technologies has rapidly grown the demand for small, lightweight and high-performance antennas that can support a wide variety of applications such as the fifth generation (5G) and emerging sixth generation (6G) wireless communications, the Internet of Things (IoT), satellite communications, wearable electronics, radar systems, autonomous vehicles, and smart sensing platforms [1]. Microstrip antennas are one of the most popular technologies among the available antenna technologies, due to their low profile, low fabrication cost, ease of fabrication, compatibility with printed circuit board technology and easy integration with microwave circuits [2]. These benefits have led to the use of microstrip antennas as an integral part of modern wireless communication systems [3]. Conventional microstrip antennas, however, still have several inherent drawbacks such as narrow bandwidth, relatively low gain, limited radiation efficiency, limited impedance bandwidth and challenges for simultaneous miniaturization, multiband operation and high isolation [4]. These problems have been a significant research topic in the field of antenna engineering [5].

Thus, a lot of research activities have been focused on the enhancement of electrical and mechanical characteristics of the microstrip antennas by various technological approaches. Recently, innovative antenna design structural techniques have been developed to enhance the bandwidth, gain, impedance matching, radiation efficiency, isolation, and miniaturization of antennas, such as defected ground structures, fractal design, metasurfaces, metamaterials, antenna arrays, and multiple-input multiple-output (MIMO) configurations [6]. Meanwhile, the development of the substrate engineering has promoted the application of flexible polymer, transparent material, composite dielectric, ceramic substrate and additive manufacturing technologies to improve electromagnetic performance and mechanical adaptability

[7]. In recent years, Artificial Intelligence, Machine Learning, Deep Learning, and Data-Driven Optimization Algorithms have become powerful tools to speed up antenna design, to enhance prediction accuracy, to save computational cost, and to enable intelligent antenna synthesis [8, 9]. All of these developments have contributed to the greatly improved capabilities of modern microstrip antennas for next-generation wireless communication systems.

The literature on these research areas is growing and shows significant advances in all of these. Many studies have been reported on innovative antenna structures, advanced materials for antenna substrates, and intelligent optimization techniques for enhancing antenna performance in various wireless applications. Moreover, there are some review papers that have summarized the developments of specific topics like antenna design methods, wearable antennas, substrate materials or artificial intelligence applications in antenna engineering [10, 11]. However, with the fast growth of research, there is a need for a wider review on the contribution of these complementary research directions towards the development of high performance microstrip antennas. A shared vision can help to clarify the state of the art, shared research problems and future research opportunities.

To satisfy this demand, this review aims to thoroughly analyze the latest developments of the microstrip antenna technology by combining three major research fields: antenna design techniques, advanced substrate materials, and intelligent design and optimization methods. Instead of addressing these topics individually, the review will focus on the interrelationships between them, the pros and cons of each, common research themes and difficulties, and new opportunities for future antenna development. This integrated approach offers a holistic view of the potential of synergistically merging structural innovation, material engineering and intelligent computational techniques to enhance antenna performance and meet the ever challenging demands of future wireless communication systems.

This is a narrative review of the literature, and a complete overview of the literature is provided. The studies recently published in the renowned journals and conference proceedings were critically analyzed and compared based on antenna design methodology, substrate characteristics, electromagnetic performance, optimization technique, application areas, and research limitations. Comparative Tables and Conceptual Figures were created to summarize the literature reviewed and present a clear picture of the current research trends and technological developments.

This review has three main contributions. First, it offers a comprehensive perspective of the recent developments in structural antenna design, substrate material engineering, and intelligent optimization in one place. Second, it provides a critical comparison of recent studies by pointing out their methodologies, advantages, limitations and application domains. Thirdly, it reveals the key research gaps and future trends, such as AI-aided antenna design, advanced functional materials, additive manufacturing, metasurface-assisted MIMO systems, and next-generation wireless communication technologies [12]. These contributions give a complete reference for the researchers and engineers in designing compact, efficient and intelligent microstrip antennas for future wireless applications.

The rest of this paper is structured as follows. Recent developments of microstrip antenna design techniques are reviewed in Section 2. Advanced substrate materials and their impact on antenna performance are discussed in Section 3. Intelligent design and optimization techniques for microstrip antennas are discussed in Section 4. Major research trends, current challenges, and future research opportunities are identified and discussed in Section 5, which includes a critical discussion on the reviewed literature. Lastly, Section 6 presents the key findings of the paper and suggests future research avenues.

2. RECENT ADVANCES IN MICROSTRIP ANTENNA DESIGN TECHNIQUES

With the recent rapid progress of modern wireless communication systems, the need for compact, high-performance microstrip antennas that can be used for wide bandwidth, high gain, miniaturization, multiband operation and efficient radiation characteristics has grown significantly. In order to overcome the inherent limitations of conventional microstrip antennas, various design approaches have been proposed such as modified ground plane, defected ground structures (DGS), fractal geometry, metasurfaces, metamaterials and integrated array configurations [13]. These techniques have significantly enhanced the performance of the antennas with a small size that is well suited for new applications like 5G/6G, satellite systems, radar, wearable electronics, and IoT [14, 15]. The major antenna design techniques and their impact on antenna performance are shown in Figure 1.

