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From Past to Present: A Comprehensive Review of Antenna Technology in Modern Wireless Communication

Brijesh Mishra[1,*], Aditya Kumar Singh[2], T Y Satheesha[3], Ramesh Kumar Verma[4] and Vivek Singh[5]

[1]Department of Electronics and Communication Engineering, School of Engineering and Technology, CMR University, Bengaluru, Karnataka, India.
[2]Department of Electronics and Communication Engineering, Noida Institute of Engineering and Technology, Greater Noida, U.P., India.
[3]School of Computer Science Engineering, REVA University, Bengaluru, Karnataka, India.
[4]Department of Computer Science and Engineering, IMS Engineering College, Ghaziabad, Uttar Pradesh, India.
[5]Department of Electronics and Communication Engineering Nagarjuna College of Engineering and Technology, Bengaluru, Karnataka, India.

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Abstract

This research looks at microwave devices, specifically, patch antenna along with electromagnetic spectrum, shape, mechanism, analytical methods, simulation tools, and feeding procedures. Patch antennas are distinguished by their rectangular form, with a patch on one side and a ground plane on the other. Patch antennas work by exciting electromagnetic waves inside the patch, which are subsequently transmitted into the surrounding environment. The report also outlines numerous ways for evaluating the performance of microstrip patch antennas. The electromagnetic characteristics of the antenna are analyzed using the transmission line model, cavity model, and multiport network model (MNM). The integral equations that regulate the behavior of the antenna are solved using the method of moments (MoM) and the finite element method (FEM). The spectral domain technique (SDT) is used to analyze the antenna's frequency response, while the finite difference time domain (FDTD) approach is used to analyze the antenna's time-domain behavior. Overall, these methodologies give a thorough understanding of microstrip patch antenna performance and may be utilized to optimize their design. Furthermore, several patch antenna feeding methods, such as probe feed, microstrip line feeding, aperture coupling, proximity coupling, and CPW feed, are investigated. Attaching a microstrip line to the patch, which is subsequently linked to the RF source, is what microstrip line feeding entails. Aperture coupling entails making a hole in the ground plane that allows the RF source to feed the patch directly. Proximity coupling is accomplished by placing a probe near the patch, which creates an electromagnetic field on the patch. Patch antenna simulation software includes programmers such as HFSS, CST, and FEKO. These tools simulate the patch antenna's performance, including its radiation pattern, gain, and input impedance. These simulations may be used to optimize the patch antenna design for specific applications. Moreover, recent antenna trends are presented in this article.

Keywords: EM spectrum, microwave devices, radiation mechanism, analysis methods, feeding techniques, EM simulator.

1. Introduction

Microstrip antennas are a common antenna type. Microstrip antennas are a common antenna type. Microstrip antenna development began about 40 years ago and is still going strong today. The discovery of low-loss, low-cost materials enable the fabrication of an efficient, low-profile microstrip patch antenna [1]. Novel analytical approaches and models help in the development of novel radiating patches that may be created and tested for use in a wide range of applications [2]. Because of advances in computer processing capability, numerical techniques have become more affordable, allowing for additional dimensions in performing parametric analysis of planned antennas [3]. Analytic methodologies not only allow designers to develop free-space patch antennas, but also to meet new requirements for new applications using new technology [4]. The defense sector was the first to push for microstrip antenna research, but it has now switched to telecommunications, automotive, aerospace, and medical applications [5]. Advances in microstrip antenna design have helped a wide range of technologies, including global positioning satellites and wide area communication networks [6, 7]. Wireless devices are increasingly requiring compact planar multiband antennas with reduced shapes [8]. As a result, one of the key goals is to minimize antenna size. Miniaturized and multiband antennas are sought as device sizes continue to shrink [9]. Meandering, bending, folding, and wrapping are examples of miniaturization techniques, whereas ground plane and radiating patch alterations, such as permanent slots, reconfigurable slots, ground strip, defective ground, and notches, are examples of multiband operation [10]. Current research calls for the investigation of multi and wideband compact microstrip antennas employing diverse substrates (rigid and flexible) of varying thicknesses for wireless and specialized applications [11]. In addition to the well-known glass epoxy (FR-4) and Duroid substrates, other polymeric substrates such as PTFE (TEFLON), Polycarbonate, FEP, and others) are sought for designing and fabricating miniaturized and multiband and broad band patch antennas for specialized purposes. The current work's subject of study comprises a complete overview of antenna as a microwave device in general, as well as research on a specific kind of antenna, namely microstrip antenna. The microstrip antenna, a kind of antenna and microwave device, is explored

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*E-mail address: brijesh.mishra0933@gmail.com

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in depth. The parts that come before it goes through the electromagnetic spectrum, microwave frequency bands, and microwave devices, as well as microstrip antenna analysis approaches, feeding schemes, and simulation tools. There includes a general introduction to antennas as well as a discussion of microstrip patch antennas.

2. Electromagnetic spectrum

Electromagnetic radiation refers to numerous types of energy that travel across space in the form of waves. The warmth radiated by a blazing fire, the bright light released by the sun, X-rays used by medical personnel, and the energy used in microwaving food are all forms of electromagnetic radiation. Despite their apparent dissimilarities, they share one feature: the display of wave-like features. Electromagnetic waves may be distinguished and organized based on their unique wavelengths and frequencies, resulting in the electromagnetic spectrum. This spectrum provides a complete framework for categorizing and comprehending the whole spectrum of electromagnetic radiation, from extremely long radio waves to extremely short gamma rays. Scientists and researchers may understand the features and behaviors of these waves by researching the electromagnetic spectrum, which opens a world of possibilities in sectors such as communication, health, astronomy, and technology. Long wave radio, AM broadcast radio, shortwave radio, VHF TV, FM broadcast radio, microwave frequencies, infrared, visible light, ultraviolet, X-rays, and gamma rays are all designated electromagnetic spectrum bands. The frequency band names for the 3105 to 31019 Hz spectrums are shown in Fig.1.

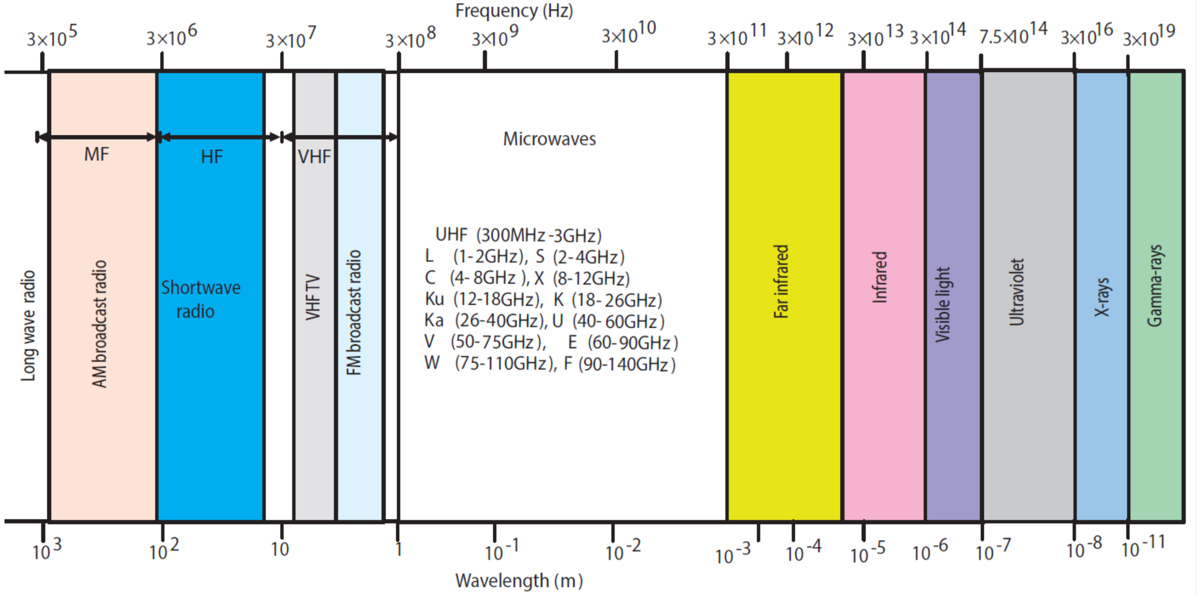


Fig. 1. Band allocations of electromagnetic spectrum

2.1 Microwave frequency band

The microwave frequency range is 300MHz to 300GHz, and different microwave devices, both active and passive, have been precisely built to perform within this band. Originally developed for military radar purposes, RF and microwave technology is now widely used in a variety of fields. Microwave technology is used extensively in satellite communication, wireless local area networks (WLAN), and cellular telephony. It is used in process control, sensing, monitoring, and curing processes in industrial contexts. Microwaves also aid the biological area through applications such as hyperthermia therapy and imaging methods. The proper frequency band is determined by the individual needs of each application as well as the unique features of electromagnetic waves. Table 1 presents a thorough overview of microwave frequency uses, demonstrating their ubiquitous effect across numerous sectors and technological breakthroughs [12]. The adaptability and effect of microwave frequencies are projected to extend further as technology advances, giving new chances for innovation and advancement.

Table 1. Applications of microwave frequency range [12]

Frequency Range (300MHz-300GHz)	**Applications**
300-400.15 MHz	Defense system, radio astronomy, Land Services (ILS), PPDR, PMR, PAMR
400.15-406 MHz	S-PCS, Sondes, weather satellite, active medical implants
406- 430MHz	EPIRBs, military systems, PMR/PAMR, radio astronomy
430-470MHz	Amateur, active sensors, ISM, PMR/PAMR, land mobile
470-960MHz	Broadcasting, PMSE, MFCN, PMSE, PPDR, GSM, IMT, alarms, MCV, RFID
960-1400MHz	Aeronautical military systems, GALILEO, GLONASS, GNSS Repeater, GPS, Active sensors, Radiolocation
1400-1559MHz	Passive sensors, Radio astronomy, Land military systems, Maritime military systems, MFCN, T-DAB, MSS Earth stations, IMT-2000
1559-1880MHz	GALILEO, GLONASS, GNSS Repeater, GPS, IMT-2000, MSS Earth stations, Radio astronomy, Meteorology, Weather satellites, Land military systems, Weather satellites, GSM, MCV, MCA
1880-2400MHz	DECT, DA2GC, MCA, MCV, MFCN, MSS Earth stations, IMT, PMSE, Aeronautical / Maritime military systems, Land military systems
2400-3100MHz	Amateur, ISM, RFID, Wideband data transmission systems, MBANS, MSS Earth stations, PMSE, MCV, MFCN, Radio astronomy, Passive sensors, Radiolocation

3100-5000MHz	Active sensors, Radio astronomy, UWB applications, Radiolocation, Amateur, BWA, FSS Earth stations, MFCN, PMSE, ESV, Passive sensors, Aeronautical military systems, BBDR, Telemetry/Tele-command
5000-5850MHz	GALILEO, Radio astronomy, Satellite navigation systems, MLS, Radio determination Applications, BBDR, Radio LANs, Active sensors, Maritime radar, Weather radar, Amateur, BFWA, ISM, TTT
5.850-10GHz	BFWA, DA2GC, FSS Earth stations, ISM, ITS, ESV, Passive sensors, UWB applications, Land military systems, MSS Earth stations, Satellite systems, Aeronautical navigation, Active sensors, Radiolocation
10GHz-13.25GHz	Amateur, BFWA, PMSE, Radiolocation, Land military systems, Radio determination applications, Passive sensors, Radio astronomy, AES, FSS Earth stations, HEST, LEST, Broadcasting, Fixed
13.25-14.5GHz	Active sensors, Airborne doppler navigation aids, Maritime radar, FSS Earth stations, Radiolocation, Passive sensors, AES, ESV, HEST, LEST, VSAT, MSS Earth stations, AGA communications,
14.5-40.5GHz	Military systems, Radio astronomy, Passive/ sensors, Radiolocation, FSS Earth stations, GBSAR, GSO ESOMPs, NGSO ESOMPs, Feeder links, HEST, LEST, PMSE, Broadcasting, SRR, ISM, Amateur, TTT, BFWA
40.5-76GHz	FSS Earth stations, Fixed, MWS, Radio astronomy, military systems, Amateur, HAPS, PMSE, Feeder links, Passive sensors, Wideband data transmission system, ISM, Land mobile, ITS, Space research
76-300GHz	Amateur, Radio astronomy, Railway applications, SRR, TTT, Passive/Active sensors, Space research, Fixed, Earth exploration-satellite

3. Classifications of microwave devices

Microwave devices are roughly categorized into two types: active and passive (see Fig.2). Active devices have the capacity to deliver energy or power to a circuit on their own, whereas passive devices do not. Active devices include a variety of components such as energy sources, amplifiers, and microwave frequency generators. Passive devices, on the other hand, may nevertheless adjust voltage and current levels despite their inability to create microwave frequencies. Microwave diodes, transistors, oscillators, mixers, Gunn diodes, IMPATT diodes, PIN diodes, Schottky barrier diodes, Klystrons, traveling-wave tubes (TWT), and magnetrons are examples of active microwave devices. These devices are used to generate, enhance, and regulate microwave waves. Passive microwave devices, on the other hand, such as microwave couplers, power dividers, magic tees, attenuators, resonators, and microwave antennas, are critical in modifying microwave signals without contributing energy to the system. Signal distribution, isolation, power regulation, filtering, and antenna transmission all rely on these passive components. Understanding the difference between active and passive microwave devices is critical for building and optimizing microwave circuits for a wide range of applications, including telecommunications and radar systems, as well as scientific research and industrial operations.

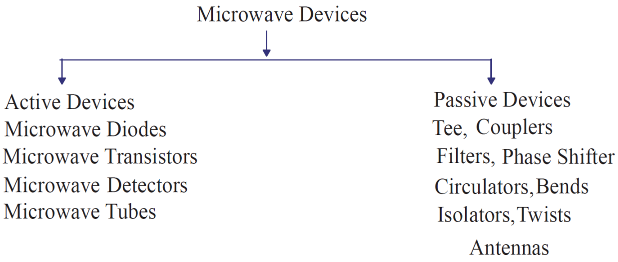


Fig. 2. Classification of microwave devices

3.1. Brief introduction of antenna

Antennas are indispensable in modern civilization, acting as vital connecting links between humans and their surroundings, even extending our reach into space. They enable the smooth transmission of information across enormous distances and are sometimes compared to electronic eyes and ears [13]. Various opinions on antennas may be found in the literature in terms of technical terminology. An antenna, according to the IEEE standard definitions of antenna terminology (IEEE Std 145-1983), is defined as an electrical device with the exceptional capacity to both transmit and receive radio waves. An antenna may also be described in the context of a circuit, where it represents the load impedance coupled to the transmission line and its radiating resistance [13]. An antenna, in essence, serves as a transition device or transducer, allowing electromagnetic energy to be exchanged between guided wave propagation and free space propagation, or vice versa. Antennas' extraordinary capacity to capture and interact with electromagnetic waves has enabled a plethora of uses in communication, wireless technology, satellite systems, and even space exploration. As civilization progresses, the role of antennas in linking people and expanding our awareness of the cosmos will become more important, making them an essential aspect of our technological advancement.

The antenna serves as a bridge between electrons in a conductor and photons in space. A guided wave flowing through an open transmission line, as shown in Fig.3, will radiate as a free space wave. The directed wave is a plane wave, whereas the free space wave expands spherically. Transmission lines are often constructed to minimize radiation loss, whereas antennas are constructed to emit or receive energy as effectively as possible [13]. A brief history of antenna development with reported works [14-20] is enumerated in Table 2. Joseph Henry reported the first wired antennas in 1842. The history of wireless antennas dates back to 1864, when James Clerk Maxwell predicted the presence of electromagnetic waves [14-15]. In 1885, Thomas Alva Edison received a patent for a communication system that featured a vertical top-loaded antenna [16]. Heinrich Hertz successfully made, transmitted, and received electromagnetic waves later that year, in 1888, verifying Maxwell's theoretical predictions [17]. Indian physicist Jagdish Chandra Bose began testing millimeter-wave transmission in 1895 and created the first horn antenna in 1897 [18]. Marconi demonstrated the capability of radio waves to maintain continuous communication with ships sailing the English Channel in 1897. In 1901, he conducted a transatlantic experiment to establish the viability of long-distance (over 300 km) radio transmission [19- 20].

