International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online) Volume 15, Issue 7, July 2026)

A Comprehensive Review of Microstrip Patch Antenna Technologies for 5G Wireless Communication Applications

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Abstract: Due to the rapid advancements in fifth-generation (5G) wireless communication, there is a significant need for antennas that are lightweight, tiny, have a high gain, and have a broad bandwidth. These characteristics are necessary for communication systems to transmit data quickly, have low latency, and have high dependability. Because of its straightforward design, affordable cost, small size, and easy compatibility with contemporary equipment, the microstrip patch antenna is one of the most widely used types of antennas. While the microstrip patch antenna has numerous benefits, it also has drawbacks, such as low radiation efficiency, low gain, and a restricted bandwidth. For this reason, studies on how to improve its performance have been conducted. Information on microstrip patch antennas was included in this study report, along with an explanation of their design. Important antenna characteristics were also covered, including return loss, gain, bandwidth, voltage standing wave ratio (VSWR), and matching impedance. Additionally, the many methods of improving the microstrip patch antennas' performance were discussed, including the use of Electromagnetic Band-Gap (EBG) structures and Defected Ground Structure (DGS). A summary of the study's findings was provided. The study's findings verify that improving the effectiveness of upcoming 5G and 6G communication networks would need the application of state-of-the-art antenna optimization techniques.

Keywords: Microstrip Patch Antenna, 5G Communication, Wireless Communication, Gain, Directivity, VSWR.

I. Introduction

The microstrip patch antenna is one of the most often used planar antennas in contemporary wireless technology because it is small, light, low-profile, and easy to make. This kind of antenna is made up of a conductive ground plane on one side of the dielectric substrate and a conducting radiating patch on the other.

Depending on the antenna's use and operating frequency, the radiating patch can be shaped in a variety of ways, including square, circular, triangular, elliptical, and hexagonal. Because printed circuit boards are used in their construction, microstrip patch antennas are inexpensive, simple to produce, and easy to combine with other electronic equipment.

One of the most common uses of microstrip patch antennas is in satellite communications radars, GPS devices, Wi-Fi Bluetooth IoT devices, wearable technology, and 5G wireless systems due to the growing need for wireless communications across faster networks. Microstrip patch antennas with many layers Patch antennas are highly appealing for a variety of applications, including mobile devices, satellite systems, and radars. The most crucial characteristics of this kind of antenna are its low profile and ease of construction, which make it ideal for use in mobile devices, ground vehicles, and airplanes. Nevertheless, because to limitations in bandwidth, gain, and efficiency, microstrip antennas do not radiate with 100% efficiency. Despite this, research has produced a wide range of methods that can improve antenna performance, including the application of technologies like stacked patches, slot loading, Electromagnetic Band Gap (EBG) metamaterials metasurfaces, Defective Ground Structure (DGS), and even MIMO technology. These advancements make it possible for microstrip antennas to play a major role in modern wireless communication systems.

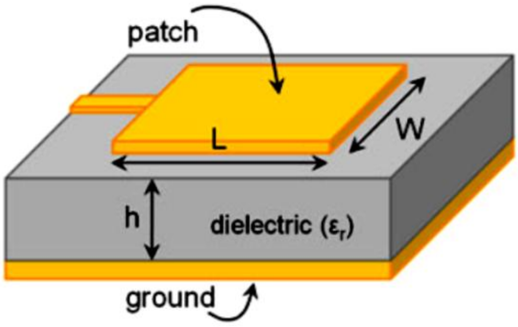

Figure 1. Basic Structure of Microstrip Patch Antenna

Figure 1 shows the three basic parts of a microstrip patch antenna: a ground plane, a dielectric substrate, and a radiating patch. While the metallic patch with length (L) and width (W) emits electromagnetic waves, the dielectric substrate with thickness (h) and dielectric constant (εr) offers mechanical support and influences antenna performance. The ground plane increases directivity and reduces back radiation. Because of its tiny size, low profile, lightweight design, and ease of manufacture, the microstrip patch antenna is widely used in modern wireless communication systems, particularly for 5G applications.

II. Literature Review

Because of its small size, low profile, cheap manufacturing cost, and simplicity of integration with contemporary communication equipment, microstrip patch antennas have emerged as one of the most explored antenna technologies for fifth-generation (5G) wireless communication. However, conventional microstrip patch antennas have disadvantages such low gain, restricted bandwidth, poor radiation efficiency, and mutual coupling in multi-element systems. Numerous techniques, including beamforming, slot loading, Defected Ground Structure (DGS), metasurfaces, metamaterials, and Multiple-Input Multiple-Output (MIMO) configurations, have been proposed by researchers to enhance antenna performance.