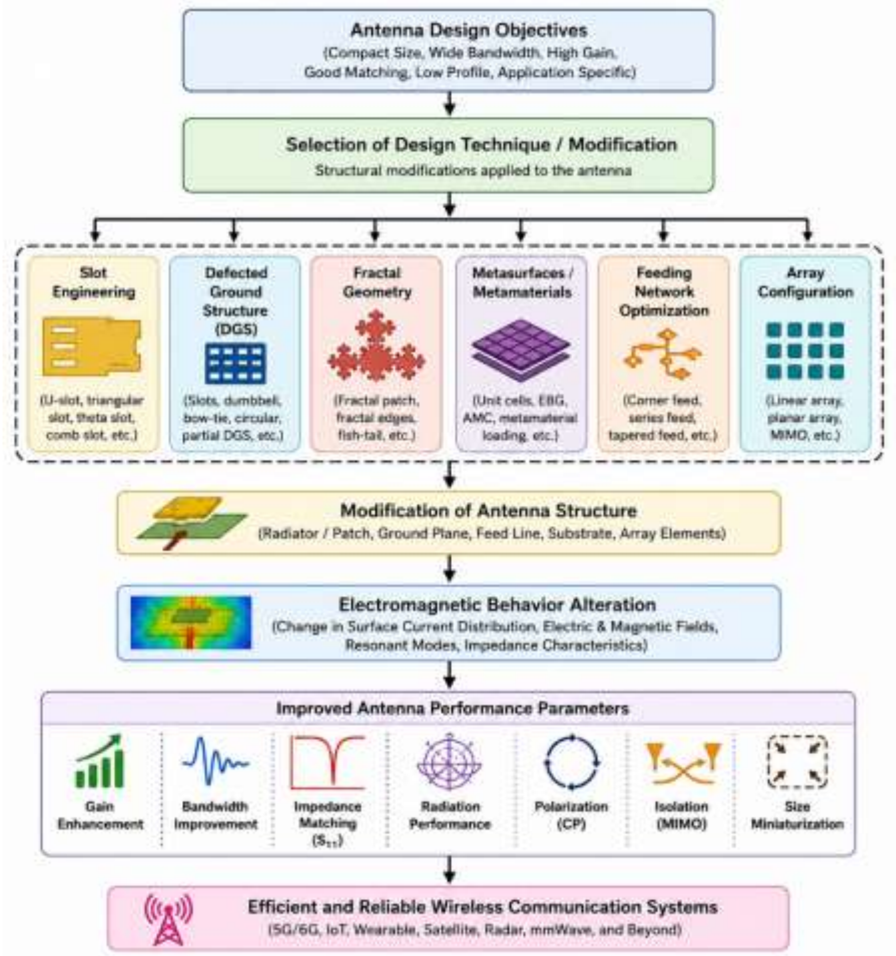

Figure 1: Antenna design optimization workflow

In recent years, many studies have been conducted to optimize the structure of antennas to enhance electromagnetic performance by using different antenna design techniques. One of the earliest methods to improve the performance of microstrip antennas is to change the ground plane, which has been shown to be effective in improving the antenna bandwidth and size simultaneously. Deshmukh et al. (2024) [16] presented a small circular microstrip antenna using a modified ground plane in the shape of a bow-tie with three rectangular slots. The antenna was experimented and validated to have a bandwidth improvement of 25%, reduction in resonant frequency of 35.12%, reduction in patch area of 66% and a maximum gain of 5.5 dBi. The study showed that the bandwidth and antenna miniaturization can be simultaneously improved by a simple modification of the ground plane without increasing the complexity of the structure. The proposed design was able to successfully achieve bandwidth enhancement along with significant size reduction when compared with conventional wideband microstrip antennas. However, the antenna was tested only for one operation condition, and further study should be conducted for the antenna application in multiband and MIMO antenna system.

Based on the idea of ground-plane modification, the defected ground structures (DGS) were introduced and used to further enhance the impedance matching, bandwidth and harmonic suppression. Maity & Nayak (2023) [17] proposed a small-sized bowtie-shaped microstrip antenna with bilateral triangular slits and an inverted U-shaped DGS. The proposed antenna was designed to work at 5.5 GHz and 17.41 GHz, provided a wideband harmonic suppression up to $3.17f_0$, reduced cross-polarization and a compact profile. The proposed DGS effectively suppressed the higher-order harmonics without any extra filtering circuits and simplified the antenna structure. Moreover, two machine learning models using artificial neural network (ANN) and convolutional neural network (CNN) were used to predict the antenna dimensions, which is an intelligent antenna design methodology. The study focused, however, on harmonic suppression, with a potential extension to multiband 5G and 6G broadband wireless communication applications.

Tsegaye et al. (2025) [18] further investigated the benefits of DGS by designing a small monopole antenna on a Taconic TLY low-loss substrate with optimized ground-plane slots. The antenna was successively optimized and experimentally verified to obtain an ultra-wide bandwidth ranging from 4.08 to 18.92 GHz (129%), along with a maximum gain of 7.4 dB.

With the embedded DGS, the antenna gain, radiation efficiency and impedance matching were improved greatly, while the antenna was still compact. This work was the first to show the ability of DGS to achieve very wide impedance bandwidth for multiple wireless communication standards as opposed to previous DGS-based studies which focused on harmonic suppression. However, the antenna was still a single element design, which means there is still potential for future integration into a compact MIMO design.

In the same vein, Nafi et al. (2024) [19] expanded the use of DGS to practical Sub-6 GHz 5G communication by introducing a slotted microstrip antenna with a unique modified defected ground structure (DGS) in the shape of a theta. The proposed antenna was fabricated on an FR-4 substrate and was designed to be a dual band radiator with frequencies of 4.19 GHz and 4.91 GHz and bandwidths of 130 MHz and 890 MHz, respectively, with reflection coefficient of about −30 dB. Parametric studies were also carried out to assess the effect of the DGS size and the substrate material on the antenna performance. This work specifically focused on practical 5G frequency bands and enhanced bandwidth and impedance characteristics as compared to previous DGS techniques. Diversity performance and mutual coupling were not investigated though, which means that it can be used in compact MIMO antenna systems in the future.

Besides the classical wireless communication systems, the DGS technology has been recently extended to flexible and wearable antennas. Soni et al. (2024) [20] designed a flexible low-profile microstrip antenna for wearable 5G application at Sub-6 GHz band optimized using Nelder–Mead simplex algorithm. The fabricated antenna on Rogers RT/Duroid 5880 substrate was found to have a reflection coefficient of −22.34 dB, peak gain of 5.57 dBi and remarkably low specific absorption rate (SAR) of 0.0959 W/kg and 0.0755 W/kg for 1 g and 10 g tissue, respectively. The antenna remained stable when subjected to different bending conditions and different placements on the body, showing its excellent suitability for wearable electronics. This work focused on flexibility, user safety and practical implementation, compared to previous DGS antennas. However, the antenna could only be used at Sub-6 GHz, so future research on flexible multiband and millimeter-wave wearable antennas is suggested.

Fractal geometries are another effective way to achieve antenna miniaturization and broadband performance, while DGS techniques primarily enhance the current distribution by modifying the ground plane. Yaminisasi et al. (2025) [21] suggested a fish-tail shaped fractal monopole antenna with defected partial ground structure and tapered feedline. The compact antenna was designed to operate at three resonant frequencies of 3.22, 7.64 and 9.41 GHz and in two broadband operating ranges of 2.5–4.2 GHz and 7–9.8 GHz. The fractal geometry was able to achieve the desired effect of increasing the electrical current path without increasing the size of the antenna, which led to a better bandwidth and radiation performance. The fractal approach has been able to attain both miniaturization and broadband characteristics as compared to conventional compact monopole antennas. The antenna was however tested in a single element configuration only and future research could be done to apply fractal concepts to compact MIMO configurations.

