Microstrip Antenna Technologies for Sub-6 GHz and 6G Wireless Communication

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Abstract—**The evolution of wireless communication technologies from 1G to 5G has revolutionized world connectivity, supporting applications ranging from voice calls to terabit-per-second data transfer and IoT networks. The next generation (6G) of wireless communication has the potential to offer even higher capabilities in the form of terabit-per-second data rates, ultrareliable low-latency communication (URLLC), and enabling applications such as holography, extended reality (XR), and intelligent transportation. To cater to these needs, antenna technologies need to be advanced to offer greater gain, wider bandwidth, and improved adaptability. Microstrip antennas, due to their small structure, low profile, and simple fabrication, find extensive application in sub-6 GHz spectrum for 5G and are expected to contribute significantly to initial 6G implementations. This survey analyzes microstrip antenna technologies for sub-6 GHz and their extension into 6G systems. It includes antenna basics, microstrip antenna types, feeding methods, performance measures like gain and bandwidth, communication frequency bands, and addresses challenges and potential opportunities for future wireless networks.**

Index Terms—**Microstrip antenna, Sub-6 GHz, 6G communication, antenna gain, bandwidth, feeding techniques, wireless communication.**

I. INTRODUCTION

Wireless communication has come a long way in the past four decades, beginning with analog voice 1G systems in the 1980s to 5G networks providing gigabit speeds and ultra-low latency. Although 5G brings millimeter-wave (mmWave) frequencies (above 24 GHz), the sub-6 GHz spectrum (3–6 GHz) is still vital because of its broad coverage, improved penetration, and optimal deployment.

In the 6G era, due to appear around 2030, wireless systems will extend to mmWave (30–100 GHz) and terahertz (THz, >100 GHz) frequencies for extremely high speeds. Nevertheless, sub-6 GHz antennas will remain essential for delivering wide-area coverage, mobility, and robust links in dense urban and rural areas [1].

Microstrip antennas are well suited for sub-6 GHz and upcoming 6G systems due to:

- They are light and compact, which makes them suitable for mobile devices and base stations.
- They can be mounted on printed circuit boards (PCBs) in a cost- and complexityeffective manner.
- They can be grouped into arrays to deliver high gain and beamforming capabilities for massive MIMO.

This paper overviews microstrip antenna technologies with an emphasis on their design, feeding structures, performance characteristics, and applicability for sub-6 GHz 5G/6G systems as well as future high-frequency 6G deployments [17].

II. ANTENNAS IN WIRELESS COMMUNICATION

An antenna is a piece of hardware that transforms guided electromagnetic waves in a transmission line into free-space waves and vice versa. It is an essential element in wireless systems, as it defines coverage, link reliability, and communication quality.

Major functions of antennas in next-gen systems:

- Radiation and Reception: Radiating efficiently in free space and receiving incoming signals.
- Mobility and Coverage: Facilitating long-range coverage in sub-6 GHz bands and beam steering in 6G mmWave/THz.
- Spectral Efficiency: Increasing capacity via beamforming and MIMO.

- Integration with Devices: Enabling form factors in smartphones, IoT devices, and vehicular systems.

Antennas are not mere passive devices in 6G but smart radiators whose patterns are dynamically adapted (through smart antennas, RIS – reconfigurable intelligent surfaces) to optimize coverage and capacity [16].

III. MICROSTRIP ANTENNAS

A microstrip antenna is one of the most common antenna forms used in today's wireless communication systems, and it is mostly composed of three parts: the patch, the dielectric substrate, and the ground plane. The patch, or the radiating part, usually is a thin metal plate of copper and is fabricated geometries like rectangular, circular, or others to regulate its radiation parameters. Underneath the patch is the dielectric substrate, which supports mechanically as well as contributes significantly to the antenna's bandwidth, efficiency, and overall performance. Typical substrate materials are FR4 and Rogers RT/Duroid, chosen according to desired dielectric constant and loss behavior. At the bottom is the ground plane, a metallic layer reflecting and guiding electromagnetic radiation, improving the efficiency of the antenna .