3.2. Classification of antenna

Antennas have a diversified set of properties that allow them to be classified based on various design standards, modes of operation, antenna parameters, and, most significantly, their specialized areas of use. As depicted in Fig. 4, we come across numerous kinds of antennas in the literature. Our focus and concentration for this work are on planar antennas, with a special emphasis on the microstrip patch antenna. As a result, the previous paragraph serves as a primer on the interesting world of microstrip antennas. Microstrip patch antennas have sparked considerable attention due to their distinct properties, small size, and simplicity of integration into a wide range of devices and systems. Because of their planar form, they are suited for applications that need a low-profile and lightweight design. These antennas may be found in wireless communication systems, satellite communication systems, radar systems, and even current smart phones and other portable electronic gadgets. We will investigate the design concepts, performance measurements, and practical applications of microstrip patch antennas throughout this study, providing light on their relevance and potential to shape the future of wireless technology and communication systems.

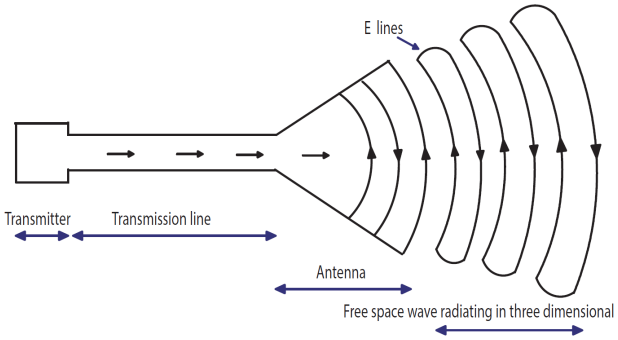


Fig. 3 Interfacing of antenna (redrawn after [13])

Table 2. Brief history of antenna growth

Ref.	Year	Inventors	Work
[14]	1842	Joseph Henry	Wire antenna was invented
[15]	1865	James Clerk Maxwell	Electric and magnetic fields travel through space as waves with velocity of light
[16]	1885	Thomas Edison	Communication system using top loaded antenna
[17]	1888	Heinrich Rudolf Hertz	Proved the existence of electromagnetic waves predicted by Maxwell
[18]	1895	Jagdish Chandra Bose	5-6 mm wavelength wireless transmission using electromagnetic waves
[19]	1897	Guglielmo Marconi,	Practical application of wireless communication system using of radio contact between shore and ships
[20]	1901	Guglielmo Marconi	First experiment for long distance communication by antennas

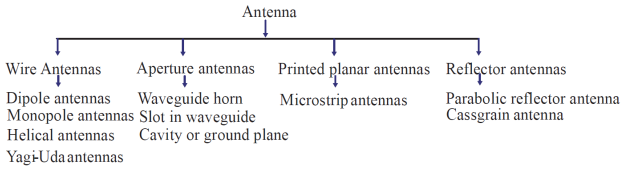


Fig. 4. Classifications of an antenna

3.3. Microstrip patch antennas

Deschamps [21] presented the notion of a microstrip patch antenna (printed antenna) in 1953. However, after 20 years, Munson and Howell built workable antennas in the1970s [22-23]. Carver published a detailed overview of theoretical analysis approaches for microstrip patch antennas in 1981 [24]. Microstrips are printed circuits that operate in the microwave band of the electromagnetic spectrum (300MHz to 300GHz). The creation and manufacture of a microstrip antenna on a printed circuit board is relatively basic and straightforward. By replacing the more onerous waveguide components with microstrip antennas, a designer may minimize the size, weight, volume, and cost of components and systems. The properties of an antenna are determined by its size and other physical aspects; hence, the realization of an antenna at microwave frequency requires greater consideration than that at low frequency.

Microstrip antennas (MSA) are closely entangled with electromagnetic (EM) waves, resulting in the stimulation of four separate types of waves within a microstrip patch antenna. To begin with, space waves are extremely desirable for efficient antenna performance. Second, there are directed waves, which are excellent for transmission lines and signal propagation. Surface waves, like leaky waves, are regarded undesirable because they can cause unintended consequences and signal deterioration. Understanding and controlling the interactions of different wave types is critical for optimizing microstrip antenna designs and obtaining desired performance parameters.

The energy received from the transmission line must be turned into space wave, and most of the wave energy must be stored in guided wave for efficient transmission and reception of electromagnetic waves in an antenna. Aside from space waves, other waves found in antennas include surface and leaky waves, both of which cause undesirable radiation losses. Surface waves are excited and travel between the ground plane and the dielectric to air interface through total internal reflection before being reflected, dispersed, and diffracted at the substrate's edges. Surface waves are introduced as the height of the microstrip substrate grows, which is normally undesirable since they take power from the total power available for direct radiation (space wave) use. These surface wave behaviors limit gain while increasing end-fire radiation and cross polarization [25]. When electromagnetic waves flow in a single direction with the field as provided in equation (1), the distinction between surface waves and leaky waves becomes obvious following field relations [26].

$$E = E_0(x)e^{-kPx} \tag{1}$$

Where x denotes the propagation direction, k the free space propagation constant, P the relative propagation constant, and $E_0(x)$ the amplitude fluctuations of the field. The type of waves is determined by the value of P, which is provided below:

$P > 1$: Surface waves

$P < 1$: Leaky waves

Table 3 lists the benefits and limitations of microstrip patch antennas over conventional microwave antennas with a large frequency range (100MHz-100GHz).

Table 3. Advantages and limitations of microstrip patch antenna

Advantages	Limitations
Light weight, low volume and thin profile	Low efficiency and narrow bandwidth (1-5%)
Easy in fabrication and low fabrication cost	Extraneous radiation from feed, junction and surface wave. Most microstrip patch antenna radiates in half space.

Have polarization diversity	Good polarization is difficult to achieve
Multiband antenna can be easily design	Lower gain (-6dB)
Compatible with MMIC	All antenna parameters are difficult to satisfy simultaneously
Feed line and matching network both can be made on same antenna structure	Good quality substrate is required with low temperature tolerance.
No cavity backing is required	Poor cross polarization at high frequency
Antenna array is easily possible	Complex feed structure is required in antenna array
Conformal array is easily possible	Limited power capacity (~100 W)
Simple feeding technique	Large resistive loss in feed structure

As shown in Table 3, researchers [27] confront new obstacles in improving the performance of microstrip patch antennas. These problems include improving numerous antenna characteristics such as bandwidth, gain, radiation efficiency, radiation pattern, and feeder systems in order to create a better and more optimum array architecture. Additionally, designers strive to minimize the total planar and volumetric dimensions of microstrip patch antennas. To satisfy the needs of current wireless networks and to permit seamless integration into diverse devices and applications with limited space and budget restrictions, cost-effectiveness and compactness are critical. By tackling these issues, researchers and designers will be able to realize the full potential of microstrip patch antennas and expand their applications in wireless communication, satellite systems, aerospace, and other industries that require high-performance, small, lightweight, and efficient antennas.

3.4 Microstrip patch antenna-geometry, general structure and radiation mechanism

A microstrip patch antenna is a small and adaptable antenna that is made up of a thin sheet of conductive material, such as copper or aluminum, that is put on top of a substrate material, such as a printed circuit board or a dielectric material. The antenna effectively transmits electromagnetic waves outward by establishing a resonant electromagnetic field within the patch. Microstrip patch antennas have become used in wireless communication systems such as cellular phones and WiFi devices due to their tiny size, low cost, and smooth integration with other electrical components. As seen in Fig. 3, these antennas are often linked to transmitters or receivers through transmission lines. The radio current is provided through specialized procedures, allowing signals to be transferred between the antenna and the ground plane. Figure 5 is a typical setup of a rectangular microstrip patch antenna, demonstrating its basic yet effective design.

A microstrip patch antenna’s radiation property may be analyzed using either the field distribution between the conducting patch and the ground plane or the surface current distribution on the conducting patch. While accurate field and current distribution calculations are difficult, researchers frequently employ approximations to construct a realistic model of the microstrip patch antenna. As given in [28], these approximations include the assumption of a zero tangential magnetic field, the presence of magnetic walls encircling the patch's perimeter, minimal electric field fluctuation throughout the patch's width and thickness, and the treatment of the patch as radiating slots. Furthermore, the electric field is considered to be normal to the patch's surface. Researchers can efficiently analyze and predict the radiation behavior of microstrip patch antennas using these simplifications, providing useful insights for their design and optimization.

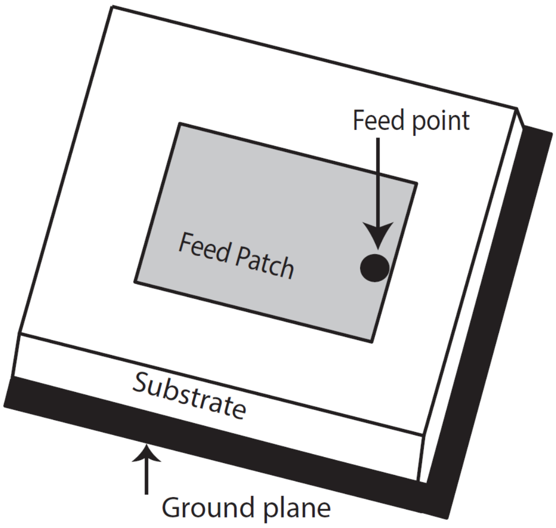
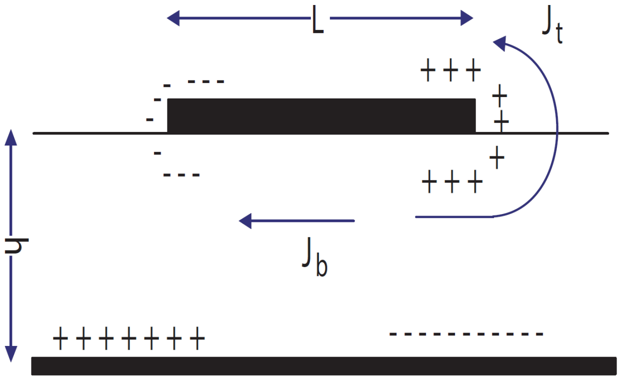


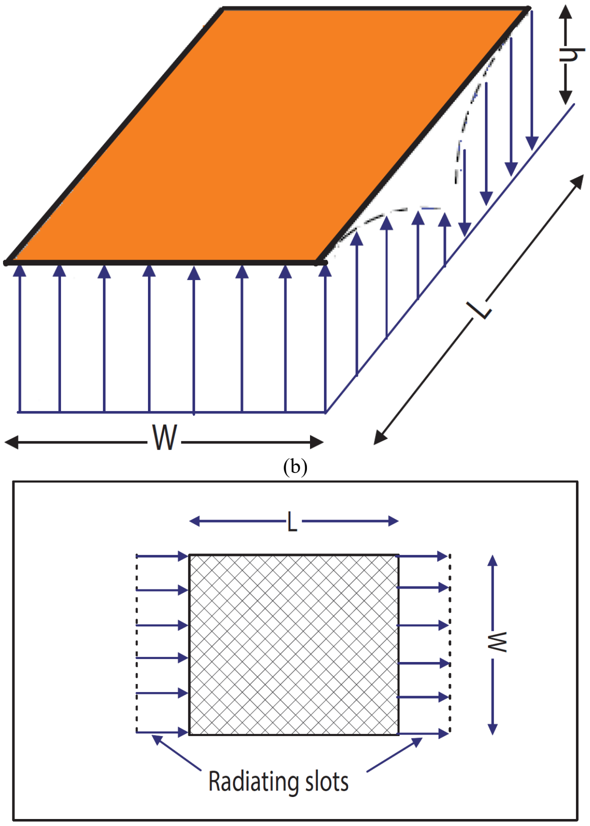
Fig. 5. Geometry of rectangular MSA, excited by coaxial feed.

When the patch antenna is attached to the microwave source, positive and negative charges are spread over the patch's upper, lower, and ground plane surfaces (see Fig. 6a). Because of the movement of charges, charges generate current densities at the top ($\vec{J_t}$) and bottom ($\vec{J_b}$) surfaces. The repulsive force between similar charges on the patch's bottom surface (ground) tends to drive certain charges from the bottom surface, across its edge, and to the patch's top surface (radiating patch).

Because the height to width ratio is so modest, the attractive attraction between opposing charges prevails, and most of the charge concentration and current flow remain underneath the radiating patch. The weak magnetic field tangential to the edges is caused by a little amount of current flowing around the perimeter of the radiating patch. As a result, an approximation is developed such that the tangential magnetic field is zero and magnetic barriers may be placed around the patch's perimeter. As a result, the patch antenna may be modelled as a hollow with electric walls at the top and bottom. We also envision four magnetic barriers around the patch's boundaries. Each slot emits the same field using the equivalence principle [28]. Because of the equal and opposing current distributions on the slots, the radiation generated by the slots along the x-axis is nearly nil. As a result, radiation from the patch can be generated in terms of two vertical slots with the same amplitude and phase. Fig. 6 b and c illustrate the electric field distribution over the patch and the effective size of the antenna, respectively.



(a)



(b)

(c)

Fig. 6. (a) Charge and current distribution **(b)** Electric field distribution **(c)** Rectangular microstrip patch antenna with effective horizontal slots

4 Analysis methods of MSA

The microstrip antenna is primarily made up of a two-dimensional radiating patch mounted on a thin dielectric substrate, classifying it as a two-dimensional planar component that can be mathematically and theoretically analyzed. Figure 7 depicts the methods used to analyze microstrip antennas, which are based on the study reported in [25]. These approaches give vital insights into the behavior and performance of microstrip antennas, assisting in their design and optimization for use in wireless communication, satellite systems, and other industries where tiny and efficient antennas are required.

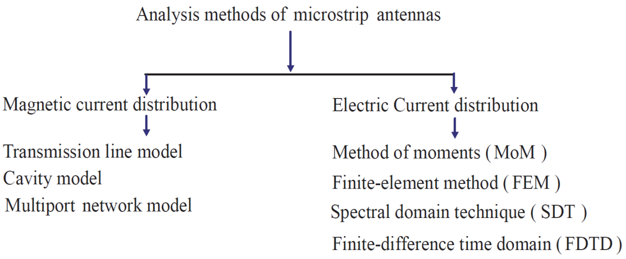


Fig. 7. Classification of analysis methods

4.1. Transmission line model

A transmission line analysis approach may be used to successfully conduct a performance examination of a Microstrip Antenna (MSA). The microstrip radiating element is equivalently represented as a transmission line resonator with no transverse field changes in this technique. The radiation is caused mostly by the fringing fields at the resonator's open-circuited ends. The pioneering work of Munson and Derneryd [29-30] may be traced back to their proposal to depict the patch as two resonant slots spaced about half wavelength for an ideal transmission line. The antenna's behavior may be better understood by estimating the input impedance based on the distance between the patch's edge and the feed point. Furthermore, this technique assesses the effectiveness of the antenna while assuming that the fields fluctuate along the length of the patch but remain constant throughout its width and thickness. It is crucial to note, however, that this transmission line model is only applicable to rectangular and square patch antennas.

4.2. Cavity model

The region between the microstrip patch and the ground plane is considered as a cavity in cavity model analysis, with magnetic walls around the perimeter and electric walls at the bottom and sides. This method takes into consideration the fringing fields surrounding the patch's periphery, substantially increasing the effective physical dimensions of the microstrip patch in comparison to its real physical dimensions. The distant field and radiated power may be computed by considering an analogous magnetic current around the cavity perimeter. Cavity model analysis provides a more accurate depiction than transmission line model analysis, although its computations are more difficult.