With the development of antenna design techniques, researchers started using metasurfaces to realize simultaneous multiband operation and polarization diversity. Sarkar & Gupta (2025) [22] presented a slotted microstrip patch antenna with metasurface for RFID, 5G and satellite communication applications. The antenna was designed to work in the frequency range of 865–868 MHz, 3.3–4.2 GHz and 3.7–4.2 GHz with the radiation efficiency of 75–85%. It also provided circular polarization in the RFID and satellite bands together with dual-linear polarization in the 5G band, demonstrating excellent operational flexibility. The metasurface design was able to combine multiband operation with polarization diversity effectively, compared with previous fractal and DGS-based antennas. However, the study was only performed with a single antenna element and future multi-port implementations are possible.

In addition to sub-6 GHz systems, recent investigations have been directed towards millimeter-wave antennas to meet the ever increasing demand for extremely high data-rate communication. Gaid et al. (2025) [23] developed a miniaturised comb-shaped microstrip antenna for 60 GHz V-band with four slits in the radiating element. Despite its compact size of only $3.8 \times 5 \times 0.118$ mm³, the antenna achieved a 2.34 GHz bandwidth, 9.24 dBi gain, 89.5% radiation efficiency, VSWR of 1.005, and an S11 value of −53.014 dB. Time-domain analyses also showed little signal distortion in the case of high-speed transmission. The proposed design was able to effectively combine high gain with compact dimensions, compared with conventional millimeter-wave antennas. However, only one antenna element was taken into account, which means that array and MIMO implementations are still required in the future.

Along with the development of millimeter-wave technology, antenna miniaturization has become more and more significant for satellite communication systems. Kola & Chatterjee (2023) [24] designed a Ku-band compact right-hand circularly polarized microstrip antenna for direct broadcast satellite applications. The antenna was miniaturized by 20.20%, with a gain of 8.46 dBic, circular polarization bandwidth of 0.54 GHz, radiation efficiency of 97% and aperture efficiency of 86% through triangular slots and central fractal geometry. The proposed design showed a significant improvement in circular polarization performance with high efficiency as compared to the conventional compact patch antenna. The design, however, was only for a single satellite communication band, which meant that there was potential for future multiband satellite antenna development.

With the need for multiple operating frequencies in communication platforms, the antenna researchers have turned to integrated array configurations. Zhu & Liu (2025) [25] presented a dual-frequency microstrip array with a small size that can be used at 24 GHz and 77 GHz simultaneously. The antenna element was miniaturized by 39.82% by using the width-reduction technique and the corner-fed 3 × 3 array was achieved with 15.34 dBi and 14.19 dBi gains at the two operating frequencies. The design was successful in minimizing feeding losses and keeping sidelobe and cross-polarization levels low. The proposed antenna offered higher integration and simpler feeding network than the conventional dual-band arrays. However, diversity properties were not explored, indicating potential future incorporation of MIMO technologies.

In more recent times, researchers have been using a combination of metamaterials and MIMO technology to further improve the performance of antennas for next generation wireless systems. Rahman et al. (2025) [26] proposed a compact tri-band MIMO antenna with a 2 × 1 epsilon-negative metamaterial array between the antenna elements. The antenna operated at 3.5 GHz, 5.2 GHz and 28 GHz, and the bandwidth enhancement was 10.01%, 6.4% and 4.43%, respectively, and the realized gain was improved to 4.8 dBi, 5.3 dBi and 9.3 dBi, respectively. Isolation was raised to 24 dB and 32 dB, and ECC was reduced to less than 0.002 and the diversity gain was improved to more than 9.98 dB. Moreover, machine learning was able to successfully validate the antenna performance with the prediction accuracy of 97.8%. The use of metamaterials and artificial intelligence greatly improved the overall system performance, compared to previous compact MIMO antennas. But the antenna structure is quite complicated and so future research will be directed to simpler low cost implementations.

Finally, Perli et al. (2025) [27] further developed the compact MIMO antenna technology by proposing a quad-port antenna using defected substrate and defected ground plane. The antenna was designed to operate in the frequency range of 2.75–4.4 GHz and 10.33–13 GHz, with isolation of better than −17.5 dB and −25 dB, respectively, despite the close proximity of the antenna elements. The polarization diversity and mutual coupling were significantly enhanced with the combined defected substrate and ground structure, and the size was kept as compact as 44 × 44 × 1.6 mm^3. The proposed design has shown high isolation without the need of additional decoupling structure which is suitable for modern 5G, IoT, vehicular and satellite communication systems. However, the antenna is still only dual-band, which means there is still potential for ultra-wideband and 6G massive MIMO applications.

Moreover, the studies show that the design of microstrip antennas has been continuously evolving from simple modification of the ground plane to advanced defected ground structures (DGS), fractal antennas, metasurfaces, metamaterials, millimeter-wave antennas and MIMO antennas. While each of these design techniques can be used to tackle a different performance issue, together they all help to enhance bandwidth, gain, impedance matching, miniaturization, radiation efficiency, isolation and multiband operation, which are all increasingly required in today's wireless communication systems. The key features of the studies reviewed are presented in Table 1.

Table 1: Comparison of recent antenna design techniques and performance improvements

Ref.	Design Technique	Size (mm)	Performance Improvement	Key Contribution	Application
[16]	Bow-tie DGS	(0.363 × 0.363) λ_c	Increased bandwidth, miniaturization	Compact wideband antenna	Wideband communications
[17]	DGS + Slots	14.9 × 15.6	Improved bandwidth, impedance matching	Compact dual-band antenna	WLAN, DBS
[18]	DGS	34 × 28	Increased bandwidth, gain	Wideband antenna design	Wideband communications
[19]	Theta slot + DGS	35 × 34	Improved bandwidth, impedance matching	Dual-band antenna design	Sub-6 GHz 5G
[20]	DGS	(0.48 × 0.40) λ_0	Improved gain, impedance matching	Wearable antenna optimization	Sub-6 GHz 5G
[21]	Fractal + DGS	24 × 40	Improved bandwidth, gain	Compact multiband antenna	5G, X-band