Microstrip antennas are lightweight, low-profile, and compact, rendering them extremely desirable for portable and integrated systems. The fabrication of microstrip antennas is straightforward and inexpensive as they can be fabricated using simple PCB technology. Microstrip antennas are also capable of dual-band or multi-band operation, and they are conveniently compatible with integrated circuits, which is a requirement for current wireless devices. While these benefits, they possess some limitations like a limited bandwidth of about 2–5% for a single patch, moderately low gain in the order of 5–8 dBi, and surface wave loss leading to degradation in performance when thicker substrates are used.

For sub-6 GHz spectrum utilization, microstrip antennas are widely utilized in cellular handsets, particularly at the 3.5 GHz band frequency for 5G communication, in base stations, WLAN, Wi-Fi 6 equipment (5.1–5.9 GHz range), IoT devices, and automotive communication systems. With advancements in wireless communication towards 6G, sub-6 GHz microstrip antennas will remain indispensable for providing wide-area coverage. Furthermore, innovative structures like antenna arrays and reconfigurable microstrip antennas will be created to support beam steering, massive MIMO, and improved spectrum efficiency. Furthermore, research is being focused on extending microstrip antenna technology for use in higher frequency bands like millimeter-wave (mmWave) and terahertz (THz) bands to address the requirements of ultra-high-speed, low-latency next-generation networks [4].

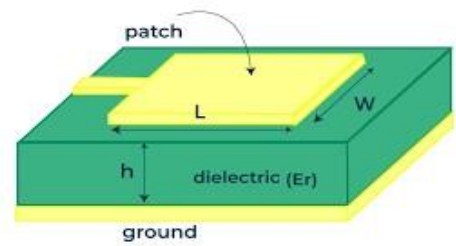

Fig.3.1 Rectangular Microstrip Patch Antenna

IV. TYPES OF MICROSTRIP ANTENNAS

Rectangular Patch Antenna:

The rectangular patch is one of the most commonly employed microstrip antennas due to its easy geometry and simplicity in analysis with models such as the transmission line and cavity model. The rectangular patch offers reliable radiation patterns and has broad application in mobile communication devices, Wi-Fi routers, and wireless sensor networks [5].

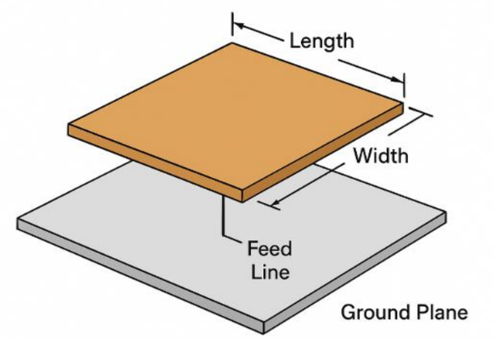

Fig. 4.1. Rectangular Patch Antenna

Circular Patch Antenna:

Circular patch antennas provide circular polarization, which makes them ideal for use in applications where device orientation can be altered, like in satellite communications, GPS systems, and some radar applications. Their symmetric geometry also facilitates easier fabrication and miniaturization.

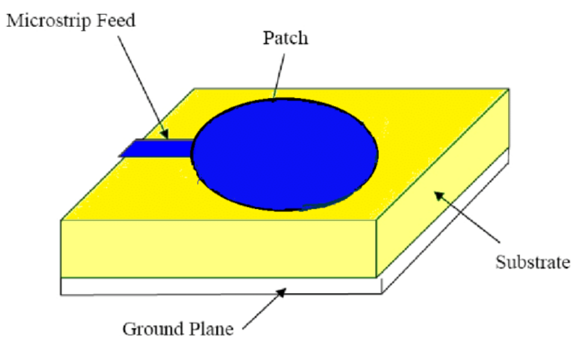

Fig. 4.2. Circular Patch Antenna

Slotted Patch Antenna:

By implementing slots within the patch, the current path becomes effective, thus enhancing bandwidth and enabling dual- or multi-band operation. Such antennas are usually employed in devices that require support of several standards, e.g., smartphones or IoT devices [9].

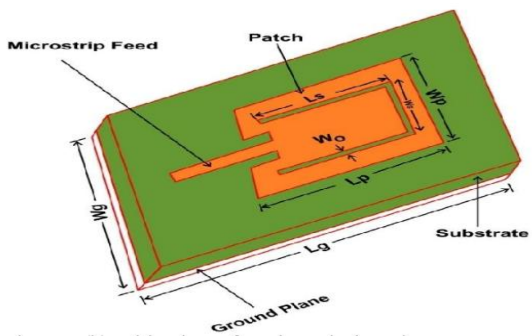

Fig. 4.3. Slotted Patch Antenna

Array Antennas:

When several patches are deployed in linear or planar configurations, they create array antennas. These offer extremely high gain (usually greater than 15 dBi) and beam steering ability, which is mandatory for 5G/6G base stations and massive MIMO technologies [12].