Unlike transmission line analysis, which is confined to rectangular and square patch geometries, cavity model analysis is flexible and may be used to any regular-shaped microstrip patch. This adaptability enables a more thorough evaluation of alternative antenna designs and geometries. Although the cavity model analysis requires more computations, the enhanced precision makes it a helpful tool for understanding and optimizing the performance of microstrip patch antennas in a variety of applications.

4.3. Multiport network model (MNM)

The Multiport network model is an extension of the cavity model analysis that allows electromagnetic fields to be modelled independently for two distinct regions: outside and under the radiating patch [25]. The patch is modelled as a two-dimensional planar network with many ports positioned all around it in this model. Assuming homogeneous fields over these tiny parts, each port represents a small section of the patch's length [27]. Typically, four ports are taken along the radiating edge of a rectangular patch and five ports along the non-radiating edge. The patch's impedance matrix is generated using Green's function, and the fields are added by including an analogous edge admittance network. The segmentation approach is then used to compute the overall impedance matrix. Using the Multiport network model, a more thorough and realistic depiction of the behavior and performance of the microstrip patch antenna may be obtained. This model allows for a better understanding of the electromagnetic interactions inside the antenna structure, making it a useful tool for optimizing antenna designs and achieving specific performance criteria in a variety of wireless communication and radar applications.

4.4. Method of moments (MoM)

MoM is a strong approach for analyzing both rectangular and non-rectangular microstrip patch antennas. The surface currents flowing on the patch's surface and volume polarization currents within the dielectric slab area are unknown in this technique [31]. In order to solve the patch currents, an integral equation is used. Computers are used to solve these integral equations, translating them into algebraic equations to simplify and improve accuracy. The MoM technique successfully forecasts the patch's currents, impedance, and resonant frequency using this methodology.

Although the MOM technique is more sophisticated than other analytic models, it has emerged as the ideal way for dealing with conformal, multiport, stacked, and linked antennas [32]. SONNET, IE3D, AWR, ENSEMBLE, and other electromagnetic simulation tools are available for the study and design of antennas utilizing MoM. These simulation tools allow antenna engineers and researchers to study and optimize the performance of microstrip patch antennas in a variety of applications, including wireless communication, radar systems, and satellite communication.

4.5. Finite element method (FEM)

The Finite Element Method (FEM) has been shown to be a useful technique for solving differential equations and discovering practical applications in antenna theory. One of its key features is its ability to adequately represent complicated antenna designs. The Finite Element Method is based on the principle of reducing the geometrical domain of a boundary value issue into smaller subdomains. The issue can be addressed computationally using linear algebra techniques by formulating the governing differential equations and related boundary conditions as a set of linear equations. The analysis of issues utilising the Finite Element Method may be divided into four parts [33]: First, the solution region is subdivided into a finite number of components. Following that, governing equations for a typical element are developed. The solution region's components are then assembled. Finally, the equation system is solved to give the required result.

The High-Frequency Electromagnetic Field Simulation (HFSS), which is commercially available from ANSYS, is a commonly used electromagnetic simulation tool based on the Finite Element Method. This program is often used to analyze antenna designs and performance. Antenna engineers and researchers may acquire critical insights into antenna behavior and optimize their designs for diverse applications in wireless communication, radar systems, satellite communication, and more by exploiting the capabilities of HFSS.

4.6. Spectral domain technique (SDT)

The Spectral Domain Technique (SDT) is a sophisticated approach for antenna research that employs a two-dimensional Fourier transform along the patch's two orthogonal directions inside the substrate plane. In the Fourier transform plane, boundary conditions are then applied. The impedance matrix is created using this approach, allowing the computation of the current distribution on the conducting patch and the analogous magnetic current distribution on the surrounding substrate surface.

The SDT approach combines two fundamental criteria to improve computational efficiency. The first guideline is to employ Basis functions to simplify the representation of fields and currents, resulting in speedier computations. The second rule includes using algebraic equations rather than integral equations, which reduces processing complexity even further. These time-saving measures ensure that the SDT approach continues to be efficient and successful in analyzing complicated antenna configurations and producing correct findings.

Antenna engineers and researchers can acquire a better knowledge of antenna performance and behavior by utilizing the Spectral Domain Technique. The SDT approach is very effective for optimizing the design of microstrip patch antennas, planar antennas, and other complicated antenna layouts. Furthermore, because of its computational benefits, it is an important tool for analysing large-scale antenna arrays and conformal antenna configurations in a variety of wireless communication and radar applications.

4.7. Finite difference time domain (FDTD)

The Finite-Difference Time-Domain (FDTD) approach is a numerical analytic tool for solving Maxwell's equations in time and space domains. It was first presented in 1966 by K. S. Yee [34]. One of the most significant benefits of the FDTD approach is its ability to reliably forecast antenna performance using a broadband pulse excitation, allowing for thorough simulations across a large frequency range in a single run [25]. This makes it appropriate for analyzing various antenna types and feeding methods.

However, as the complexity of the antenna construction grows, the FDTD approach becomes computationally difficult and time-consuming, necessitating more memory resources [35]. Tables 4 and 5 provide an overview of several analysis approaches, presenting a comparative study of their applicability and limits to assist designers and producers in selecting a suitable method. To summarize, the FDTD approach is an effective tool for analyzing antennas and their performance across a wide frequency range. It comes in handy especially when working with basic antenna structures. However, due to computational and memory limits, different analytical approaches may be better appropriate for more complicated antenna designs. Designers may make educated decisions and pick the best suited solution for their individual antenna design and simulation needs by examining the information offered in Tables 4 and 5.

Table 4. Comparative description of magnetic current distribution-based analysis methods

Application	Transmission line model	Cavity model	Multiport network model
Patch shape	Rectangular	Regular shapes	Separable geometries
Substrate thickness	Thin	Thick	Thin
Antenna polarization	Linearly polarized	Circularly polarized	Circularly polarized
Patch layers	Single layer	Multilayer	Single layer
Feeding techniques	Probe feed, edge feed	Probe feed, edge feed, aperture coupler	Probe feed, edge feed, proximity coupling
Antenna array	Yes	No	Yes
Surface wave effect	Yes	Yes	Yes
Mutual coupling between edges	Explicitly included	Implicitly include	Explicitly included

Table 5. Comparative description of electric current distribution-based analysis methods

Application	Method of moments	Finite element method	Finite difference time domain
Patch shape	Rectangular, triangular, quadrilateral	Arbitrary shapes	Arbitrary shapes
Tool based on	IE3D, ENSEMBLE, SONNET, AWR	HFSS, FEKO	OPTIWAVE , XFdtd, QUICKWAVE
Patch layers	Multilayer	Single & Multilayer	Single & Multilayer
Solving equation	Integral equation	Differential equation	Difference equation

Domain	Frequency	Frequency	Time
Solving matrices	One for all ports	One for all ports	Does not require matrix
Antenna structure	Planar	3-D structure	3-D structure

5. Electromagnetic simulation tools

Electromagnetic modelling techniques are critical in antenna design because they provide useful insights into antenna parameters such as return loss, current distribution, radiation pattern, group delay, and antenna efficiency. These simulation tools are computer software programs that are based on several antenna analysis approaches. It is critical to validate the theoretical hypothesis and antenna behavior before building a prototype of a proposed antenna, since this strategy is both cost-effective and time saving.

Fortunately, a large selection of commercial electromagnetic modelling tools is now accessible, making the verification process easier. Engineers can continue with confidence to manufacture the prototype of the suggested antenna design after comparing the simulation results to the theoretical hypothesis. One of the primary benefits of electromagnetic simulations is that they enable simple access to electromagnetic fields and current distributions, allowing for a thorough knowledge of antenna performance. There is several commercially accessible electromagnetic modelling software, each with its own set of methods for analysis. SONNET, IE3D, AWR, and ENSEMBLE are a few examples of program that use the method of moments (MoM) algorithm.

The finite difference time domain analysis (FDTD) is used by QUICKWAVE, FEKO, and XFdtd, while the finite element method (FEM) and finite integral technique (FIT) are used by CST and HFSS, respectively. Antenna engineers may use these powerful simulation tools to effectively optimize designs, explore alternate configurations, and achieve greater antenna performance across a wide range of applications, including wireless communication, satellite systems, radar technology, and more.

HFSS is a versatile electromagnetic simulation tool based on the finite element approach that is used to analyse the electrical behaviour of high-frequency and high-speed components. It includes antenna design, sophisticated RF/microwave circuit design, high-frequency IC packaging, and biomedical devices among its applications. HFSS was created by Professor Zoltan Cendes and his students at Carnegie Mellon University and was later bought by Ansoft products, which was then acquired by ANSYS.

When HFSS is compared against IE3D, a method-of-moments-based program, it is found that IE3D conducts simulations faster and with less time required per iteration, although HFSS excels at analyzing more broad antenna shapes. Furthermore, Ansoft HFSS offers a clean and adaptable mesh refinement, whereas CST enables better management of difficult electromagnetic interaction between different components. Given the current trend towards tiny and compact antenna designs, programs based on the finite element method (FEM) and finite integral technique (FIT) are thought more appropriate than other simulation tools. These research-based conclusions [36] emphasize the capabilities and applicability of HFSS and other electromagnetic modelling tools, aiding antenna engineers in selecting the best tool for their individual design needs.

6. Feeding techniques

To transfer microwave power to the radiating patch, microstrip antennas can be effectively stimulated using either direct or indirect feeding approaches. With the growing demand for and uses of microstrip antennas, researchers have investigated a variety of feeding systems, each with its own set of advantages and disadvantages. Coaxial feed, microstrip line feed, proximity coupled microstrip feed, aperture-coupled microstrip feed, and coplanar waveguide feed are some of these approaches. The feeding strategy used is a vital aspect that has a considerable impact on the antenna's performance. The selected feed must enable perfect matching between the feed and the radiating structure, allowing the antenna's characteristics to be optimized. Furthermore, when employed in array architectures, the feed should be carefully adjusted to minimize side lobes and cross-polarization. To attain maximum antenna efficiency, issues such as low spurious radiation and surface wave loss must also be considered. Antenna engineers may improve the performance of microstrip antennas and meet particular design criteria for a variety of applications, including wireless communication, satellite systems, radar technology, and more, by carefully selecting the proper feeding strategy.

6.1. Coaxial or probe feed

Power coupling through a probe is a crucial technique for power transmission in antenna designs. The coaxial probe feed has a special shape, as shown in Fig. 8, in which the coaxial probe is attached to the ground side of the prototype and its inner conductor provides a direct connection to the metallic patch via a dielectric substrate. The outside curved surface of the probe is insulated by a non-conducting layer to prevent spurious radiation. The flexibility of the coaxial probe allows it to be positioned at any spot on the patch, resulting in perfect input impedance matching. Furthermore, because of its simple design and accessible availability, the coaxial probe is a common choice in antenna engineering. The coupling constant of the probe feed is an essential parameter to examine since it has a major influence on overall antenna performance, impacting aspects such as gain, radiation pattern, and efficiency. Antenna engineers may improve the performance of microstrip antennas and other antenna designs for wireless communication, radar systems, and satellite technologies by successfully exploiting the coaxial probe feed.

$$\text{Coupling constant } \approx \cos\left(\frac{\pi x_0}{L}\right) \tag{2}$$

where L and x_0 represent resonating length and feed location along the x-axis on the patch, respectively. The above equation shows that maximum coupling is possible at ($x_0 = 0 \; or \; L$).

The coaxial feed has many significant drawbacks [25, 28]: For starters, using a probe feed causes the antenna's flat construction to become unbalanced since one part of the connection is energized from the ground. Second, the coaxial feed is unsuitable for antenna arrays because it needs a significant number of solder connections, which might change the impedance of the circuit, add stray capacitance, and negatively influence the overall antenna properties. Furthermore, when working with thicker substrates, longer probes are required, which causes challenges like spurious radiation, surface wave power, and higher total feed inductance, further complicating the antenna's design and performance.

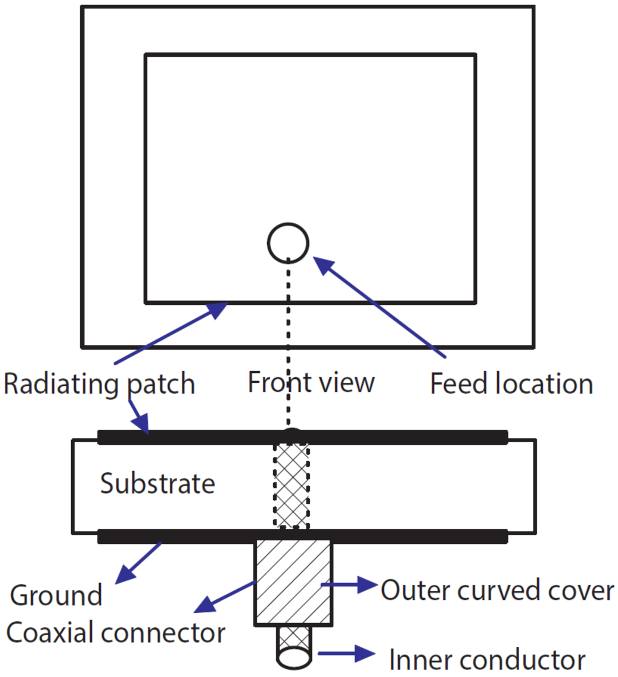


Fig. 8. Geometry of co-axial feed

6.2. Microstrip line feed

Because the feed may be etched on the same substrate as the patch, both the patch and the feed can be manufactured concurrently using the microstrip line feeding approach. This method allows for two methods of stimulating the patch. The first method is direct edge coupling, in which the feed is linked directly to the radiating patch. The second approach, on the other hand, is edge coupling with a gap, also known as indirect edge coupling, in which the feed and the radiating patch are separated by an electrically connected gap [27]. Figure 9 depicts the geometrical configurations of edge-coupled and edge-gap-coupled antennas.

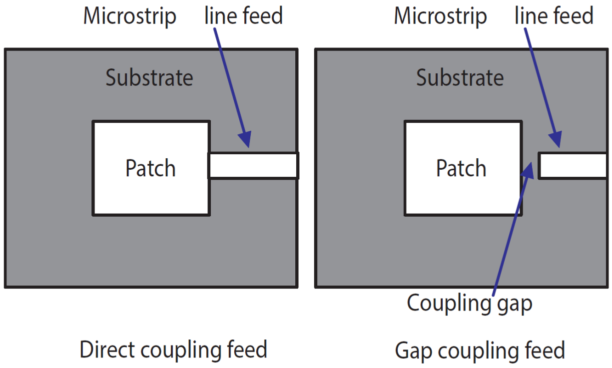


Fig. 9. Geometry of microstrip line feed

While the edge-coupled feed has advantages, it has drawbacks such as increasing cross-polarization levels owing to spurious radiation from the feed line, which is especially noticeable in tiny antennas where the feed line size becomes equivalent to the patch size. Due to the high impedance at the patch's edge, thick substrate antennas may also exhibit poor performance. Furthermore, microstrip line feeding is not appropriate for antenna arrays, because gap-coupled feed lines have limited power handling capabilities.

The inset feed lines can be utilized to overcome these limits, and the feed location should be carefully chosen to produce an overall input impedance of 50. Cross-polarization effects can be reduced by optimizing the patch's aspect ratio (width to length ratio of 1.5). It's worth noting that coaxial probe feed and microstrip line feed, also known as coplanar feed, are best suited for situations where performance requirements aren't too stringent, and the feed must be coplanar with the patch [28].

6.3. Electromagnetic coupling (proximity feed)

The proximity feed is a non-coplanar feed technique in which the feed is not linked to the radiating patch directly. The proximity feed is shown in Fig. 10 on the top surface of the lower layer substrate-2, which has a ground plane on its bottom side. The radiating patch, on the other hand, is located on the top of the upper substrate-1, where there is no ground plane at its bottom surface. Capacitive coupling exists between the feed line and the patch [28]. The coupling capacitor is chosen within a certain range to provide perfect impedance matching and maximize the predicted bandwidth. Increasing the antenna's impedance bandwidth is possible by employing a thinner lower layer substrate and a thicker upper layer substrate.