Ref.	Design Technique	Size (mm)	Performance Improvement	Key Contribution	Application
[22]	Slots + Metasurface	(0.28 × 0.28) λ_0	Improved bandwidth, circular polarization	Multiband CP antenna	RFID, 5G, SatCom
[23]	Comb-shaped radiator	3.8 × 5	Increased gain, bandwidth	Millimeter-wave antenna	60-GHz 5G
[24]	Triangular slots	7.5 × 7.5	Improved gain, axial-ratio bandwidth	RHCP antenna design	DBS
[25]	Reduced patch + Corner-series feeding	—	Increased gain, miniaturization	Compact dual-band array	Automotive radar
[26]	Metamaterial loading	36 × 36	Improved gain, isolation	Metamaterial-based MIMO antenna	5G, IoT
[27]	Tapered radiator + DGS	44 × 44	Improved isolation, bandwidth	High-isolation MIMO antenna	5G, X-band

3. ADVANCED SUBSTRATE MATERIALS FOR MICROSTRIP ANTENNA PERFORMANCE ENHANCEMENT

The choice of substrate material is one of the most critical parameters in determining the performance of a microstrip antenna because the material parameters directly influence the performance parameters of the antenna, such as resonant frequency, bandwidth, gain, radiation efficiency, impedance matching and antenna size [28]. Over the past few years, research has moved beyond traditional dielectric substrates to flexible polymers, transparent substrates, composite dielectrics, ceramics, and 3D-printed substrates, which offer enhanced electrical performance, mechanical flexibility, and fabrication capabilities [29-31]. As shown in Figure 2, various substrate materials and fabrication techniques are available to influence the antenna performance in different ways, according to the dielectric, mechanical, and conductive properties of the materials, and provide solutions for modern wireless communication applications. As a result, optimization of the substrate properties has been a subject of intensive research for the purpose of obtaining compact, efficient and application-specific antenna designs [32]. Recent developments in substrate materials are reviewed in the following studies and the effect of the substrate on the antenna performance in various applications is discussed.

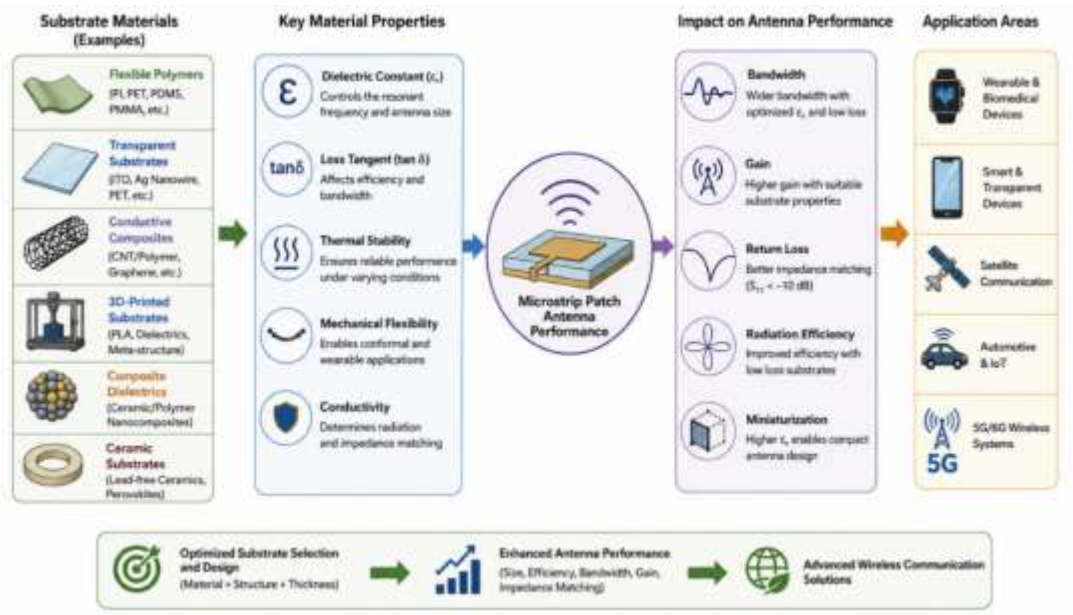

Figure 2: Influence of substrate materials on antenna performance

Some recent studies have been presented on different materials and design methods to improve the performance of microstrip antennas. Giftsy et al. (2023) [33] conducted a review of flexible and wearable antennas for biomedical applications, highlighting the effect of substrate and conductive materials on the antenna performance. The authors examined the current designs and compared the parameters like gain, bandwidth and specific absorption rate (SAR). They found that flexible substrates offer a better wearer comfort and mechanical flexibility, and the right material choice can boost electromagnetic characteristics. The study offers a detailed account on material selection approaches for wearable antennas and presents some design issues for biomedical systems. The main advantage is the extensive assessment of flexible materials, but the review is largely qualitative and doesn't provide any standardised criteria for the choice of substrates. It is broader than previous surveys in its discussion of flexible antenna materials and suggests that quantitative evaluation of materials and unified design guidelines are needed.

Similarly, Banale et al. (2025) [34] performed a systematic review to investigate the effects of conductive and dielectric materials on flexible wearable microstrip patch antennas. The authors reviewed 46 published studies and concluded that copper-based conductors generally have better electrical properties, while conductive polymers have better flexibility and lower conductivity. Their primary contribution is a systematic comparison of material properties, fabrication techniques and antenna designs. Although the structured review helps in understanding the current research trends, there is no experimental validation and it is noted that materials that can achieve high flexibility and high electrical performance are still limited. This work is more systematic than previous reviews, and highlights the need for new conductive materials with good mechanical and electrical properties.

In addition to the review of the existing materials, Popela et al. (2024) [35] explored the use of advanced manufacturing techniques for printed patch antennas using Lights-Out Digital Manufacturing (LDM) technology. Antennas were fabricated using conductive and dielectric inks and compared with the conventional Arlon 25N and FR-4 substrates. The results showed high fabrication accuracy without post processing and direct soldering. The study introduces a practical manufacturing method which is favorable to producing antennas with simpler manufacturing process and higher dimensional accuracy. However, only a few substrate materials were examined. LDM printing offers more manufacturing flexibility and production efficiency than conventional fabrication techniques, but more research is needed to explore other printable materials and higher frequency applications.