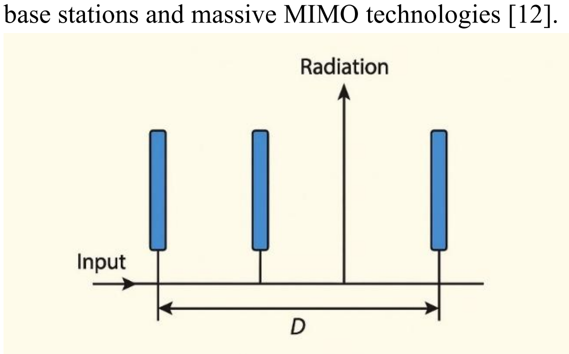

Fig. 4.4. Array Antennas

Reconfigurable Antennas:

Reconfigurable microstrip antennas contain electronic elements such as PIN diodes, MEMS, or varactors so that they can dynamically alter their operating frequency, polarization, or radiation pattern. Such adaptability makes them immensely useful in future communication systems like 6G, where adaptive connectivity and spectrum agility are critical [20].

V. FEEDING TECHNIQUES TO MICROSTRIP ANTENNAS

Microstrip antennas are widely used since they are lightweight, inexpensive, and simple to construct. The four most common feed techniques employed are the microstrip line feed, coaxial probe feed, aperture coupled feed, and proximity coupled feed [6].

Microstrip line feed: - In the fig 5.1, the microstrip patch edge is directly connected to a conducting strip. The benefit of placing this type of feed is that the feed can be etched in the same substrate to create a planar structure. However, as the thickness of dielectric substrate grows, surface waves and spurious feed radiation also grow. Because it gives ease of fabrication and model simplicity in addition to impedance matching. This kind of feeding technique causes unwanted cross polarization effects [8].

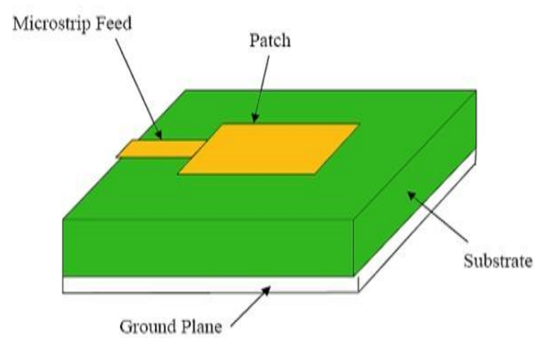

Fig 5.1: Microstrip line feed

Coaxial Feed:- The most common method for microstrip patch antennas' feed is Probe Feed or the so-called Coaxial Feed. The major advantage of this feed structure is its impedance matching system. It makes the feed positional at any preferable location in the patch sequence which results in impedance matching. But the demerit of the model is that it consists of a low bandwidth and is a complicated model because a hole is to be drilled in the substrate. To enhance the bandwidth, we employ a thick dielectric substrate, the coaxial and microstrip feed produces different hinderance like spurious feed radiation and matching issues [3].

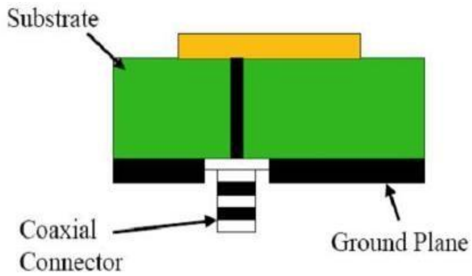

Fig 5.2: Coaxial Feed

Aperture Coupled Feed: - In aperture coupling model, The antenna substrate top contains a patched radiating element and for keeping the aperture coupling intact a microstrip feed is provided at the bottom of the model. For optimizing the independent distinct electrical functions of circuitry and radiation the thickness as well as the dielectric constants can be selected independently based on the required utility. The lower cross polarization is obtained by symmetrical modelling of the model and thus

The coupling aperture is centred typically under the patch. This is a type of aperture coupled model that has around 21% bandwidth. It is a challenging model to fabricate due to multiple layers which also thickens the antenna [5].