The overlapping region of the feed line and the patch influences the behaviour of input impedance and resonance frequency. Positioning the edge of the feed line closer to the centre of the patch is advised for minimum variations in the specified resonance frequency [37]. It might be difficult to get exact alignment between the patch and the feed while fabricating this feed line. However, because no soldering is required, it is a viable solution for some antenna designs. Despite the limitations of manufacturing, the proximity feed provides advantages in terms of enhanced impedance matching and greater bandwidth, making it a desirable approach in antenna engineering.

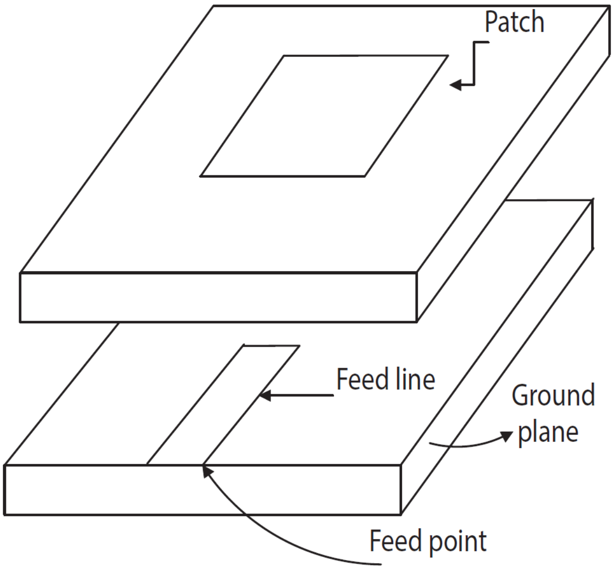


Fig. 10. Geometry of proximity feed

6.4. Aperture-coupled microstrip feed

Another non-coplanar feeding technology that employs two substrate layers is the aperture connected feed line. The feed line is etched on the lower substrate-2's bottom surface, while the radiating patch is etched on the higher substrate-1's top surface. The conducting ground plane is sandwiched between these two layers, and the feed line links microwave power to the radiating patch through an aperture slot produced on the ground plane [cf. Fig. 11]. To increase the antenna's bandwidth, the aperture slot can be of various forms and sizes. The aperture coupled feed coupling constant is critical in determining antenna parameters and may be computed as follows:

$$\text{Coupling constant} \approx \sin\left(\frac{\pi x_0}{L}\right), \tag{3}$$

(x_0 is the offset of the slot from the patch edge)

Aperture linked feed is a flexible and efficient microstrip antenna feeding method that ensures higher performance and greater bandwidth. Because it is non-coplanar, it enables small and space-saving designs while preserving excellent impedance matching and radiation properties. Furthermore, the versatility in slot form and size allows for extra tuning possibilities for specialised antenna applications. To achieve optimum coupling and resonance, however, exact alignment and manufacturing precision are essential. Overall, the aperture coupled feed approach is useful in current antenna engineering, supporting a wide range of wireless communication, satellite, and radar applications.

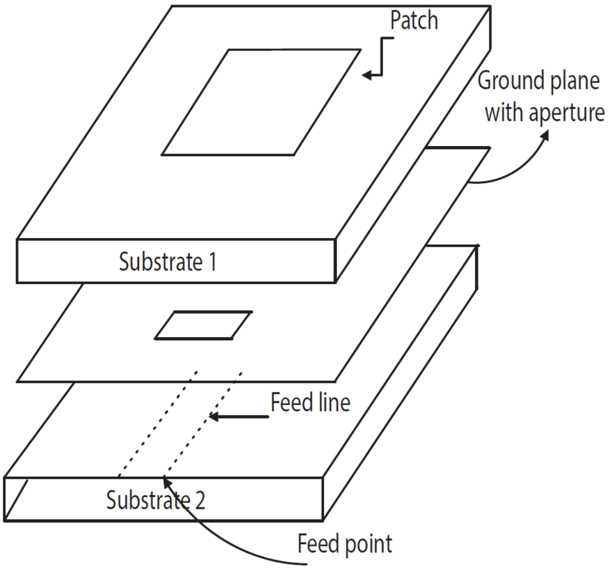


Fig. 11. Geometry of aperture-coupled feed

Several research [25, 28, 38-39] recommend the following factors to improve the performance of the aperture linked antenna:
The dielectric constant of the feed substrate should preferably be between 2 and 5. The feed substrate thickness should be in the range of 0.01 to 0.02, where denotes the wavelength of the operating frequency. The aperture slot's aspect ratio is commonly set at 1/10. A narrower feed line is preferable for better coupling. To guarantee optimal power connection, the feed line should be positioned at 90° to the center of the slot. To maximize power coupling, the patch should be centered over the slot and well aligned. These factors are crucial in fine-tuning the aperture coupled antenna, allowing for greater impedance matching, increased bandwidth, and superior radiation characteristics, making it an excellent choice for a variety of wireless communication, satellite, and radar applications.

6.5. Co-planar waveguide feed (CPW)

CPW feeds are a cost-effective way to make tiny antennas compatible with MMICs (Monolithic Microwave Integrated Circuits). The patch and ground in an antenna with CPW feed are in the same plane, as shown in Fig. 12. The CPW is etched into the ground plane and connects to the patch through a coupling slot. In CPW-fed antennas, several forms of coupling slots are used to reduce the front-to-back ratio, with a slot loop being described as an effective excitation source [40]. The use of CPW feed in the construction of UWB (Ultra-Wide Band) small microstrip patch antennas with continuous group delay and excellent matching across the full bandwidth is significant [41]. The connection between the CPW feed and the patch might be inductive or capacitive. The benefit of CPW feed is that it eliminates spurious radiation from the feed, making it suitable with compact devices [28]. Table 6 presents an overview of several feeding approaches to assist readers in picking an appropriate meal based on their unique needs.

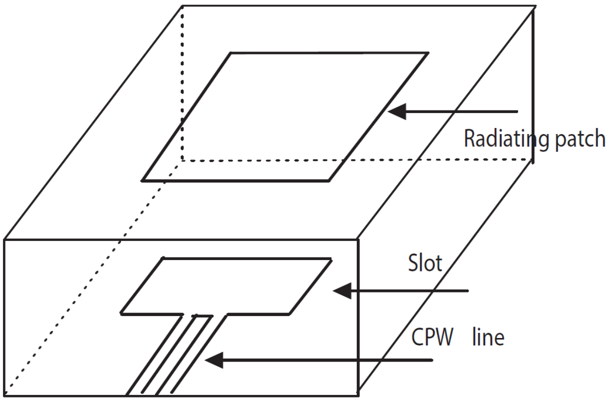


Fig. 12. Geometry of Co-planar waveguide feed (CPW)

Table 6. Comparative description of feeding techniques

Feeding types	Geometry	Spurious feed radiation	Polarization	Impedance matching	% Bandwidth/ [reference]	Fabrication
Coaxial feed	Non-coplanar	More	Poor	Easy	25.09/ [42]	Little difficult
Edge coupled feed	Coplanar	Less	Good	Poor	9-12	Easy
Gap coupled feed	Coplanar	More	Poor	Easy	2-5	Easy
Inset feed	Coplanar	More	Poor	Easy	68.69/ [43]	Easy
Proximity feed	Planar	More	Poor	Easy	45/ [44]	Difficult
Aperture feed	Planar	More	Excellent	Easy	17.9/ [45]	Difficult
CPW feed	Planar	Less	Good	Easy	18.3/ [41]	Difficult

7. Design mechanism of microstrip patch antenna

Design mechanism in terms of substrate material selection, radiating patch geometry and dimensions, feeding method selection and ground plane structure of the microstrip patch antenna is carried out in this section.

The choice of dielectric substrate in the design of microstrip patch antennas is crucial in defining the properties and performance of the antenna. The dielectric constant, substrate thickness, loss tangent, temperature stability, cost-effectiveness, and manufacturability are some of the factors that influence this decision process. The size and bandwidth of the antenna are directly influenced by the dielectric constant; smaller antennas are usually the result of higher values. The thickness of the substrate affects the radiation pattern and bandwidth of the antenna, frequently necessitating a trade-off between electrical performance and mechanical resilience. To promote effective transmission and reduce signal attenuation, low loss tangent materials are the preferable choice. Moreover, thermal stability is necessary for dependable performance in a range of environmental circumstances. The dielectric substrate that is selected has to meet these standards and work with the particular limitations and specifications of the antenna. Substrates including Teflon, Rogers, Duroid, flexible substrate, substrate integrated waveguide and FR-4 are frequently used. When designing antennas, FR4 epoxy is frequently chosen over substrates like Teflon, Rogers, Duroid because it is more affordable, readily available, and simple to manufacture. Teflon, Rogers, and Duroid are much more expensive and could need specific production techniques, even if they have better electrical qualities including reduced dielectric loss and increased temperature stability. A cost-effective and performance-balancing material, FR4 epoxy is a sensible option for a variety of antenna applications [46].

In order to create the reference radiating patch shape, antenna theory principles must be applied and important parameters like substrate height (H), resonant frequency (f_r), and dielectric substrate permittivity (ε_r) must be specified. According to antenna theory, it is recommended to calculate the dimensions of a rectangular conducting strip ($L_0 \times W_0$) on the radiating plane (cf. Fig. 5), as reported in [47].

$$W_0 = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{4}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+\frac{12\mathrm{H}}{W_0}\right)^{-\frac{1}{2}} \tag{5}$$

$$\text{residual length } (\Delta \mathrm{L}_0) = 0.412\mathrm{H} \times \frac{(\varepsilon_{eff}+0.30)(\frac{W_0}{H}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W_0}{H}+0.8)} \tag{6}$$

$$L_0 = \frac{c}{2f_r\sqrt{e_{ff}}} - 2\Delta \mathrm{L}_0 \tag{7}$$

$$\text{substrate length } (L_s) = 6H + L_0 \tag{8}$$

$$\text{substrate width } (\mathrm{W_s}) = 6H + W_0 \tag{9}$$

$$substrate\ height\ (H) = \frac{0.0606\lambda_0}{\sqrt{\mathcal{E}_r}} \tag{10}$$

$$\text{feed length } (L_f) = \frac{\lambda_0}{4\sqrt{\mathcal{E}_e}} \tag{11}$$

In designing of monopole antenna , a transmission line model approach is used to calculate the resultant length. Trnasmission line theory is utilized with surface current distributions at design frequency modes. The effective monopole antenna length is approximated by quarter wavelength $\lambda_0/4$ and given as reported in [48].

$$L = \frac{c}{4f_r\sqrt{e_{ff}}} \tag{12}$$

After that, a variety of methods can be used to optimize and modify the antenna geometry. These consist of neural networks [49], Simulated Annealing (SA) [50], genetic algorithms [51], impedance transformation techniques [52], machine learning algorithms [53], and Particle Swarm Optimization (PSO) [54]. These techniques are frequently used to expedite the design process and effectively investigate the vast design space. Moreover, the techniques such as thick substrate, stacking substrate, parasitic elements, shorting pin, shorting wall, introduction of slots and notches, antenna array and metamaterials and metasurfaces reported in [10] are used to enhance the antenna performance.

To achieve the best possible antenna performance, a number of important elements must be carefully considered throughout the design process of the ground plane construction for patch antennas. The radiation properties, impedance matching, and overall efficiency of the patch antenna are all significantly influenced by the ground plane. First, the intended operating frequency and radiation pattern specifications are used to define the ground plane's size and form. Usually, the ground plane should be bigger than the patch element in order to reduce edge diffraction effects and give the antenna enough grounding. The thickness and material characteristics of the ground plane also have a big impact on the radiation efficiency and bandwidth of the antenna. The structures such as defected ground structure (DGS) [55], split ring resonator (SRR) [56], electromagnetic band gap (EBG) structure [57], meandered ground plane [58], metamaterial-inspired ground plane [59], frequency selective surface (FSS) ground plane [60] and photonic crystal ground plane [61] are used to improve the radiation performance of the antenna.

One important factor that greatly affects a microstrip patch antenna's performance is the feeding choice. In order to achieve desired requirements such impedance matching, radiation pattern control, and bandwidth optimization, it is imperative to select the feeding approach that will assure efficient power transfer and radiation characteristics. Microstrip line feed, aperture coupling, proximity coupling, Co-planar waveguide (CPW) and probe feed are examples of common feeding techniques and that have clearly shown in Figs. 8-12 of section 6 and discussed accordingly. Different approaches have different benefits and drawbacks concerning bandwidth, size, impedance matching, and implementation simplicity. The best performance of the microstrip patch antenna in a variety of communication systems and wireless applications is ensured by selecting the feeding mechanism based on the particular requirements of the application, such as the frequency of operation, polarization, and desired radiation pattern.

It is clear from the feeding technique comparison table 6 for microstrip patch antennas that every technique has a different set of advantages and disadvantages. Despite not being planar, coaxial feed has a somewhat good bandwidth but has poor impedance matching and spurious feed radiation. The three coplanar techniques-edge coupled feed, gap coupled feed, and inset feed-show different levels of spurious feed radiation and impedance matching; edge coupled feed has the best impedance matching. With its excellent impedance matching, moderate bandwidth, and relatively low spurious feed radiation, aperture feed stands out as a particularly good option. Even while the fabrication is more involved than with certain other methods, the overall performance benefits make the effort worthwhile. Aperture feed stands out as a viable option for maximum performance in microstrip patch antenna applications, especially where strict impedance matching, and moderate bandwidth are sought. As such, the feeding technique selection should be based on individual needs. The design procedure described in [62–63] can be used to create the feed when a suitable feeding methodology has been chosen.

8. Design methodology of microstrip patch antenna

The development of a microstrip antenna design technique is a methodical approach with the goal of attaining optimal performance and integration for practical applications. A complete design flow of an antenna methodology is presented in Fig. 13. The initiating phase is where the project is outlined and conceptualized. A thorough assessment of the literature and a technological survey are then conducted to acquire information on current microstrip antenna designs and industry developments. The following stage is to fix antenna specifications first, such as substrate type, dielectric constant, substrate height, and operating frequency. The core parameters for later design stages are established by these requirements.

The process of defining the antenna's shape involves synthesizing physical dimensions according to equations (4)-(12) once the antenna parameters have been set. Then, to improve performance and fine-tune antenna characteristics, optimization techniques are applied. Engineers may see and examine the antenna's behavior in many scenarios thanks to the design and simulation of the antenna performed with HFSS software. When there are differences between the predicted and simulated outputs, the design is iteratively improved until alignment is attained. The suggested prototype's functioning is confirmed by theoretical analysis utilizing circuit theory models after a successful simulation.

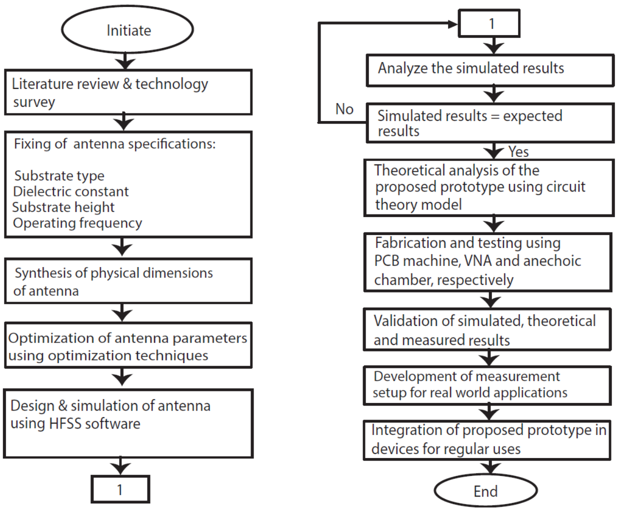


Fig. 13. Complete flow chart of antenna design methodology.