Besides fabrication technologies, Aljahwari et al. (2025) [36] investigated the transparent and flexible substrate materials for modern wireless communication systems. A compact decagonal fractal antenna was fabricated by screen printing silver nanoparticles on transparent PET substrate and the performance of the fabricated antenna was evaluated both under flat and bent conditions. The antenna was demonstrated to operate in a wideband from C-band to X-band with a radiation efficiency of about 72%, and to have a stable performance when bent. The study's key innovation is the integration of optical transparency, flexibility and broadband performance, achieved via a simple printing process. The proposed design has better mechanical flexibility and unobtrusive installation than conventional rigid antennas. The investigation was however limited to a single transparent substrate and operating bands, and further transparent materials and long-term durability should be investigated.

Similarly, Ziani et al. (2024) [37] studied polymer-based flexible antennas based on a PMMA substrate and conductive materials made of carbon nanotubes (CNTs) for sub-6 GHz applications. The proposed rectangular and circular antennas were tested in flat and bending conditions for various thicknesses of the substrate. The antenna gains were greater than 5 dBi and the bandwidths were around 200 MHz and 500 MHz, respectively, with good radiation stability under deformation. The study presents an efficient hybrid of light-weight polymers and CNT conductors as flexible antenna. It has the advantage of assessing the mechanical bending effects, but only PMMA substrates and frequencies below 6 GHz were taken into account. The proposed method is more flexible than the traditional copper-based antenna without compromising the electrical performance, which opens the door for further research on other polymer materials and higher frequency applications.

Moreover, Jha et al. (2023) [38] explored the use of additive manufacturing to fabricate low-dielectric PLA substrates using varying 3D-printing infill densities to further enhance the substrate properties. Experimental characterization revealed that the 80% infill structure had lower dielectric constant and loss tangent than the fully filled substrate, which is beneficial for high frequency antenna applications. The main contribution is the proof of the possibility of tailoring of the dielectric properties without changing of the base material. The method is simple and inexpensive to manufacture, but was only tested with PLA substrates and at limited frequencies. Additive manufacturing offers much more flexibility in the design of substrates than conventional substrates, but more experimental validation is required.

Following this idea, Rani et al. (2025) [39] further expanded the use of AM by incorporating 3D-printed PLA meta-structure substrates featuring varying infill patterns and top-layer configurations. It was shown that the internal geometry could be modified to control the dielectric constant without affecting the operation frequency of 2.45 GHz. The main contribution is the practical approach of tuning the electromagnetic properties of the substrate by its structural design, instead of changing the material. It has the advantage of a high design flexibility and low fabrication costs. However, only PLA materials and one operating frequency were investigated. The proposed meta-structure provides more control of the dielectric properties than conventional rigid substrates and previous 3D-printing methods, but more validation is needed for other materials and frequencies.

In addition to polymer-based substrates, Mercy (2024) [40] explored composite dielectric materials for enhancing the performance of microstrip patch antennas in the C- and X-bands. The study optimized the thickness of the substrate and the volume fraction of the composite using the Maxwell-Garnett effective medium theory and HFSS simulations. The proposed composite substrate was able to provide a gain of 10 dB, an efficiency of 96%, and dual-band operation, which is better than conventional dielectric substrates. The key contribution is the proof of the potential of composite material engineering to improve the performance of antennas. The optimization strategy is detailed, but the study is based primarily on simulation, and is limited to a single composite system. The composite design has a higher gain and efficiency than conventional substrates, which shows the potential of engineered dielectric materials for future antenna design.

In a similar fashion, Samal et al. (2024) [41] suggested the use of a lead-free $Bi_{0.5}Na_{0.5}TiO_3$ (BNT) ceramic substrate for designing X-band microstrip patch antennas. The Ceramic material was synthesized, characterized and optimized by changing the thickness of the substrate. The optimized substrate (εr = 4.34, $\tan\delta$ = 0.0186, thickness = 1.02 mm) realized dual-band operation at 8.99 GHz and 10.34 GHz with good return-loss performance. The key contribution is the introduction of an environmentally friendly ceramic substrate that can enhance the miniaturization of the antenna and its electromagnetic properties. The incorporation of the material synthesis and antenna design is a major asset, but only one ceramic composition and X-band operation was studied. The ceramic material has better dielectric properties than the traditional polymer substrates, and the research of other kinds of lead-free ceramics is still very important.

Recently, Rana et al. (2024) [42] integrated material selection with machine learning to optimize the microstrip patch antennas for 28 GHz 5G applications. This study compared Rogers RT5880 and FR-4 substrates and created a predictive model to determine the antenna performance. The machine-learning model significantly reduced the antenna design effort, and Rogers RT5880 outperformed FR-4 in gain (7.63 dBi), efficiency (89.66%) and return-loss characteristics. The major contribution is the combination of substrate optimization and data-driven prediction techniques, which is a step towards intelligent antenna development from traditional trial-and-error design. But the two substrate materials and one operating frequency were investigated. Future research should be expanded to include other substrate materials and more advanced AI algorithms for automated antenna optimization.

Based on the studies reviewed, it is seen that the properties of the substrate material such as the dielectric constant, loss tangent, substrate thickness, and the composition of the material play a significant role in the performance of the antenna. Various wireless communication applications have been proposed with different materials and fabrication techniques to enhance gain, bandwidth, radiation efficiency, impedance matching and antenna miniaturization. The comparative summary of the substrate materials, material properties, key antenna performance and major findings of the reviewed studies is shown in Table 2.

Table 2: Comparison of substrate materials and antenna performance

Ref.	Substrate Material	Material Properties	Effect on Antenna Performance	Main Finding
[33]	Flexible wearable substrates	Flexibility, biocompatibility, mechanical stability	Enhanced conformability and radiation performance	Flexible substrates improve wearable antenna reliability.
[34]	Flexible polymer substrates	Mechanical flexibility, lightweight	Improved adaptability and wearable performance	Flexible materials facilitate wearable antenna integration.
[35]	3D-printed dielectric materials	Tunable dielectric properties, printable geometry	Improved design flexibility and electromagnetic performance	Additive manufacturing enables customized antenna substrates.
[36]	Transparent conductive substrate	Transparency, conductivity, flexibility	Improved transparency and radiation performance	Transparent substrates support wearable and smart-surface antennas.
[37]	PMMA/CNT composite	Low dielectric loss, conductive CNT layer	Improved gain, impedance matching, and flexibility	CNT composites improve flexible antenna performance.
[38]	PLA Pro+	Air-gap engineering, tunable dielectric constant	Reduced dielectric constant and improved performance	Air-gap engineering tailors substrate properties.
[39]	3D-printed meta-structure substrate	Tunable effective dielectric constant	Enhanced gain and radiation efficiency	Internal substrate design optimizes antenna performance.
[40]	Nanocomposite substrate	Engineered dielectric properties	Improved impedance matching and radiation performance	Nanocomposite substrates enhance antenna characteristics.
[41]	Lead-free BNT ceramic	Moderate dielectric constant, low dielectric loss	Improved miniaturization and radiation performance	Lead-free ceramics are promising for high-frequency antennas.
[42]	Rogers RT5880 and FR-4 substrates	Dielectric constant, dielectric loss	Improved gain, bandwidth, and efficiency	Substrate selection significantly influences antenna performance.