Mitha and Gajera [1] offered a comprehensive review of next-generation microstrip patch antennas operating at sub-6 GHz frequencies for 5G applications. By outlining recent advancements in antenna reduction, bandwidth augmentation, gain enhancement, and substrate selection, their research demonstrated the growing importance of tiny and efficient antenna designs. Saeed and Nwajana [2] proposed a wideband 1x6 linear antenna array for automotive radar and 5G millimeter-wave applications, demonstrating similar enhancements in gain and beam steering characteristics. Ding et al. [3] developed a tiny single-layer dual-band microstrip patch antenna that can operate at two 5G frequency bands while maintaining a simple design and compact dimensions. Goswami et al. [4] demonstrated a real S-shaped slot-loaded broadband microstrip antenna that significantly expanded impedance bandwidth while maintaining acceptable radiation performance. A multi-slotted multiband microstrip patch antenna with improved bandwidth characteristics that can support multiple 5G frequency bands was also developed by Nahas [5].

In order to boost bandwidth and isolation in upcoming wireless systems, Ullah et al. [6] introduced a wideband coplanar waveguide-fed MIMO antenna with a Defected Ground Structure (DGS) to offer enhanced isolation and wider impedance bandwidth for 6G millimeter-wave applications. Djouimaa and Bencherif [7] developed a compact circular microstrip patch antenna specifically for 5G applications, demonstrating consistent radiation characteristics with lower antenna dimensions. Iriqat proposed an I-shaped microstrip patch antenna with an enlarged ground plane structure that achieved super-wide bandwidth suitable for 5G and beyond-5G communication systems [8]. Janarthanan et al. [9] suggested a miniaturized microstrip patch antenna that is suitable for portable 5G devices because to its compact size and high radiation efficiency. In order to boost bandwidth and isolation in upcoming wireless systems, Ullah et al. [6] introduced a wideband coplanar waveguide-fed MIMO antenna with a Defected Ground Structure (DGS) to offer enhanced isolation and wider impedance bandwidth for 6G millimeter-wave applications.

Josephine et al. [11] constructed a coaxial-fed MIMO microstrip patch antenna that operates in the millimeter-wave spectrum for 5G communication, achieving adequate return loss and increased isolation. For sub-6 GHz applications, Radhakrishnan and Gupta [12] developed a metasurface-inspired circularly polarized patch antenna coupled with a Defected Ground Structure that greatly enhanced circular polarization bandwidth and radiation performance. In a similar vein, Anooz and Ammar [13] proposed that without increasing antenna size, a redesigned ground plane optimization can greatly enhance antenna impedance bandwidth. Alrashdan et al. [14] improved a microstrip patch antenna's radiation characteristic by maximizing its directivity using the Taguchi optimization technique. Josephine et al. [11] constructed a coaxial-fed MIMO microstrip patch antenna that operates in the millimeter-wave spectrum for 5G communication, achieving adequate return loss and increased isolation.

Many scholars have focused on multiband and broadband antenna designs to address the diverse spectrum requirements of 5G communication. El-Hakim and Mohamed developed a multiband microstrip patch antenna that can accommodate several 5G frequency bands while maintaining tiny

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dimensions [16]. Joshiba and Judson [17] created an eye-bolt-shaped slotted microstrip patch antenna connected to a substrate-integrated waveguide to boost bandwidth and gain. Zhang et al. [18] suggested a low-profile dual-polarized double-layer microstrip antenna with enhanced polarization diversity and isolation for 5G and Wi-Fi applications. Gaid and Ali [19] developed a tri-band rectangular microstrip patch antenna that successfully achieved multiband operation with improved bandwidth and radiation performance using a π-shaped slot. Salehi and Oraizi [20] developed a metasurface-based 4T4R MIMO antenna with highly isolated ports that provides wide bandwidth, high gain, and excellent isolation for sub-6 GHz 5G communication.

Reducing mutual coupling and expanding bandwidth remain important concerns in MIMO antenna systems. As demonstrated by Kim et al. [21], a Defected Ground Structure may effectively boost the bandwidth of square microstrip patch antennas while enhancing impedance matching. Similarly, Güler and Keskin [22] constructed a compact four-port MIMO antenna with DGS that reduced mutual coupling between antenna components and obtained high isolation. Tiwari et al. [23] developed 2x2 and 4x4 dumbbell-shaped microstrip patch antenna arrays for 5G Wi-Fi connectivity. They found enhanced gain suitable for high-speed wireless applications and improved array performance.