The next stages include testing and fabrication with specialist tools like anechoic chambers, PCB machines, and Vector Network Analyzers (VNAs). This guarantees correctness and dependability by enabling thorough validation of measured, theoretical, and simulated outcomes. To evaluate the antenna's performance in real-life scenarios, it is also essential to create a measurement setup that is suited for the real world. The integration of the proposed prototype into everyday devices signifies the completion of the design technique and highlights the device's preparedness for implementation in several applications.

9. Recent antenna technology trends and innovations

9.1. Cellular Communications

5G cellular communications systems have been developed using modern planar antenna technology, allowing for greater data speeds and enhanced coverage. To improve antenna performance and network efficiency, algorithms like as beamforming and MIMO approaches have been employed. To facilitate high-speed data transfer in 5G networks, researchers built planar antenna arrays that can handle numerous frequency bands, including sub-6 GHz and millimetre wave (mm Wave) bands [64]. One of the most difficult difficulties in building microstrip patch antennas for 5G applications is keeping a high gain while preserving a wide bandwidth. Several strategies, including the use of metamaterials, fractal geometry, and artificial magnetic conductors (AMCs), have been proposed to achieve this aim.

The National University of Singapore suggested a microstrip patch antenna design in 2017 that used a metamaterial structure known as a split-ring resonator (SRR) to reach a bandwidth of 2.5 GHz for the 5G cellular range (3.4-3.6 GHz) [65]. Figure 14 is a fabricated image of the four-port antenna described in [65]. In 2018, researchers from China's University of Electronic Science and Technology presented a microstrip patch antenna design based on a fractal geometry known as a Sierpinski fractal to attain a bandwidth of 2.5 GHz for the 5G cellular spectrum (3.4-3.6 GHz) [66]. AMCs have been proposed as a strategy for enhancing the bandwidth and gain of microstrip patch antennas for 5G applications, in addition to metamaterials and fractal geometry. A microstrip patch antenna design employing an AMC structure was presented in a 2019 study by researchers at the University of Victoria to reach a bandwidth of 3.5 GHz for the 5G cellular spectrum (3.4-3.6 GHz) [67]. To summarise, microstrip patch antennas are an essential component in 5G cellular communications applications, and recent research has focused on techniques such as metamaterials, fractal geometry, and artificial magnetic conductors (AMCs) to improve the bandwidth and gain of these antennas for 5G applications.

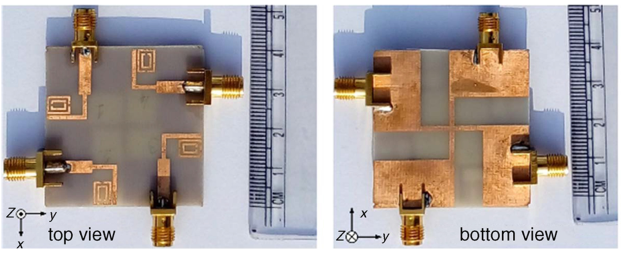


Fig. 14. Photograph of antenna prototype for 5G cellular phone [65].

9.2. Cellular communications

Microstrip patch antennas are widely utilised in cellular communications and other wireless communication systems. With the advent of 6G cellular communications, there has been a surge in demand for high-performance microstrip patch antennas with improved bandwidth and gain. This article will go through the most current advances and approaches in microstrip patch antenna design for 6G cellular communications applications. One of the most difficult aspects of building microstrip patch antennas for 6G wireless communications is achieving a wide bandwidth while keeping good gain. Researchers have suggested a variety of ways to overcome this difficulty, including the use of metamaterials, fractal forms, and artificial neural networks (ANNs). In research [68], a stacked microstrip patch antenna on flexible material with a broad bandwidth of 90–128.5 GHz and a gain of 7.95 dBi is presented. The material's ability to adapt to irregularly shaped surfaces, such as those seen in flexible electronics and wearable gadgets, is a significant benefit. Because of this, they are suitable for use in mobile and portable electronics where a standard rigid antenna would be problematic. The usage of fractal forms is another method for increasing the bandwidth of microstrip patch antennas. However, in [69], a fractal shaped microstrip patch antenna with resonating bands of 170 to 260 GHz (WR-4) and 110 to 170 GHz (WR-6) and a gain of 3.13 dBi is presented. The fractal form was proven to increase the antenna's bandwidth by lowering the patch's resonance frequency. ANNs have been utilised to optimise the design of microstrip patch antennas for 6G cellular communications, in addition to metamaterials and fractal designs.

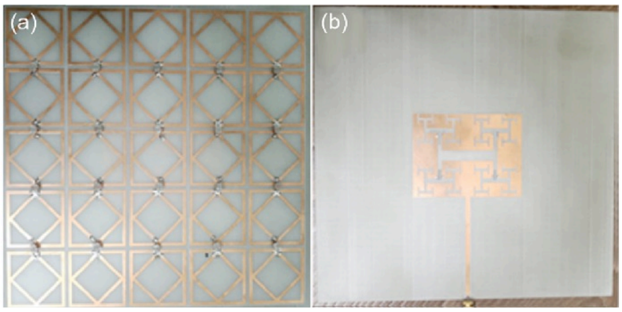


Fig. 15. Photograph of antenna prototype for 6G cellular phone [70].

The authors of a paper [70] presented a photonic controlled metasurface smart beam steering antenna for 6G applications. The suggested metasurface improves antenna patterns, and the greatest beam deflection achievable using the proposed mechanism is 48 degrees from -24 to + 24 degrees in the elevation plane. Figure 15 is an image of a constructed antenna for 6G usage. Finally, because of their small size and simplicity of manufacture, microstrip patch antennas have been widely employed in 6G cellular communications applications. Metamaterials, fractal forms, and ANNs have recently been employed to improve the bandwidth and gain of microstrip patch antennas for 6G wireless communications. ANNs have been utilised to optimise the design of microstrip patch antennas for 6G cellular communications, in addition to metamaterials and fractal designs. To increase the performance of microstrip patch antennas for 6G cellular communications, more research is required.

9.3. Internet of things (IoT)

Planar antenna technology is widely used in Internet of Things (IoT) applications such as smart home systems, industrial automation, and healthcare monitoring. Machine learning and artificial intelligence algorithms have been used to optimise antenna performance and increase communication dependability. Researchers [71] proposed using metamaterial-based planar antennas to miniaturise and increase the performance of IoT devices. A microstrip patch antenna was employed in a recent study [72] for a wireless sensor network in an agricultural context. Another research [73] created a microstrip patch antenna with a 2.4–2.5GHz broad frequency range for application in a wireless body area network. With a gain of 6.2 dBi, the antenna was adequate for long-distance communication in a busy setting. There are several approaches for optimising the performance of microstrip patch antennas for IoT applications. One such strategy is the use of metamaterials, which may be utilised to improve the antenna'sgain and bandwidth [74]. Another method is to utilise a folded meandered MIMO antenna that covers both the LTE and RFID bands [73]. Figure 16 is a fabricated image of the antenna reported in [73] for IoT applications.

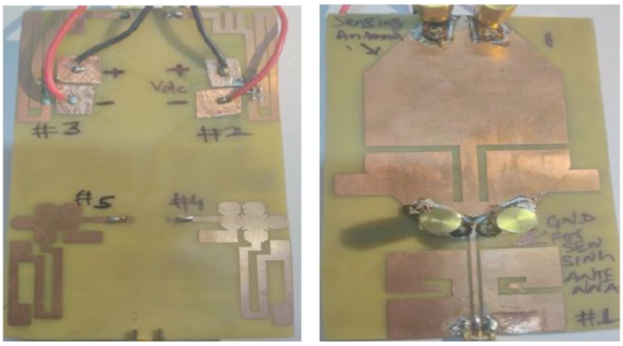


Fig. 16. Photograph of antenna prototype for IOT applications [73].

9.4. Automotive Radar Systems

Planar antenna technology has been used to create sophisticated radar systems for self-driving cars. Target tracking and object identification algorithms have been added to improve radar performance and promote vehicle and pedestrian safety. Planar antenna arrays have been proposed by researchers to accomplish high resolution and long-range object detection [75]. One of the primary benefits of microstrip patch antennas is their ability to operate at millimetre wave frequencies, which are often utilised in vehicle radar systems. This is owing to the antenna's tiny size, which allows it to operate at high frequencies without considerable performance loss. Furthermore, microstrip patch antennas have a high bandwidth, allowing them to function across a wide variety of frequencies. Recent research has also shown that microstrip patch antennas have the potential to be used in multiple-input multiple-output (MIMO) radar systems. Multiple antennas are utilised in these systems to send and receive radar signals, resulting in greater performance and resolution.

Researchers have demonstrated that microstrip patch antennas may be employed in MIMO systems to provide great performance while requiring little complexity [76]. Another area of study has been the use of microstrip patch antennas in car radar systems for adaptive beamforming. Beamforming is a technique for directing the radar beam in a certain direction, which allows for better resolution and target recognition. The CSRR structure has recently been utilised to create a MIMO antenna for automobile radar applications. The CSRR array arrangement yielded maximum gain and isolation of 11.8 and 44.26 dB respectively [77]. Figure 17 is a fabricated image of the alleged antenna [77].

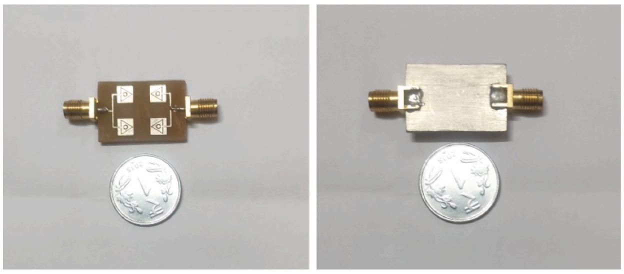


Fig. 17. Photograph of antenna prototype for automotive radar applications [77].

9.5. Satellite communications

Planar antenna technology Planar antenna technology has been used in the construction of satellite communications systems, resulting in better coverage and data rates. To improve antenna performance and network efficiency, algorithms like as beamforming and MIMO approaches have been employed. Planar antenna arrays have been presented by researchers as a means of achieving high-gain and low-profile antenna systems for satellite communications. One of the primary benefits of microstrip patch antennas is their high gain and directivity. This is owing to their capacity to work in a resonant state, which allows for efficient energy transmission between the patch and its surroundings. Recent research has concentrated on enhancing the performance of microstrip patch antennas used in satellite communications. Metamaterials, which are purposefully designed materials that can control electromagnetic waves in novel ways, are one method. According to [78], adding a metamaterial structure onto a microstrip patch antenna can greatly increase its gain and directivity.

Another method is to create microstrip patch antennas with precise performance characteristics using sophisticated optimisation algorithms. In [79], a particle swarm optimisation approach has been employed, for example, to build a microstrip patch antenna with high gain and low cross-polarization. Researchers have also investigated the use of microstrip patch antennas in arrays to attain even better gain and directivity. In this, a tiny (128mm2) patch antenna design with increased performance is presented for satellite applications using a multilayered construction. Antenna [80] has a maximum gain of 8.4 dB and a group delay of 0.8 ns, making it appropriate for satellite applications. The antenna's small size allows it to be integrated into smart gadgets. Figure 18 shows the front aspect of the antenna [80], which has been constructed and is published here with permission to reprint.

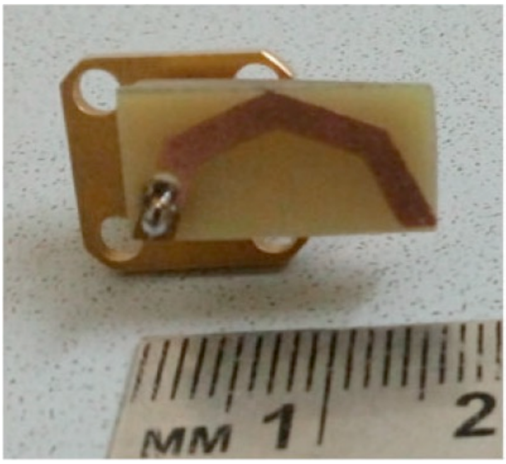


Fig. 18. Photograph of antenna prototype for satellite applications [80].

9.6. Wireless power transfer

Planar Planar antenna technology has been used in the creation of wireless power transfer (WPT) systems, enabling effective energy transmission without the need for physical connections. To optimise antenna performance and boost energy transfer efficiency, algorithms such as resonance matching and beamforming have been applied. Planar antennas have been proposed by researchers to provide high efficiency and long-range power transmission [81]. One significant benefit of utilising microstrip patch antennas for WPT is their excellent efficiency, which allows for large power densities at the receiver. This is especially critical in WPT applications when the receiver is far from the transmitter, as high efficiency guarantees that the greatest amount of power is delivered. The study [81] demonstrated an astounding advance with a two-port MIMO antenna, achieving an excellent 54.98% power conversion efficiency at a significant 20 dB input power level. This remarkable efficiency makes it a great candidate for use in sensors and tiny power-operated devices, demonstrating its potential to revolutionise a wide range of field applications. Figure 19 is a faked image of the antenna [81].

Recent research has concentrated on the development of novel algorithms and approaches for optimising the performance of microstrip patch antennas for WPT. The genetic algorithm (GA) is one such technique that has been used to optimise the design of microstrip patch antennas for WPT by varying factors like as patch size, shape, and substrate thickness [82]. The use of metamaterials has also been proven to increase the performance of microstrip patch antennas for WPT. Metamaterials are materials that have been intentionally designed to exhibit unique electromagnetic characteristics and have been utilised to improve the bandwidth and directivity of microstrip patch antennas [83]. Overall, because of their high efficiency and simplicity of manufacturing, microstrip patch antennas are an appealing alternative for WPT. New algorithms and approaches, such as GA and metamaterials, offer the potential to increase these antennas' performance in WPT applications.

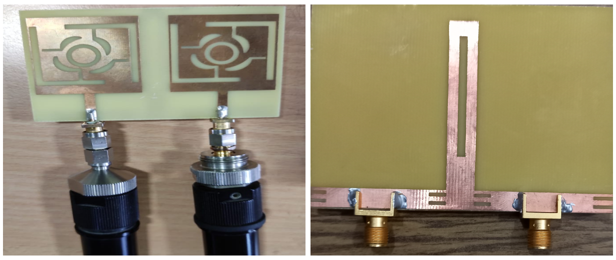

(a) (b)

Fig. 19 Photograph of antenna prototype for energy harvesting applications [81] (a) Front view (b) Back view.

9.7. Medical imaging

Planar Planar antenna technology has been used in the construction of modern medical imaging systems, resulting in higher picture quality and diagnostic accuracy. Image processing and machine learning algorithms have been used to optimise antenna performance and increase diagnostic capabilities. Planar antenna arrays have been proposed by researchers to obtain high sensitivity and resolution in magnetic resonance imaging (MRI) and other medical imaging modalities [84]. These antennas have been used in a variety of medical imaging modalities, including MRI, computed tomography (CT), and ultrasound imaging. Authors in [85] presented a tiny microstrip patch antenna for MRI applications in recent research. The antenna was designed to function at 14T MRI, a typical frequency in MRI equipment. The proposed antenna had a compact size of 19×30 mm^2, making it suitable for integration into MRI systems.

The work [86] presented a microstrip patch antenna for CT imaging applications in another paper. The antenna was built to work at an 80 MHz frequency, which is typical in CT systems. The suggested antenna was 30mm by 30mm in dimension and had an 8 dBi gain, making it appropriate for inclusion into CT systems. In addition to the construction of microstrip patch antennas for certain imaging modalities, numerous methods and approaches for optimising these antennas have been developed. The particle swarm optimisation (PSO) method is one such technique that has been utilised to optimise the design and performance of microstrip patch antennas for medical imaging applications [87]. A unique antenna [88] using 3D printed polylactic acid (PLA), 3M EMI shielding tape, and RS Pro silver paint has been published in the literature. This one-of-a-kind design was tested on humans and attempts to improve the performance of microstrip patch antennas for ISM band applications. Figure 20 shows an image of the completed ISM band antenna [88].