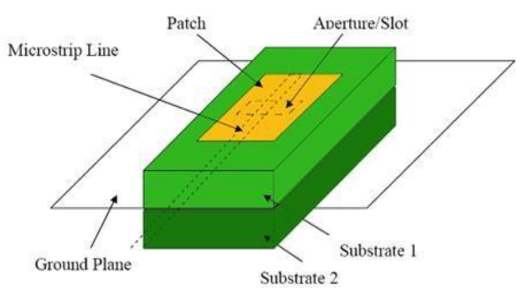

Fig 5.3: Aperture Coupled Feed

Proximity Coupled Feed:- Proximity coupled feed is a next-generation feeding method for microstrip patch antennas wherein the feed line is embedded in between two dielectric substrates and electromagnetically couples with the radiating patch on the top substrate.

It successfully suppresses spurious feed radiation and provides much higher impedance bandwidth (of about 13%, extendible to 25% through the stacked geometry). The other benefit is design flexibility since varying dielectric media can be chosen for the feed line and for the patch to enhance performance. But the technique also has some drawbacks, including thicker antenna and complexity in fabrication because of the need for precise substrate alignment. To further promote miniaturization and performance, Defected Ground Structures (DGS) are utilized, in which slots or patterns are formed on the ground plane to alter the distribution of currents. DGS minimizes antenna size by almost 68% compared to traditional designs and is now a common solution to compact high-performance wireless communication systems [7].

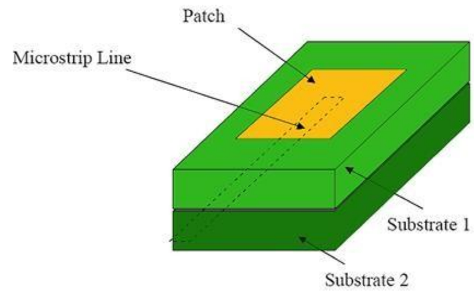

Fig 5.4: Proximity Coupled Feed

6G Implication: Proximity and aperture coupling are preferred for broadband antennas required in high-frequency systems.

VI. MICROSTRIP ANTENNA PERFORMANCE PARAMETERS

Microstrip antennas are assessed in terms of gain, bandwidth, and operation communication bands, which directly impact their performance in Sub-6 GHz (5G) and 6G wireless networks.

6.1 Gain

The gain of an antenna is a measurement that describes both its directivity, which describes the capacity to radiate power in a particular direction, and its efficiency, which describes how well the input power is converted into radiated energy. It can be mathematically described as:

$$G = D \times \eta$$

For microstrip antennas, typical values of the gain depend on the design. A basic microstrip patch antenna would typically provide a gain of 5–8 dBi, which is adequate for use in Sub-6 GHz devices like mobile phones and low-power base stations. But where multiple patches are combined in an array using methods like MIMO and beamforming, the gain is dramatically increased to 12–20 dBi. This enhancement is also especially important for 6G networks, where directional antennas with high gain are needed to counteract the extreme propagation

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Sr. No.	Frequency Range	Application (5G/6G)	Typical Microstrip Bandwidth	Enhancement Techniques
1.	3.3 – 3.6 GHz (n78)	5G NR Sub-6	100 – 150 MHz (~3–4%)	Slots, stacked patches
2.	4.4 – 4.9 GHz (n79)	5G NR Sub-6	150 – 200 MHz (~3–4.5%)	Thick substrate, array structures
3.	5.1 – 5.9 GHz (WLAN, Wi-Fi 6)	5G + Wi-Fi	200 – 300 MHz (~4–5%)	EBG, dielectric loading
4.	28 – 39 GHz (mmWave)	5G / Pre-6G	1 – 2 GHz (~5–7%)	Arrays, SIW (Substrate
5.	90 – 140 GHz (THz window)	6G (Short-range Tbps	5 – 10 GHz (~7–10%)	Graphene antennas, metamaterials, nano-fabrication

losses at terahertz (THz) and millimeter-wave (mmWave) frequencies [13].