4. INTELLIGENT DESIGN AND OPTIMIZATION TECHNIQUES FOR MICROSTRIP ANTENNAS

In the modern wireless communication systems, due to the complexity of these systems, use of intelligent antenna design methodologies that reduce the amount of computation while increasing the accuracy of the design has increased. Traditional antenna development is based on iterative electromagnetic simulation and manual tuning of the parameters, which is inefficient for complex antenna structures [43, 44]. Thus, the use of artificial intelligence (AI), machine learning (ML), deep learning (DL) and optimization algorithms have come to the fore as effective tools for antenna synthesis, performance prediction and design optimization. These techniques can effectively model nonlinear electromagnetic relationships, reduce design cycles, and automatically generate optimized antenna configurations [45]. Fig. 3 shows the development of intelligent techniques and their applications in the present scenario of antenna design for microstrip antennas.

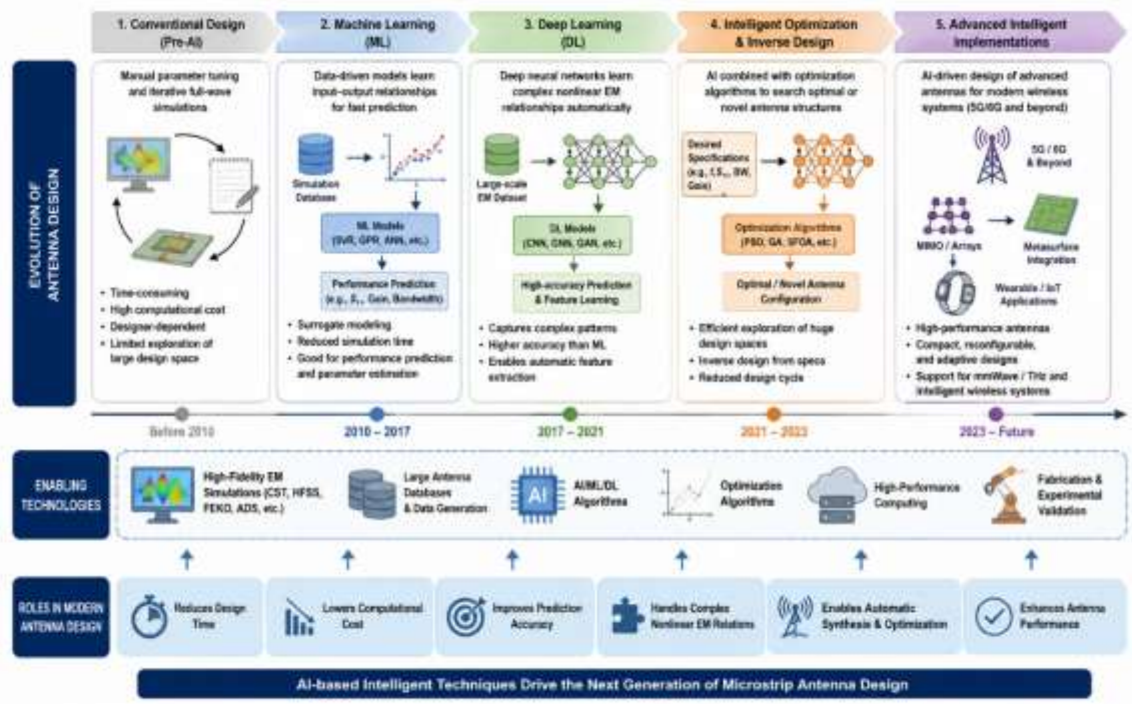

Figure 3: Evolution of intelligent techniques for modern microstrip antenna design

The first attempts at intelligent antenna optimization were based on the understanding of the influence of the design parameters prior to the use of machine learning algorithms. Joler & Mihalić (2022) [46] studied an inset-fed rectangular microstrip antenna designed on an ultra-thin Pyralux substrate for wearable applications. The impact of inset-gap width on the impedance matching was studied and an impedance bandwidth of ~2% was obtained with an average directivity of 5.8 dB. The work showed that the tolerances of the fabrication process have a significant effect on the antenna performance and served as a good starting point for the next optimization studies. But only one antenna configuration was investigated and future work could involve sensitivity analysis and machine learning to enable automated tolerance-aware design.

In this context, Prabhakar et al. (2024) [47] used an Auto-Metric Graph Neural Network (AMGNN) trained with Sheep Flock Optimization Algorithm (SFOA) to directly predict the dimensions of the antenna based on the design specifications. The proposed model achieved better results than the traditional regression models such as Support Vector Machines and Gaussian Process Regression using the datasets generated by CST, and significantly shortened the design time. The graph neural network effectively captured complex relationships between antenna parameters, which is different from traditional analytical methods. However, the study was primarily aimed at dimensional prediction and future research should involve simultaneous prediction of gain, bandwidth, efficiency and radiation characteristics.

ElAbbasi et al. (2025) [48] proposed a unified machine-learning framework with 1,500 antenna designs to compare Support Vector Regression, Gaussian Process Regression, Artificial Neural Networks, and Convolutional Neural Networks for further enhancing intelligent optimization. A simulation strategy based on uncertainty reduced unnecessary electromagnetic simulations and ensured a high prediction accuracy. The framework was able to support multiple antenna geometries and slot configurations as compared to previous single-model approaches. However, there is still a lack of experimental validation and future research should include real-time fabrication and multi-objective optimization.