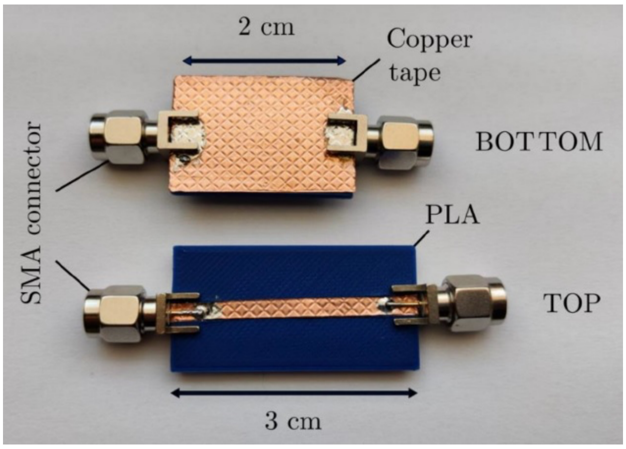


Fig. 20. Photograph of antenna prototype for medical imaging applications [88].

9.8. RFID systems

Planar Planar antenna technology is commonly used in radio-frequency identification (RFID) systems, allowing for enhanced communication reliability and data throughput. Signal processing and error correction algorithms have been devised to increase antenna performance and system efficiency [89]. Antenna [90] shows that using a modified particle swarm optimisation (PSO) technique, microstrip patch antennas may be optimised for enhanced performance in RFID systems. The optimised antenna had a gain of 5.5 dBi and a return loss of -15 dB, which is a substantial improvement above typical microstrip patch antennas, according to the research. Another recent work [91] looked at how a genetic algorithm (GA) may be used to optimise the design of microstrip patch antennas for RFID systems. The optimised antenna had a gain of 4.2 dBi and a return loss of -10 dB, which is an improvement over the previous design, according to the research. These investigations show that optimization methods have the potential to increase the performance of microstrip patch antennas in RFID systems. Metamaterials [92] and C-shape antenna designs [93] are two more strategies that have been utilised to increase the performance of microstrip patch antennas for RFID systems. Figure 21 is a front view produced image of a C-shape antenna [93].

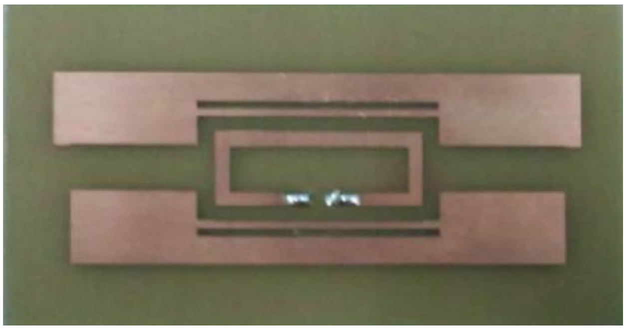


Fig. 21. Photograph of antenna prototype for RFID tag applications [93].

9.9. GPS systems

Planar Planar antenna technology has been used to produce better global positioning systems(GPS), allowing for greater accuracy and coverage. Signal processing and error correction algorithms have been introduced to increase antenna performance and system dependability [94]. According to recent research, microstrip patch antennas can provide excellent gain and wide bandwidth for GPS systems. Authors [95] shown in 2017 that a microstrip patch antenna with a fractal-shaped patch may give up to 5 dBi of gain and a bandwidth of more than 15% for GPS L1 (1575.42 MHz). Chen et al. [96] shown in 2018 that utilising a metamaterial-inspired design may enhance the gain and directivity of a microstrip patch antenna for GPS L1 band by up to 3 dBi and 5 degrees, respectively. In addition to these researches, numerous strategies and algorithms for optimising the performance of microstrip patch antennas for GPS systems have been developed. The use of genetic algorithms (GA) to optimise the shape and material characteristics of antennas is one such technology [97, 98]. The particle swarm optimisation (PSO) approach is utilised to optimise the antenna's size and feeding places [99]. These strategies can aid in the enhancement of the gain, directivity, and bandwidth of microstrip patch antennas used in GPS systems. Another folded annular slot and stacked antenna approach is employed to increase GPS antenna performance [100]. Figure 22 depicts the antenna's constructed side view picture [100].

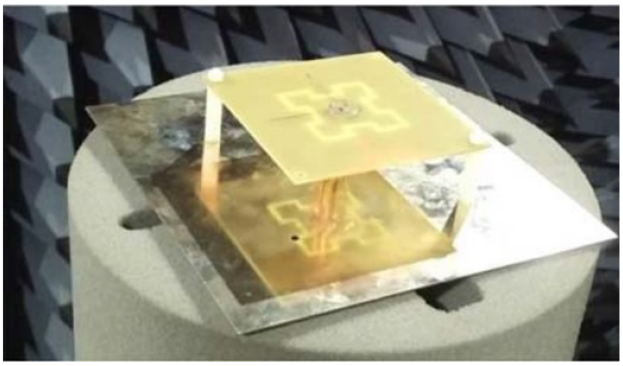


Fig. 22. Photograph of antenna prototype for GPS applications [100].

9.10. Biomedical applications

Planar antenna technology has been used in the construction of modern biomedical devices, allowing for more accurate monitoring and diagnostics. Image processing and machine learning algorithms have been used to optimise antenna performance and increase diagnostic capabilities [101]. Wireless body area networks (WBANs), wireless capsule endoscopy, and wireless medical telemetry systems have all utilised these antennas. A microstrip patch antenna for wireless capsule endoscopy was created in a recent work [102]. The antenna was meant to operate in the 2.45 GHz ISM band and was just 5mm×5mm in size. The antenna exhibited a high gain of -23 dBi and a steady radiation pattern, making it acceptable for wireless capsule endoscopy applications, according to the study.

Another research [103] suggested using a microstrip patch antenna in wireless medical telemetry systems. The antenna was meant to operate in the 404 MHz MICS (Medical Implant Communication Service) band and was just 14×14 mm^2 in size. According to the research, the antenna has a high gain of 6.5 dBi and a steady radiation pattern, making it appropriate for wireless medical applications. To build and optimise microstrip patch antennas for biomedical applications, several methods and methodologies have been employed. The particle swarm optimisation (PSO) technique is one famous approach that has been utilised in research [99] to optimise the size and form of the antenna. The popular metamaterials technology was employed in the work [104] to improve the antenna's performance. Another circular planer inverted-F antenna method for biological applications has been disclosed in the literature [105].

For ISM applications, this approach yielded a maximum bandwidth of 41%. Figure 23 depicts a constructed antenna [105] and measurement setup.

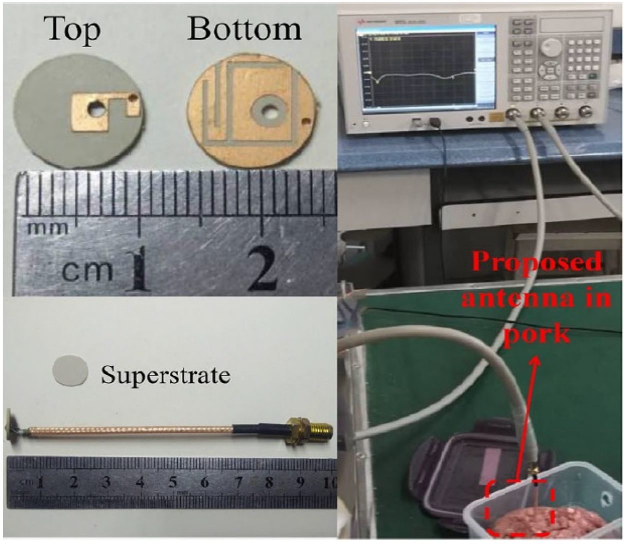


Fig. 23. Photograph of antenna prototype for biomedical applications [105].

9.11. Wireless sensor networks

Planar antenna Planar antenna technology has been widely employed in wireless sensor networks (WSNs), allowing for greater data rates and enhanced communication dependability. Signal processing and error correction algorithms have been used to increase antenna performance and system efficiency. In recent years, they have been widely researched and enhanced in order to address the rising need for high-performance wireless communication systems in WSNs. One of the most difficult aspects of developing microstrip patch antennas for WSNs is achieving a wide bandwidth while keeping a high gain and a low profile. Several strategies, including the usage of metamaterials, frequency selective surfaces (FSSs), and multi-layer structures, have been proposed in recent years to overcome this difficulty. Metamaterials, often known as artificial materials, are created to have features that natural materials do not have. They have been used to improve the bandwidth and gain of microstrip patch antennas by introducing negative permittivity and permeability, which can increase the antenna's effective surface area while decreasing its size. In [106], for example, a metamaterial-inspired design was presented to obtain a wide bandwidth and high gain in WSN microstrip patch antennas.

By incorporating a frequency-dependent reactance, FSSs, also known as frequency dependent surfaces, have been employed to produce a broad bandwidth in microstrip patch antennas. This is accomplished by employing a periodic array of components, such as slots, which interact with incident electromagnetic waves to generate the correct frequency response. In [107], for example, a frequency selective surface was employed to create a broad bandwidth in a WSN microstrip patch antenna. By lowering the thickness of the substrate and the patch, multi-layer architectures for WSNs [108] have been employed to achieve a low profile in microstrip patch antennas. This is possible by employing a multilayer construction, such as a substrate integrated waveguide (SIW) or a coplanar waveguide (CPW), which can minimise the thickness of the substrate and patch while retaining good gain. In another study [109], an elliptical ring slot and two crescent-shaped slots are placed on a circular patch to improve the performance of a WSN antenna. The antenna produced a 9.3 GHz bandwidth, making it appropriate for UWB WSN applications. Figure 24 depicts a manufactured antenna [109] for WSN applications.

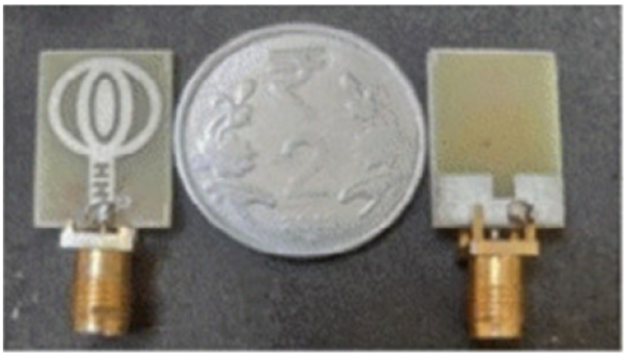


Fig. 24. Photograph of antenna prototype for WSN applications [109].

9.12. Space exploration

Planar antennas Planar antennas have been employed in space exploration to provide long-distance and dependable communications between spacecraft and ground stations. Planar antenna arrays have been proposed as a viable solution for achieving high-gain and low-profile antenna systems for space exploration [110], according to a study conducted by experts at India's National Aerospace Laboratories. Microstrip patch antennas may be built to operate in the S-band (2–4 GHz) and X-band (8–12 GHz) frequency ranges, making them appropriate for use in space communications and radar applications [111]. A research by [112], for example, revealed the viability of utilising a microstrip patch antenna for X-band radar imaging of the lunar surface. Microstrip patch antennas may be built to offer a broad range of emission patterns in addition to their frequency band adaptability. According to study [113], a microstrip patch antenna with a changed form of the patch and the substrate may be engineered to have a highly directed radiation pattern, making it appropriate for use in a range of space exploration applications such as remote sensing and navigation. Advanced modelling and optimisation approaches are required when designing microstrip patch antennas for space exploration applications.

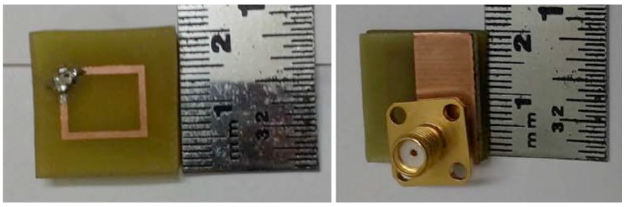


Fig. 25. Photograph of antenna prototype for space exploration applications [7].

A genetic algorithm, for example, was employed in research [114] to optimise the design of a microstrip patch antenna for use in a CubeSat spacecraft. The researchers were able to attain a high gain and a minimal return loss using this method, making the antenna ideal for use in space communications. A tiny UWB stacked microstrip patch antenna for Ku/K band applications is presented in research [7], with 8.5 dBi antenna gain and 88.5% radiation efficiency. Figure 25 depicts the antenna's manufactured front and bottom views [7].

9.13. Antenna using machine learning (ML)

The investigation The investigation of microstrip patch antennas utilising artificial intelligence (AI) and machine learning (ML) techniques is an enthralling subject of study with enormous promise in the world of wireless communication. The integration of AI and ML enables the creation of intelligent algorithms and models capable of optimising the design and performance of microstrip patch antennas. Researchers have made substantial progress in this area in recent years, applying different AI and ML approaches such as neural networks, evolutionary algorithms, and particle swarm optimisation to improve the efficiency, bandwidth, and radiation properties of microstrip patch antennas. These approaches allow for the automated investigation of design parameters as well as the discovery of optimal solutions, resulting in increased antenna performance. Furthermore, combining AI and ML with other technologies like as metamaterials and reconfigurable structures improves the capabilities of microstrip patch antennas. A prominent recent study in this field of AI and ML is [115], in which the authors offer a unique technique for optimising the radiation properties and impedance matching of microstrip patch antennas using deep neural networks. The findings show that AI-based approaches may provide higher antenna performance, opening the path for the development of sophisticated wireless communication systems. An antenna design was presented in research [116], and performance was optimised using ML methods based on ANN, KNN, and KBNN. Figure 26 is a front and bottom view manufactured image of the antenna [116].

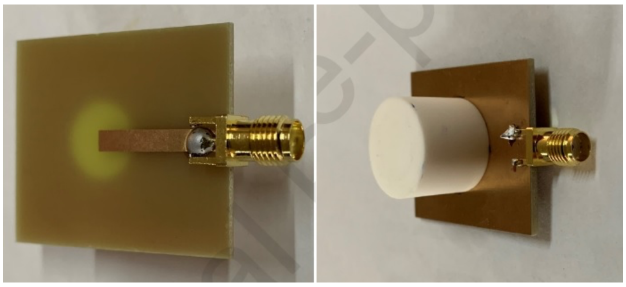


Fig. 26. Photograph of antenna prototype using ML method [116].

10. Circularly polarized dielectric resonator antenna (CP-DRA)

The outstanding circular polarization features, high radiation efficiency, and compact size of circularly polarized dielectric resonator antennas (CP-DRAs) have made them attractive candidates for a range of wireless communication systems [117]. Satellite communication, radar systems, wireless local area networks (WLANs), and cutting-edge technologies like 5G, 6G and the Internet of Things (IoT) are just a few of the industries that use these antennas [118-120]. With an emphasis on their design principles, traits, and applications, this study investigates the most current developments in CP-DRAs. A conventional geometry of rectangular dielectric resonating microstrip patch antenna is portrayed in Fig. 27. Wherein, central component placed over the patch antenna is dielectric resonator, which acts as the radiating element and is usually made of a high-permittivity ceramic material. The purpose of placing this resonator above the microstrip patch is to allow it to resonate at the required frequency and match the resonator's mode. The geometry of DRA consists of rectangular, hemispherical, cylindrical, triangular, hexagonal, conical, stack and modified shapes (pentagonal, half regular shape, trapezoidal). Modification and optimization in DRA shape is used to reduce the effective dielectric constant to improve the antenna bandwidth [121].