Recent research has also focused on advanced performance enhancement techniques using frequency selective surfaces and array topologies. Kumar and Dhubkarya [24] proposed an ultra-wideband compact microstrip patch antenna combined with a special star-shaped frequency selective surface to achieve excellent directivity and improved radiation characteristics. Abraham and Suriyan [25] demonstrated efficient multiband operation with improved radiation efficiency and impedance matching in their examination of a triple-band single-layer proximity-fed 2x2 microstrip patch array antenna.

III. Fundamentals of Microstrip Patch Antenna

The performance of a microstrip patch antenna is influenced by a number of design elements, including patch shape, substrate material, dielectric constant, substrate thickness, feeding technique, and ground plane dimensions. Numerous patch geometries, including as rectangular, circular, square, triangular, elliptical, hexagonal, and slot-loaded systems, are employed to provide the required resonance frequencies and radiation characteristics. The rectangular microstrip patch antenna is the most often used of these because to its simple design and reliable electromagnetic performance.

3.1 Basic Structure of Microstrip Patch Antenna

The basic structure of a microstrip patch antenna consists of three primary components:

- Radiating Patch
- Dielectric Substrate
- Ground Plane

The metallic patch transmits electromagnetic waves, while the dielectric substrate provides mechanical support and regulates important antenna characteristics including resonance frequency, bandwidth, and radiation efficiency. The conducting ground plane suppresses back radiation and improves the antenna's directed radiation pattern.

3.2 Components of Microstrip Patch Antenna

A. Radiating Patch

The radiating patch is the primary element responsible for transmitting and receiving electromagnetic waves. It may be constructed in a number of ways and is frequently composed of copper, depending on the intended operating frequency and application. The size of the patch, particularly its length (L) and width (W), has a significant influence on the resonant frequency, bandwidth, gain, and radiation pattern.

B. Dielectric Substrate

The dielectric substrate separates the radiating patch from the ground plane. It is defined by its thickness (h) and dielectric constant (εr). A substrate with a lower dielectric constant frequently provides more bandwidth and better radiation efficiency, whereas a higher dielectric constant helps reduce antenna size. Common substrate materials include alumina, Taconic, Rogers RT/Duroid, and FR-4.

C. Ground Plane

The ground plane is positioned beneath the dielectric substrate to improve antenna directivity and impedance characteristics while lowering back radiation. Modern antenna designs often include modified ground structures, such as Defected Ground Structure (DGS), to improve bandwidth, gain, and isolation.

3.3 Operating Principle

The operation of a microstrip patch antenna is based on the fringing field phenomena. When radio-frequency (RF) energy is supplied through a feeding mechanism, electromagnetic fields are produced inside the dielectric substrate. The fringing electric fields formed on the edges of the patch release electromagnetic waves into free space. The primary determinants of the antenna's resonant frequency are

International Journal of Recent Development in Engineering and Technology
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the patch's physical dimensions and the substrate's dielectric properties. Appropriate impedance matching between the radiating patch and the feed line ensures efficient power transfer and decreased return loss.

3.4 Types of Microstrip Patch Antenna

Microstrip patch antennas are available in a range of geometrical designs to satisfy the various demands of modern wireless communication systems. The selection of a particular patch form is influenced by a number of factors, including operating frequency, bandwidth, gain, polarization, radiation qualities, size limitations, and manufacturing complexity. The current distribution on the radiating surface, which is affected by various patch shapes, affects the antenna's electromagnetic performance. Over the years, researchers have suggested a number of patch designs to enhance bandwidth, gain, radiation efficiency, impedance matching, and multiband operation for fifth-generation (5G) wireless communication systems. The most popular microstrip patch antenna forms include rectangular, circular, square, triangle, elliptical, hexagonal, slot-loaded, and fractal.