When the prediction models started to mature, the focus of research turned to automatic antenna generation. Gonçalves & Malheiros-Silveira (2024) [49] suggested Generative Adversarial Network (GAN) and Conditional GAN (CGAN) models for the synthesis of microstrip antennas in the frequency range 1 to 30 GHz. The CGAN was able to generate antenna geometries for given operating frequencies and substrate dielectric constants that maintained the important electromagnetic features. This was a first in the antenna synthesis field since previous methods were based on prediction. However, its reliance on large training sets is an impetus to future research into more efficient generative models.

Recent advances have further pushed the automation of antennas forward by inverse design, in which the desired electromagnetic responses are directly translated into optimized antenna geometries. In 2025, Chen et al. [50] used a Convolutional Neural Network and Binary Particle Swarm Optimization to optimize a 10 × 10 pixelated microstrip antenna with almost 10^{30} possible configurations. The proposed framework converged faster and produced smaller S11 errors with 150,000 simulated samples compared to Genetic Algorithms and Simulated Annealing. The inverse design approach provided more control to satisfy the predefined performance requirements than the GAN-based synthesis. However, it requires a large amount of training data, which means that lightweight models of deep learning are needed for real-time optimization.

Intelligent algorithms can speed up antenna optimization, but practical implementation is key. Ahasan & Billah (2025) [51] developed a small size 2.4 GHz Wi-Fi microstrip antenna with a defected ground structure. The optimized antenna resonated at 2.416 GHz and 2.45 GHz with return losses of −21.97 dB and −15.10 dB, respectively, and radiation efficiency of more than 52% with a gain enhancement of 21.86% after the incorporation of the defected ground. This study verified that the optimization techniques are effective to improve the practical performance of IoT antennas. The design is however aimed at short-range communication, and further research into wideband and higher gain designs is encouraged.

Intelligent optimization has been extended to millimeter-wave antenna arrays. A small W-band 2 × 2 microstrip array on a low-loss fused silica glass substrate was proposed by Li et al. (2025) [52]. The antenna was able to obtain 10.1% impedance bandwidth (76.11–83.87 GHz) with a gain of more than 10 dBi over the entire band. The glass substrate not only lowered the dielectric loss but also enhanced the radiation characteristics, as compared with conventional silicon-based arrays. Future research can involve the use of machine learning for adaptive beam steering and real-time array optimization in 6G systems.

Optimized arrays have naturally evolved to MIMO antenna systems. To enhance the impedance matching and diversity performance, Farghaly et al. (2025) [53] introduced a 28 GHz 4 × 4 MIMO antenna with L-shaped and rectangular slots. The design was measured to have a return loss of −33.04 dB, a peak gain of 10.11 dBi, a VSWR of 1.04, and a diversity gain of around 10 dB, with measured values being close to the simulated ones. The proposed MIMO configuration exhibited a significant improvement in diversity performance over previous single element antennas with a compact size. Nevertheless, it is an important research direction for future 6G networks to extend the design for multiband operation.

Last but not least, Elabd et al. (2025) [54] combined a hybrid metasurface (MS) and frequency selective surface (FSS) in a small four-port MIMO antenna for the frequency band 24–50 GHz. The proposed design was able to attain a mutual coupling of less than −33 dB, a peak gain of 10.35 dBi, a radiation efficiency of nearly 90%, a diversity gain of 9.99, and an ECC of 6 × 10-3. The metasurface-assisted structure simultaneously improved gain, isolation and efficiency when compared to the conventional decoupling techniques. However, due to its higher structural complexity, it may be difficult to manufacture, and future studies should focus on simplifying the architecture, while introducing AI-based adaptive beamforming and electromagnetic optimization.

Finally, the reviewed studies clearly show that there is a progression from parameter sensitivity analysis to machine learning prediction, deep learning, inverse design and AI-assisted optimization of advanced antenna structures. These techniques have greatly enhanced the design efficiency, the accuracy of prediction and the electromagnetic performance, and have shortened the development time. These methods are further extended to millimeter-wave arrays, compact MIMO systems and metasurface-assisted antennas in more recent studies, which show the increasing importance of intelligent optimization for future 5G and 6G wireless communication systems. A summary of the main features of the studies reviewed is provided in Table 3.

Table 3: Comparison of intelligent techniques for microstrip antenna design and optimization

Ref.	Intelligent Technique	Objective	Application	Key Performance	Contribution
[46]	Parameter sensitivity	Design tolerance analysis	Wearable antenna	2% BW, 5.8 dB gain	Sensitivity evaluation
[47]	GNN + SFOA	Dimension prediction	Microstrip antenna	Higher prediction accuracy	Automated design prediction
[48]	SVR, GPR, ANN, CNN	Performance prediction	Multiple antenna types	High prediction accuracy	Unified ML framework
[49]	GAN / CGAN	Antenna generation	1–30 GHz antennas	Accurate geometry generation	AI-based antenna synthesis
[50]	CNN + BPSO	Inverse design	Pixelated antenna	Lower S11, faster convergence	Intelligent inverse design
[51]	DGS optimization	Performance enhancement	2.4 GHz Wi-Fi antenna	2.45 dB gain, 52.07% efficiency	Practical antenna optimization
[52]	Array optimization	W-band array design	2 × 2 array	10.1% BW, >10 dBi gain	High-gain mmWave array
[53]	MIMO optimization	28 GHz MIMO	4 × 4 MIMO	−33.04 dB RL, 10.11 dBi gain	Compact MIMO design

Ref.	Intelligent Technique	Objective	Application	Key Performance	Contribution
[54]	MS/FSS optimization	mmWave MIMO	Four-port MIMO	10.35 dBi gain, 90% efficiency	Metasurface-assisted MIMO

5. DISCUSSION

Based on the reviewed studies, it is found that the recent developments of the microstrip antenna technology are fueled by the confluence of three complementary research directions: structural antenna design, advanced substrate materials and intelligent optimization techniques. Instead of a single improvement approach, recent research is increasingly combining these approaches to meet the ever increasing demands of modern wireless communication systems such as 5G, upcoming 6G, Internet of Things (IoT), satellite communications, wearable electronics, and millimeter-wave applications. All of these advances have allowed significant improvements in bandwidth, gain, radiation efficiency, impedance matching, miniaturization, isolation and operational flexibility. Meanwhile, they demonstrate a distinct shift from the traditional trial-and-error approach to antenna design to data-driven and automated design techniques.