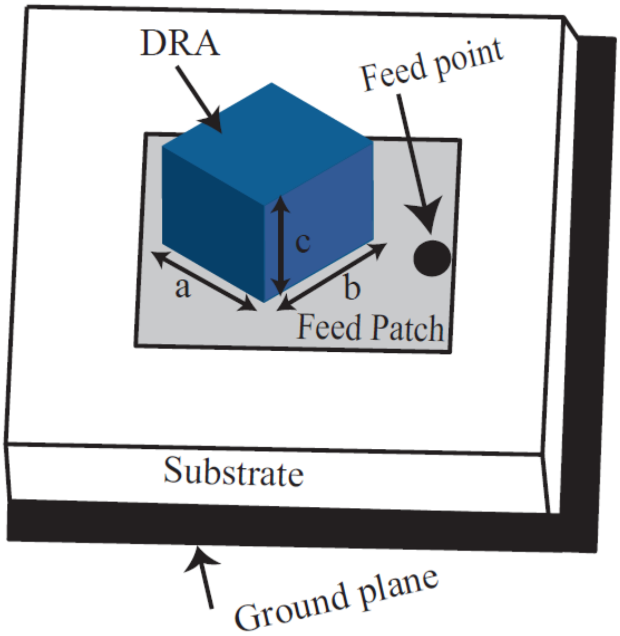


Fig. 27. Geometry of rectangular DRA

CP-DRAs are often made up of a coaxial or microstrip feed feeding a dielectric resonator that is positioned on a ground plane. By stimulating two orthogonal modes in the dielectric resonator, circularly polarized radiation is produced, which is how circular polarization is accomplished in CP-DRAs. The Phase difference ($\Delta\varphi$) between two resonant modes must be maintained at 90^0 to minimize path difference (ΔP) and generate circular polarization mode. The CP-DRA antenna should the phase difference criteria as reported in [121] and given in equation (1). Antenna performance is improved by using a variety of techniques, including feed structure modification, mode excitation, multilayer DRA and dielectric material selection, to increase bandwidth, efficiency, gain and axial ratio [122].

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta P \tag{13}$$

Compared to traditional antennas, CP-DRAs have a number of benefits. They have steady radiation patterns, a large impedance bandwidth, and good radiation efficiency [123]. Additionally, CP-DRAs are appropriate for broadband and multi-band applications because they can achieve circular polarization throughout a broad frequency range [124]. Furthermore, when compared to linearly polarized antennas, CP-DRAs provide better signal reception in non-line-of-sight (NLOS) settings and are less prone to multipath fading [125].

The goal of recent CP-DRA research has been to improve the performance and adaptability of the antenna. Artificial neural networks, genetic algorithms, and metamaterial-based structures are examples of advanced design techniques that have been used to optimize antenna settings and attain desired properties. To enhance impedance matching and lower losses, new feeding strategies have also been developed, such as proximity-coupled feeding and substrate integrated waveguide (SIW) feeding [121, 126-127].

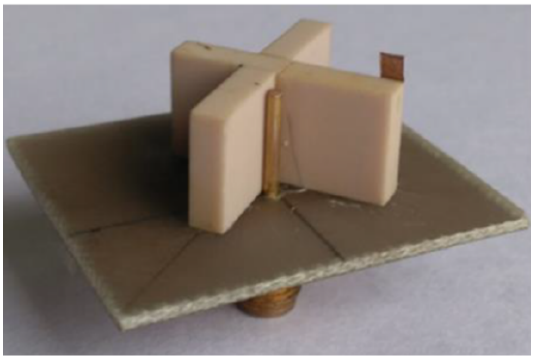


Fig. 28. Photograph of dielectric resonator antenna for circular polarization applications [128]

The coaxial probe feeding approach was used in the study of the CP DRA antenna, a compact asymmetric cross-shaped dielectric resonator antenna with broadside wideband circular polarization [128]. A metal strip, positioned at the corner of the asymmetric cross-shaped DR to reduce excessive tangential electric field and serve as a mirror for normal field components, is included in the design along with a coaxial feed (cf. Fig. 28). Many different types of communication systems use CP-DRAs. CP-DRAs are used in satellite communication to achieve circular polarization and reduce the impacts of signal fading for earth station antennas. CP-DRAs provide enhanced target tracking and detection in radar systems. In addition, CP-DRAs are used in wireless sensor networks and WLANs to provide dependable connectivity and fast data transfer. As 5G and IoT technologies advance, CP-DRAs are anticipated to be essential in allowing dependable and effective wireless networks.

11. Conclusions

Because of its small size and ease of production, the patch antenna is a popular form of antenna in wireless communication systems. The geometry of the patch antenna is critical in determining its electrical performance, with a rectangular patch being the most frequent design. Mechanism, feeding methodologies, analytical methods, and simulation tools are all significant components in patch antenna design and optimization. Engineers may precisely analyze and anticipate the performance of patch antennas using these tools and methodologies, resulting in the construction of more efficient and effective wireless communication systems.

Because of its design flexibility, the microstrip patch antenna has proven to be a versatile and efficient option for wireless communication in current electronics. The antenna's geometry, which includes the size and shape of the patch as well as the dielectric substrate, is critical in defining its radiation mechanism and performance. Furthermore, various feeding approaches may be utilized to improve the antenna's radiation characteristics and impedance matching. The use of microstrip patch antennas in numerous products such as smart phones, laptops, and drones has substantially improved wireless communication capabilities and continues to drive technological developments. To analyze and design the antenna, several models have been developed, including the Transmission line model, Cavity model, Multiport network model (MNM), Method of moments (MoM), Finite element method (FEM), Spectral domain technique (SDT), and Finite difference time domain (FDTD). Each model has benefits and disadvantages, and the model chosen is determined by the unique application and needs. Because it can handle complicated geometries and deliver reliable results, the Method of moments (MoM) is regarded as the best model for current communication systems. The MoM approach is similarly easy to use and has been frequently employed in the construction of microstrip patch antennas. It is worth mentioning, however, that the FDTD approach is a potential tool for modeling electromagnetic fields in complicated structures and is widely regarded as the most accurate method available today [129]. As a result, the model used is determined by the unique application and system requirements.

Finally, numerous feeding approaches have been devised to improve the performance of the microstrip patch antenna. Coaxial or probe feed, microstrip line feed, electromagnetic coupling (proximity feed), aperture-coupled microstrip feed, and coplanar waveguide feed (CPW) are examples of these. Each of these strategies has its own set of pros and disadvantages. The aperture-coupled microstrip feed is the best feeding mechanism for current communication systems. This method has a high radiation efficiency, a low insertion loss, and excellent impedance matching. It can also withstand high power levels and has a small footprint, making it perfect for incorporation into current communication systems. Furthermore, novel feeding strategies are being applied to increase the performance of smart antenna systems. One such method is to feed the antenna with metamaterials [83]. This method makes use of the unique features of metamaterials to improve the antenna's radiation efficiency and gain. Another approach is to employ reconfigurable feeding networks, which allow the antenna to adapt to changing operating circumstances and surroundings [130]. These novel feeding approaches hold a lot of potential for the advancement of sophisticated smart antenna systems. In summary, there are several feeding approaches for microstrip patch antennas, with the aperture-coupled microstrip feed being the best appropriate for current communication systems due to its high radiation efficiency and superior impedance matching. Furthermore, novel feeding strategies are being applied to improve the performance of smart antenna systems, such as the usage of metamaterials and reconfigurable feeding networks. Now, researches are moving with fast pace to develop a massive MIMO patch antenna using AI & ML on flexible substrate for medical and satellite applications.

The use of circular polarized dielectric resonator microstrip patch antennas have shown great promise for several current applications, resulting in important advances in radar systems, satellite communication, wireless communication systems, and other fields. These antennas, which provide benefits such small size, lightweight construction, and improved performance characteristics, have been crucial in meeting the changing needs of contemporary communication technology. Circular polarized dielectric resonator microstrip patch antennas are expected to maintain their influential role in determining the direction of wireless communication infrastructures in the future due to compatibility in smart devices and continuous research and development efforts focused at improving their capabilities and broadening their applicability.

References

[1] B. Mishra, V. Singh and R. Singh, "Dual and wide-band slot loaded stacked microstrip patch antenna for WLAN/WiMAX applications," *Microsyst Technol.,* vol. 23, no. 8 pp. 3467–3475, Aug. 2017. https://doi.org/10.1007/s00542-016-3120-z

[2] G. Kumar and K. P. Ray, *Broadband microstrip antennas*. in Artech House antennas and propagation library. Boston London: Artech House, 2003.

[3] S. G. Kirtania A. W. Elger M. R. Hasan, W. Wisniewska, K. Sekhar, T. Karacolak, and P. K. Sekhar, "Flexible antennas: A review," *Micromachines*, vol. 11, no. 9, pp. 1–43, Sept. 2020, https://doi.org/10.3390/mi11090847

[4] M. U. Khan, M. S. Sharawi and R. Mittra, "Microstrip patch antenna miniaturisation techniques: a review," *IET Microw. Antennas Propag*., vol. 9, no. 9, pp. 913–922, Jun. 2015, https://doi.org/10.1049/iet-map.2014.0602

[5] Y. Liu, L.-M. Si, M. Wei, P. Yan, P. Yang, H. Lu, C. Zheng, Y. Yuan, J. Mou, X. Lv, and H. Sun, "Some recent developments of microstrip antenna," *Int. J. Antennas Propag.,* vol. 2012, pp. 1–10, Mar. 2012, https://doi.org/10.1155/2012/428284

[6] P. K. Malik, S. Padmanaban, and J. B. Holm-Nielsen, *Microstrip Antenna Design for Wireless Applications*, 1st ed. New York: CRC Press, 2021. doi: 10.1201/9781003093558.

[7] B. Mishra, V. Singh, R. K. Singh, N. Singh and R. Singh, "A compact UWB patch antenna with defected ground for Ku/K band applications," *Microw. Opt. Technol. Lett.,* vol. 60, no. 1, pp. 1–6, Dec. 2017, https://doi.org/10.1002/mop.30911

[8] M.-A. Chung and C.-W Yang, "Miniaturized broadband-multiband planar monopole antenna in autonomous vehicles communication system device," *Electronics*, vol. 10, no. 21, pp. 1–13, Nov. 2021. https://doi.org/10.3390/electronics10212715

[9] B. Fady, J. Terhzaz, A. Tribak and F. Riouch, "Integrated miniature multiband antenna designed for WWD and SAR assessment for human exposure," *Int. J. Antennas Propag.*, vol. 2021, pp. 1–15, Apr. 2021, https://doi.org/10.1155/2021/5548834

[10] B. Mishra, R. K. Verma, N. Yashwanth and R. K. Singh, "A review on microstrip patch antenna parameters of different geometry and bandwidth enhancement techniques," *Int. J. Microw. Wireless Technol.*, vol. 14, no. 5, pp. 652–673, Jun. 2022, https://doi.org/10.1017/S1759078721001148

[11] B. Tiwari, S. H. Gupta and V. Balyan, "Design and comparative analysis of compact flexible UWB antenna using different substrate materials for WBAN applications," *Appl. Phys. A,* vol. 126, pp. 1–11, Oct. 2020, https://doi.org/10.1007/s00339-020-04011-5

[12] Electronic Communications Committee (ECC) within the European Conference of Postal and Telecommunications Administrations (CEPT), "The European table of frequency allocations and application in the frequency range 9 kHz to 3000 GHz," ERC Report 25, Nov. 2020. [Online]. Available: https://docdb.cept.org/download/2051

[13] J. D. Kraus and R. J. Marhefka, *Antennas for all applications*, 3rd ed. New York: McGraw-Hill, 2002.

[14] J. Ramsay, "Highlights of antenna history," *IEEE Commun. Mag*., vol. 19, no. 5, pp. 4–8, Sept.1981.

[15] J. C. Maxwell, "A dynamical theory of the electromagnetic field," *Philos.Trans. R. Soc.*, vol. 155, pp. 459–512, Jan. 1865.

[16] K. Fujimoto and H. Morishita, *Modern small antennas*. Cambridge: Cambridge university press, 2013.

[17] F. Bevilacqua, "H. Hertz's experiments and the shift towards contiguous propagation in the early nineties," *Rev. Stor. Sci.,* vol. 1, no. 2, pp. 1–18, 1984.

[18] D. T. Emerson, "The work of Jagadis Chandra Bose: 100 years of millimeter-wave research," *IEEE Trans. Microw. Theory Techn*., vol. 45, no. 12, pp. 2267–2273, Dec. 1997, doi: 10.1109/22.643830.

[19] T. S. Rappaport, *Wireless communications: principles and practice*, 2. ed., 18. printing. in Prentice Hall communications engineering and emerging technologies series. Upper Saddle River, NJ: Prentice Hall, 2009.

[20] A. Sinha, S. A. Saoudy, and B. P. Sinha, "An investigation of Marconi's transmitter during the 1901 transatlantic experiment," in *1998 Symp. Ant. Techn. Applied Electromagn.*, Ottawa, Canada: IEEE, Aug. 1998, pp. 29–32. doi: 10.1109/ANTEM.1998.7861773.

[21] G. A. Deschamps, "Microstrip microwave antennas," in *3rd USAF Symp. Antennas*, Monticello, Illinois, USA, Oct. 1953, pp. 189–195.

[22] R. Munson, "Conformal microstrip antennas and microstrip phased arrays," *IEEE Trans. Anten. Propag.,* vol. 22, no. 1, pp. 74–78, Jan.1974, doi: 10.1109/TAP.1974.1140723.

[23] J. Howell, "Microstrip antennas," *IEEE Trans. Anten. Propag*., vol. 23, no. 1, pp. 90–93, Jan. 1975, doi: 10.1109/TAP.1975.1141009.

[24] K. Carver and J. Mink, "Microstrip antenna technology," *IEEE Trans. Anten. Propag.,* vol. 29, no. 1, pp. 2–24, Jan. 1981, doi: 10.1109/TAP.1981.1142523.

[25] C. A. Balanis, *Antenna theory: analysis and design*, Fourth edition. Hoboken, New Jersey: Wiley, 2016.

[26] T. A. Milligan, *Modern antenna design*, 2nd ed. Hoboken, N.J: IEEE Press : Wiley-Interscience, 2005.

[27] P. S. Hall and J. R. James, *Handbook of microstrip antennas. Volume 2*. London, U.K.: P. Peregrinus on behalf of the Institution of Electrical Engineers, 1989.

[28] R. Garg, Ed., *Microstrip antenna design handbook*. in Artech House antennas and propagation library. Boston, MA: Artech House, 2001.

[29] R. Munson, "Conformal microstrip antennas and microstrip phased arrays," *IEEE Trans. Anten. Propag.,* vol. 22, no. 1, pp. 74–78, Jan.1974.

[30] A. Derneryd, "Linearly polarized microstrip antennas," *IEEE Trans. Anten. Propag.,* vol. 24, no. 6, pp. 846–851, Nov. 1976.

[31] E. Newman and P. Tulyathan, "Analysis of microstrip antennas using moment methods," *IEEE Trans. Anten. Propag.,* vol. 29, no. 1, pp. 47–53, Jan. 1981.

[32] D. Morris, "Which electromagnetic simulator should I use?," *Eng. Phys.,* Vol. 1., pp. 1–10, Jan. 2012

[33] M. N. O. Sadiku, "A simple introduction to finite element analysis of electromagnetic problems," *IEEE Trans. Educ.,* vol. 32, no. 2, pp. 85–93, May 1989.

[34] X. Zhang, J. Fang, K. K. Mei and Y. Liu, "Calculations of the dispersive characteristics of microstrips by the time-domain finite difference method," *IEEE Trans. Microw. Theory Techn.,* vol. 36, no. 2, pp. 263–267, Feb. 1988, doi: 10.1109/22.3514.

[35] A. Reineix and B. Jecko, "Analysis of microstrip patch antennas using finite difference time domain method," *IEEE Trans. Anten. Propag.,* vol. 37, no. 11, pp. 1361–1369, Nov. 1989, doi: 10.1109/8.43555

[36] G. A. E. Vandenbosch and A. Vasylchenko, "A Practical Guide to 3D Electromagnetic Software Tools," in *Microstrip Antennas*, N. Nasimuddin, Ed., InTech, 2011. doi: 10.5772/14756.

[37] J. S. Roy, S. K. Shaw, P. Paul, D. R. Poddar and S. K. Chowdhury, "Some experimental investigations on electromagnetically coupled microstrip antennas on two-layer substrates," *Microw. Opt. Technol. Lett.,* vol. 4, no. 6, pp. 236–238, May 1991.