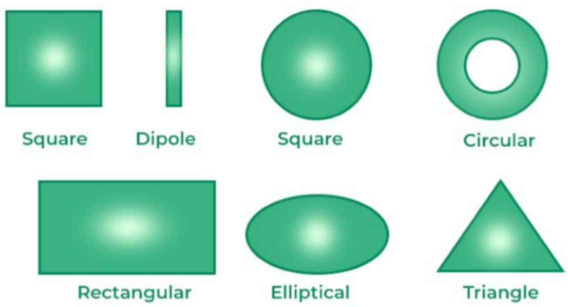

Figure 2. Different Types of Microstrip Patch Antennas

3.5 Advantages of Microstrip Patch Antenna

- Compact and low-profile structure
- Lightweight and easy to fabricate
- Low manufacturing cost
- Easy integration with microwave integrated circuits
- Suitable for MIMO and antenna array configurations
- Compatible with 5G, IoT, satellite, and wearable communication systems

3.6 Limitations of Microstrip Patch Antenna

- Narrow impedance bandwidth
- Relatively low gain
- Lower radiation efficiency
- Surface wave losses
- Limited power-handling capability
- Mutual coupling in MIMO antenna systems

IV. Methodology and Mathematical Analysis

Designing and evaluating microstrip patch antennas requires a systematic methodology supported by electromagnetic theory and mathematical modeling. By examining design techniques, performance enhancement tactics, and published research articles, this study provides a comprehensive analysis of existing microstrip patch antenna technologies for fifth-generation (5G) wireless communication applications. The research focuses on antenna geometries, substrate materials, feeding techniques, and advanced technologies such as slot-loaded designs, metamaterials, Electromagnetic Band-Gap (EBG) structures, Defected Ground Structure (DGS), and Multiple-Input Multiple-Output (MIMO) configurations. Mathematical formulae based on the transmission line model are frequently used to explain the computation of essential antenna properties, including patch size, resonance frequency, effective dielectric constant, return loss, bandwidth, and Voltage Standing Wave Ratio (VSWR). These analytical formulas provide the theoretical basis for developing efficient microstrip patch antennas and enable a comparative evaluation of different antenna designs reported in the literature.

4.1 Mathematical Analysis of Microstrip Patch Antenna

The mathematical design of a microstrip patch antenna is based on the transmission line model, which provides a simple and accurate way to determine the antenna dimensions for a given resonant frequency. The main factors influencing antenna performance are patch width, patch length, dielectric constant, and substrate thickness. These characteristics are calculated using standard design formulae to provide proper impedance matching, efficient radiation, and stable operation in 5G wireless communication systems.

A. Patch Width

$$W = \frac{c\sqrt{\frac{2}{1+\epsilon r}}}{2fr}$$

The width of the radiating patch is calculated as (1)

B. Effective Length

$$Leff = \frac{c}{2fr\sqrt{\epsilon reff}}$$

The effective resonant length is (2)

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C. Effective Dielectric Constant

$$\in reff \equiv \frac{(\in r+1)}{2} + \frac{(\in r-1)}{2\sqrt{1+12\left(\frac{h}{w}\right)}}$$

The effective dielectric constant is expressed as (3)

D. Fringing Length Extension

$$\Delta L = 0.412 \frac{(\in reff + 0.3)\left(\frac{w}{h} + 0.2264\right)}{(\in reff - 0.258)\left(\frac{w}{h} + 0.8\right)}$$

The fringing field extension is given by (4)

E. Actual Patch Length

$$L = Leff - 2\Delta L$$

The actual patch length is (5)

V. Conclusion

Because of its small size, low profile, lightweight design, ease of manufacture, and compatibility with contemporary integrated circuits, microstrip patch antennas have become a crucial enabling technology for fifth-generation (5G) wireless communication systems. This research addressed the fundamental structure, operational principles, antenna geometries, mathematical design issues, and recent developments in microstrip patch antenna technology. A variety of performance-enhancing techniques were evaluated for their ability to increase bandwidth, gain, radiation efficiency, and impedance matching. These techniques included Defected Ground Structure (DGS), Electromagnetic Band-Gap (EBG) structures, metamaterials, slot-loading, beamforming, and Multiple-Input Multiple-Output (MIMO) configurations. According to the reviewed literature, these state-of-the-art techniques have significantly enhanced antenna performance, making microstrip patch antennas suitable for sub-6 GHz and millimeter-wave 5G applications. However, problems including bandwidth limitations, mutual coupling, downsizing, and manufacturing complexity still require more investigation. Future research should focus on integrating artificial intelligence-based optimization, reconfigurable antenna architectures, metasurfaces, and intelligent beamforming algorithms to allow wireless communication systems beyond 5G and 6G. All things considered, this assessment is a valuable tool for engineers and researchers involved in the design and development of next-generation microstrip patch antennas.

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