Structural modifications are still the basic methods to improve antenna performance among the design techniques reviewed. Defected ground structures (DGS) always improved the impedance matching, bandwidth and radiation properties with little antenna size. Miniaturisation was further enhanced by fractal geometries which increased the effective electrical path without increasing the physical size of the antenna. Meanwhile, array and MIMO configurations were used to meet the ever-growing demand for higher data rates and better communication reliability, while metasurfaces and metamaterials brought in other advantages such as gain, polarization diversity, isolation and multiband operation. Each of these design techniques is aimed at optimizing different performance parameters, but none of them optimizes all of the antenna parameters. This has led to the use of hybrid design approaches, combining several structural techniques, to obtain a compromise between the different wireless applications.

The selection of the antenna substrate material was also found to be a critical factor that affects antenna performance. On the other hand, flexible polymer substrates enhance mechanical flexibility and comfort of wear for wearable electronics, while transparent substrates allow for seamless integration into smart surfaces and portable devices. Compared to composite and ceramic substrates, plastic substrates tend to have poorer dielectric properties, which leads to lower gain, lower radiation efficiency and poorer impedance matching, especially at microwave and millimeter-wave frequencies. In addition, the use of additive manufacturing and 3D-printing technologies has opened new possibilities for the customization of the substrate dielectric properties, the decrease of manufacturing costs, and the customization of antenna geometry. However, the choice of a suitable substrate is a compromise between electrical performance, mechanical flexibility, manufacturing complexity, environmental durability and cost. Therefore, new materials should be developed that can offer multifunctionality, meaning that they can deliver a high level of electrical performance, mechanical strength, and sustainable manufacturing.

The use of AI has revolutionized the approach to antenna design. By leveraging machine learning algorithms like Support Vector Regression, Artificial Neural Networks, and Graph Neural Networks, the design time has significantly been reduced as the algorithms can accurately predict the required antenna dimensions and electromagnetic properties from simulation datasets. Further advances in deep learning, such as Convolutional Neural Networks, Generative Adversarial Networks, and inverse design methods have enabled the automatic synthesis of antennas by directly generating optimized antenna geometries from a set of desired performance specifications. AI-based optimization approaches can converge more quickly, reduce the computational expense when exploring design space, and possess a higher capability of dealing with highly nonlinear electromagnetic relationships compared to traditional optimization approaches that involve repeated electromagnetic simulation. But, these approaches are still very data and resource-intensive when building models. The generalization of the model, the complexity of the training process, and the interpretability of the model are still important issues to be addressed before intelligent antenna design can truly be autonomous.

Although the progress indicated in recent studies is remarkable, there are still some research challenges which are not solved. While many antenna designs focus on optimizing one or two performance parameters, practical wireless communication systems demand improvements in bandwidth, gain, efficiency, miniaturization, isolation and fabrication cost. Experimental validation is also rather limited in several studies, especially in the area of artificial intelligence, where a numerical simulation is often more important than making a prototype and conducting measurements. Furthermore, no benchmark dataset is available for the evaluation of AI-assisted antenna design algorithms, which makes it difficult to directly compare different approaches for antenna optimization. Another obvious drawback is that there are relatively few investigations that combine the advanced substrate engineering, intelligent optimization algorithms, metasurface technology and MIMO architectures in a single antenna design framework. Solving these problems will be critical in the design of next generation high performance antenna systems.

Future research should focus on multidisciplinary antenna design, including structural optimization, advanced material engineering and intelligent computational techniques in a unified design framework. New technologies like physics-informed machine learning, explainable artificial intelligence, reinforcement learning, digital twins, and generative AI are promising to take antenna synthesis one step further towards automation and increase the reliability of prediction and decrease the cost of computation. Meanwhile, the focus should be on environmentally friendly substrate materials, low-cost 3-D printing, reconfigurable intelligent surfaces, and large-scale MIMO for future 6G wireless networks. The research directions suggest that future microstrip antenna development will involve more and more intelligent optimization, advanced materials and innovative antenna structures to realize compact, adaptive, and high-performance wireless communication systems. The correlation between the structural optimization, advanced substrate materials, advanced optimization techniques and their combined effect on the development of next generation microstrip antennas is summarized in Figure 4.

Figure 4: Integrated research directions for next-generation microstrip antenna development

6. CONCLUSIONS

This review gave a detailed analysis of the latest developments in the field of microstrip antenna technology by considering three closely related research areas: antenna design techniques, advanced substrate material, and intelligent design and optimization methods. The goal was to offer a holistic view of the ongoing research and development activities, to pinpoint new research trends, and to point out future research opportunities for next generation wireless communication systems.

The literature reviewed shows that significant improvement of the performance of the microstrip antenna has been made in terms of structural innovation, substrate engineering and intelligent optimization. The bandwidth, gain, radiation efficiency, impedance matching, and antenna miniaturization have been improved greatly by using advanced antenna design techniques such as defected ground structures, metasurfaces, metamaterials, fractal geometries, and MIMO configurations. Concurrently, advancements in substrate materials have enhanced the electromagnetic performance and mechanical flexibility of antennas, and artificial intelligence and machine learning techniques have speeded up the design process of antennas, facilitated the prediction of antenna performance, and decreased the computational complexity. All of these complementary research directions are representative of the synergy between electromagnetic design, materials engineering, and computational intelligence that is found in the development of modern antennas.

However, there are still a number of challenges. Even though there are many existing studies, they are mostly concerned with optimizing a single performance parameter and not multi-objective optimization. Furthermore, more deep integration between advanced substrate materials and intelligent optimization techniques is required, along with more uniform evaluation methods, more extensive experimental validation, more scalable fabrication, and actual applications under realistic operating conditions. To make these emerging antenna technologies into reliable real-world applications will be critical to addressing these challenges.

The results of this review can serve as a single source of information for researchers and practicing engineers to choose the appropriate design strategy and identify potential research areas. Future research should be directed towards the integration of advanced materials, additive manufacturing, artificial intelligence, digital-twin technologies, reconfigurable and metasurface-assisted antennas, and sustainable fabrication methods to meet the growing demands of 5G and beyond 5G wireless communication systems, satellite communications, wearable electronics, and the Internet of Things.

Finally, the ongoing trend of innovative antenna structures, advanced substrate engineering, and intelligent optimization techniques is anticipated to be a key factor in the future development of high-performance microstrip antennas. This review will serve as a valuable basis for further research and development of next generation microstrip antenna technologies, as it provides a unified synthesis of recent developments, identifies current challenges and outlines future research directions.

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