6.2 Bandwidth

The bandwidth of a microstrip antenna is the range of frequencies over which the antenna is effective, typically defined by an input reflection coefficient (S11) of less than –10 dB or by a voltage standing wave ratio (VSWR) of less than 2. Traditionally, microstrip antennas are narrowband in nature with a bandwidth of about 2–5% of the resonant frequency, restricting their performance in wideband communication systems. To avoid this limitation, various improvement techniques are utilized. Stacked patches may be utilized to achieve a number of resonances, thus extending the operating bandwidth. Slot loading on the patch adds dual- or multi-band functionality, and utilization of thick substrates with low dielectric constant improves fringing fields, which further enhances bandwidth. More sophisticated methods include incorporating electromagnetic bandgap (EBG) or metamaterial structures, which are useful in surface wave suppression and greatly improving impedance bandwidth and radiation efficiency [14].

6.3 Communication Bands

Microstrip antennas operating at Sub-6 GHz frequencies are critical to 5G and initial deployments of 6G. The most significant frequency allocations are 3.3–3.6 GHz (5G NR band n78), the popular mobile broadband frequency used in many places, 4.4–4.9 GHz (band n79), which is mainly used in nations such as China, Japan, and Korea, and 5.1–5.9 GHz, which is used for WLAN and Wi-Fi 6 operation in the unlicensed bands. Sub-6 GHz offers strong coverage with minimal propagation loss but has minimum capacity to support very high data rates [15].

Table 6.1 Microstrip Antenna Bandwidth Comparison (Sub-6 GHz vs 6G)

In 6G, communication is anticipated to be extended to higher frequency bands beyond Sub-6 GHz. The Sub-6 GHz band will be the coverage layer, providing wide-area coverage, particularly for rural and indoor areas. For super-high-capacity services, 6G will heavily depend on the mmWave band (30–100 GHz), with multi-gigabit-per-second data rates but line-of-sight communication because of the high path loss. Apart from this, terahertz frequencies (>100 GHz) are projected to provide terabit-per-second rates, supporting futuristic applications like holographic communication, immersive extended reality (XR), and smart IoT systems [15][16].

VII. CHALLENGES AND OPPORTUNITIES

Challenges:

The major challenge in microstrip patch antennas is their inherently narrow bandwidth, typically restricted to merely 2–5%. This limitation does not allow it to support wideband communication, which is inevitable in next-generation systems such as 6G. Another limitation is the relatively low gain of a single patch (typically 5–8 dBi), which becomes inadequate in high-frequency applications in mmWave and THz bands.

At higher frequencies, efficiency decreases drastically owing to higher conductor and dielectric losses, and it becomes more difficult to achieve consistent performance. Additionally, during antenna design for mmWave and THz, fabrication tolerance is a serious concern since even slight discrepancies in patch size can cause significant frequency shifts and inferior performance. These issues point towards the requirement for sophisticated materials, novel fabrication methods, and intelligent design approaches [18].

Opportunities:

Even with these constraints, microstrip antennas present tremendous 6G opportunities as well. Massive MIMO arrays can remedy low-gain problems by aggregating multiple patches into high-performance beamforming arrays. These arrays not only provide higher gain but also spatial multiplexing, which is very important in achieving ultra-high data rates for 6G.

Reconfigurable antenna architectures offer another promising opportunity. With tunable components like varactors, MEMS, or PIN diodes, antennas can switch dynamically between various frequencies and radiation patterns, enabling various 6G use cases such as IoT, autonomous vehicles, and smart cities.

In addition, metamaterial and Electromagnetic Band Gap (EBG) structures may be integrated with microstrip patches to maximize bandwidth and gain. Lastly, the most cutting-edge potential is realized by integrating antennas with AI-managed Reconfigurable Intelligent Surfaces (RIS). These dynamically reorient signals in real-time, enabling intelligent 6G environments with enhanced coverage, efficiency, and connectivity.

VIII. CONCLUSION

Microstrip antennas continue to be a bulwark of sub-6 GHz wireless communications because of their small size, low cost, and ease of integration. For 5G, microstrip antennas support robust mid-band spectrum connectivity, and for 6G, they will shape up as reconfigurable, high gain, and wideband arrays to facilitate new applications. Advanced feeding schemes, stacked and slotted configurations, and metamaterials will come together to make microstrip antennas support both sub-6 GHz and high-frequency 6G communication systems.

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