[38] D. M. Pozar, "A review of aperture coupled microstrip antennas: history, operation, development, and applications," pp. 1–12, May 1996.

[39] P. Sullivan and D. Schaubert, "Analysis of an aperture coupled microstrip antenna," *IEEE Trans. Anten. Propag.,* vol. 34, no. 8, pp. 977–984, Aug. 1986, doi: 10.1109/TAP.1986.1143929.

[40] L. Giauffret, J.-M. Laheurte and A. Papiernik, "Study of various shapes of the coupling slot in CPW-fed microstrip antennas," *IEEE Trans. Anten. Propag.,* vol. 45, no. 4, pp. 642–647, Apr. 1997.

[41] A. K. Gautam, S. Yadav and B. K. Kanaujia, "A CPW-fed compact UWB microstrip antenna," *IEEE Anten. Wirel.Propag. Lett.,* vol. 12, pp. 151–154, 2013, doi: 10.1109/LAWP.2013.2244055.

[42] B.-L. Ooi, S. Qin and M.-S. Leong, "Novel design of broad-band stacked patch antenna," *IEEE Trans. Anten. Propag.,* vol. 50, no. 10, pp. 1391–1395, Oct. 2002, doi:10.1109/TAP.2002.802087.

[43] Z. Ali, V. K. Singh, A. K. Singh, and S. Ayub, "Wide Band Inset Feed Microstrip Patch Antenna for Mobile Communication," in *2013 Int. Conf. Commun. Syst. Netw. Technol.*Gwalior: IEEE, Apr. 2013, pp. 51–54. doi: 10.1109/CSNT.2013.20.

[44] A. Deshmukh and K. P. Ray, "Proximity fed gap-coupled half E-shaped microstrip antenna array," *Sadhana - Acad. Proc. Eng. Sci.*, vol. 40, no. 1, pp. 75–87, Feb. 2015, doi.org/10.1007/s12046-014-0293-y

[45] A. Singh and S. Singh, "Miniaturized wideband aperture coupled microstrip patch antenna by using inverted U-slot," *Int. J. Anten. Propag*., vol. 2014, pp. 1–7, May 2014, doi.org/10.1155/2014/306942

[46] Y. El Hasnaoui and T. Mazri, "Comparative study of different dielectric substrates on microstrip patch antenna for new generation (5G)," *Adv. Mater. Process. Technol*., vol. 8, no. 2, pp. 1400–1407, Dec. 2022. https://doi.org/10.1080/2374068X.2020.1860496

[47] R. K. Verma, D. K. Srivastava and B. Mishra, "Circuit theory model based analysis of triple-band stub and notches loaded epoxy substrate patch antenna for wireless applications," *Int J Commun Syst.,* vol. 35, no. 4., pp. 1–22, Mar. 2022, https://doi.org/10.1002/dac.5052

[48] S. Ullah, S. Ahmad, B. A. Khan and J. A. Flint, "A multi-band switchable antenna for Wi-Fi, 3G Advanced, WiMAX, and WLAN wireless applications. *Int. J. Microw. Wirel. Technol.*, vol. 10, no. 8, pp. 991–997, May 2018. https://doi.org/10.1017/S1759078718000776

[49] D. Ustun, A. Toktas and A. Akdagli, "Deep neural network–based soft computing the resonant frequency of E–shaped patch antennas," *AEU - Int. J. Electron. Commun.,* vol. 102, pp. 54–61, Apr. 2019, https://doi.org/10.1016/j.aeue.2019.02.011

[50] Y. He, J. Huang, W. Li, L. Zhang, S. -W. Wong and Z. N. Chen, "Hybrid method of artificial neural network and simulated annealing algorithm for optimizing wideband patch antennas," *IEEE Trans. Anten. Propag*., vol. 72, no. 1, pp. 944–949, Jan. 2024, doi: 10.1109/TAP.2023.3331249.

[51] M. Boudjerda, A. Reddaf, A. Kacha, K. Hamdi-Cherif, T. E. A. Alharbi, M. S. Alzaidi and S. S. M. Ghoneim, "Design and optimization of miniaturized microstrip patch antennas using a genetic algorithm," *Electronics*, vol. 11, no. 14, pp. 1–14, Jul. 2022 https://doi.org/10.3390/electronics11142123

[52] H. F. Pues and A. R. Van de Capelle, "An impedance-matching technique for increasing the bandwidth of microstrip antennas," *IEEE Trans. Anten. Propag.,* vol. 37, no. 11, pp. 1345–1354, Nov. 1989, doi: 10.1109/8.43553.

[53] K. Sharma and G. P. Pandey, "Efficient modelling of compact microstrip antenna using machine learning," *AEU - Int. J. Electron. Commun.,* vol. 135, Art. no. 153739, Jun. 2021

[54] P. Manikandan and P. Sivakumar, "A novel pinwheel fractal multiband antenna design using particle swarm optimization for wireless applications," *Int. J. Com. Sys.,* vol. 34, no. 15, pp. 1–15, Oct. 2021.

[55] S. Ullah, C. Ruan, T. U. Haq and X. Zhang, "High performance THz patch antenna using photonic band gap and defected ground structure," *J. Electromagn. Waves Appl*,, vol. 33, no. 15, pp. 1943–1954, Aug. 2019, https://doi.org/10.1080/09205071.2019.1654929

[56] T. K. Nguyen, S. K. Patel, S. Lavadiya, J. Parmar, and C. D. Bui, "Design and fabrication of multiband reconfigurable copper and liquid multiple complementary split-ring resonator based patch antenna," *Wav. Rand. Compl. Med*., pp. 1–24, Jan. 2022, doi: 10.1080/17455030.2021.2024623.

[57] M. K. Abdulhameed, M. S. B. M. Isa, Z. Zakaria, I. M. Ibrahim, M. K. Mohsen, M. L. Attiah and A. M. Dinar, "Radiation control of microstrip patch antenna by using electromagnetic band gap," *AEU - Int. J. Electron. Commun.,* vol. 110, Art. no. 152835, pp. 1–11, Oct. 2019.

[58] M. Singh, N. Kumar, S. Dwari and P. Kala, "Metamaterial-inspired miniaturized antenna loaded with IDC and meander line inductor using partial ground plane," *Int J RF Microw Comput Aided Eng*., vol. 29, no. 9, Sept. 2019. https://doi.org/10.1002/mmce.21863

[59] H. Umair, M. J. Uddin, M. H. Ullah, T. B. A. Latef, W. L. B. W. Mahadi and M. B. Othman, "A unique meta material inspired star-slot UWB antenna with soft surface ground," *Electromagnetics*, vol. 40, no. 2, pp. 152–163, Jan. 2020. https://doi.org/10.1080/02726343.2019.1710686

[60] S. Maity, T. Tewary, S. Mukherjee, A. Roy, P. P. Sarkar and S. Bhunia, "Wideband hybrid microstrip patch antenna and gain improvement using frequency selective surface. *Int J Commun Syst.,* vol. 35, no. 14, Jun. 2022. https://doi.org/10.1002/dac.5268

[61] E. C. Britto, S. K. Danasegaran and W. Johnson, "Design of slotted patch antenna based on photonic crystal for wireless communication," *Int J Commun Syst.,* vol. 34, no. 1, Jan. 2021, https://doi.org/10.1002/dac.4662

[62] A. Jafargholi, M. Kamyab, M. Veysi and M. N. Azar, "Microstrip gap proximity fed-patch antennas, analysis, and design," *AEU - Int. J. Electron. Commun.,* vol. 66, no. 2, pp. 115–121, Feb. 2012, https://doi.org/10.1016/j.aeue.2011.05.011

[63] A. Bansal and R. Gupta, "A review on microstrip patch antenna and feeding techniques," *Int. J. Inf. Tecnol.,* vol. 12, no. 1, pp. 149–154, 2020, https://doi.org/10.1007/s41870-018-0121-4

[64] X. Li, Y. Li and Y. Zhang, "5G antennas: A key enabler for 5G communications," *IEEE Commun. Mag.*, vol. 56, no. 2, pp. 28–35, 2018. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8316580

[65] D. Sarkar and K. V. Srivastava, 'Compact four-element SRR-loaded dual-band MIMO antenna for WLAN/WiMAX/WiFi/4G-LTE and 5Gapplications," *Electron. Lett.,* vol. 53, pp. 1623–1624, Dec. 2017. https://doi.org/10.1049/el.2017.2825

[66] M. S. Maharana, G. P. Mishra, and B. B. Mangaraj, "Design and simulation of a Sierpinski carpet fractal antenna for 5G commercial applications," in *2017 Int. Conf. Wirel. Commun., Sign. Proces. Network. (WiSPNET)*, Chennai: IEEE, Mar. 2017, pp. 1718–1721. doi: 10.1109/WiSPNET.2017.8300056.

[67] C. T. Neil, M. Shafi, P. J. Smith, P. A. Dmochowski and J. Zhang, "Impact of microwave and mmWave channel models on 5G systems performance," *IEEE Trans. Anten. Propag.*, vol. 65, no. 12, pp. 6505–6520, Dec. 2017, https://doi.org/10.1109/TAP.2017.2759958.

[68] M. H. Maktoomi, Z. Wang, H. Wang, S. Saadat, P. Heydari and H. Aghasi, "A sub-terahertz wideband stacked-patch antenna on a flexible printed circuit for 6G Applications," *IEEE Trans. Anten. Propag.,* vol. 70, no. 11, pp. 10047–10061, Nov. 2022, https://doi.org/10.1109/TAP.2022.3185497.

[69] M. A. Paun, M.V. Nichita, V. A. Paun, and V. P. Paun, "Minkowski's Loop Fractal Antenna Dedicated to Sixth Generation (6G) Communication," *Fractal Fract.,* vol. 6, no. 7, p. 402, Jul. 2022, https://doi.org/10.3390/fractalfract6070402

[70] Z. S. Muqdad, M. Alibakhshikenari, T. A. Elwi, Z. A. A. Hassain, B .S. Virdee, R. Sharma, S. Khan, N. T. Tokan, P. Livreri, F. Falcone and E. Limiti, "Photonic controlled metasurface for intelligent antenna beam steering applications including 6G mobile communication systems," *AEU - Int. J. Electron. Commun.,* vol. 166, Art. no. 154652, Jul. 2023

[71] N. Kishore and A. Senapati, "5G smart antenna for IoT application: A review," *Int. J. Commun. Sys.* vol. 35, no. 13, Sept. 2022, doi:10.1002/dac.5241

[72] R. Roges and P. K. Malik, "Planar and printed antennas for Internet of Things enabled environment: Opportunities and challenges,*" Int J. Commun. Syst*., vol. 34, no. 15, Oct. 2021. https://doi.org/10.1002/dac.4940

[73] K. R. Jha, B. Bukhari, C. Singh, G. Mishra and S. K. Sharma, "Compact planar multi-standard MIMO antenna for IoT applications," *IEEE Trans. Anten. Propag.,* vol. 66, no. 7, pp. 3327–3336, Jul. 2018, https://doi.org/10.1109/TAP.2018.2829533.

[74] W. Jan Krzysztofik and T. Nghia Cao, "Metamaterials in Application to Improve Antenna Parameters," in *Metamaterials and Metasurfaces*, J. Canet-Ferrer, Ed., IntechOpen, 2019. doi: 10.5772/intechopen.80636.

[75] A. Haddad et al., "1×16 Rectangular dielectric resonator antenna array for 24 Ghz automotive radar system*," Bull. Electr. Eng. Informatics*, vol. 11, no. 4, pp. 2115–2123, Aug. 2022, https://doi.org/10.11591/eei.v11i4.3068

[76] S. Mathivanan and A. Rajeswari, "Omnidirectional microstrip MIMO antenna for intelligent vehicle RADAR communication," *Wirel. Pers. Commun*. vol. 127, no. 4, pp. 3407–3421, Jul. 2022, https://doi.org/10.1007/s11277-022-09923-4

[77] D. Subitha, S. Velmurugan, M. V. Lakshmi, P. Poonkuzhali, T. Yuvaraja and S. Alemayehu, "Development of Rogers RT/Duroid 5880 substrate-based MIMO antenna array for automotive radar applications," *Adv. Mater. Sci. Eng.,* vol. 2022, ArticleID 4319549, pp. 1–11 Jul. 2022. https://doi.org/10.1155/2022/4319549

[78] A. Pandya, T. K. Upadhyaya and K. Pandya, "Design of metamaterial based multilayer antenna for navigation/WiFi/Satellite applications," *Prog. Electromagn. Res. M.*, vol. 99, pp. 103–113, Oct. 2021. https://doi.org/10.2528/PIERM20100105

[79] C. Arora and S. S. Pattnaik, "Particle swarm optimization based metamaterial inspired circularly polarized patch antenna for S

band applications," *Evol. Intel.*, vol. 14, pp. 801–810, Nov. 2021. https://doi.org/10.1007/s12065-020-00455-z

[80] B. Mishra, "An ultra compact triple band antenna for X/Ku/K band applications," *Microw. Opt. Technol. Lett.*, vol. 6, pp. 1857–186, Feb. 2019, https://doi.org/10.1002/mop.31812

[81] A. Kumar, N. K. Narayaswamy, H. V. Kumar, B. Mishra, S. A. Siddique and A. K. Dwivedi, "High-isolated WiFi-2.4 GHz/LTE MIMO antenna for RF-energy harvesting applications," *AEU - Int. J. Electron. Commun.,* vol. 141, Art. no. 153964, Nov. 2021 https://doi.org/10.1016/j.aeue.2021.153964.

[82] L. V. Tung, N. Ha-Van, and C. Seo, "A Novel Metamaterial Design Using Genetic Algorithm for High Gain Energy Harvesting Antenna," in *2020 IEEE Wir. Pow. Trans. Confer. (WPTC)*, Seoul, Korea (South): IEEE, Nov. 2020, pp. 123–126. doi: 10.1109/WPTC48563.2020.9295587.

[83] T. Q. Li, B. Ma and W. R. Lv, "A novel design of microstrip patch antenna array with modified-I-shaped electromagnetic metamaterials applied in microwave wireless power transmission," *Optik,* vol. 173, pp. 193 – 205, Nov. 2018, https://doi.org/10.1016/j.ijleo.2018.08.012

[84] M. Z. Mahmud, M. T. Islam, N. Misran, A. F. Almutairi and M. Cho, "Ultra-wideband (UWB) antenna sensor based microwave breast imaging: A review," *Sensors*, vol. 18, no. 9, 2951, Jun. 2018. https://doi.org/10.3390/s18092951

[85] D. Kim, D. Hernandez and K-N.Kim, "Design of a dual-purpose patch antenna for magnetic resonance imaging and induced RF heating for small animal hyperthermia," *Appl. Sci.*. vol. 11, no. 16, Art. no. 7290, Aug. 2021. https://doi.org/10.3390/app11167290

[86] M. Samsuzzaman, M. S. Talukder, A. Alqahtani, A. G. Alharbi, R. Azim, M. S. Soliman and M. T. Islam, "Circular slotted patch with defected grounded monopole patch antenna for microwave-based head imaging applications," *AEJ - Alex. Eng. J.,* vol. 65, pp. 41–57, Feb. 2023, https://doi.org/10.1016/j.aej.2022.10.034.

[87] H. A. Elkayal and N. E. Ismail, "Efficient focusing of microwave hyperthermia for small deep-seated breast tumors treatment using particle swarm optimization," *Comput. Methods Biomech. Biomed. Engin.,* vol. 24, no. 9, pp. 985–994, Jul. 2021, https://doi.org/10.1080/10255842.2020.1863379

[88] R. Proesmans, K. Deprez, M. Velghe and A. Thielens, "An on-body antenna for control of a wireless prosthesisin the 2.45 GHz industrial scientific & medical frequency band.," *IET Microw. Antennas Propag.* vol. 16, no. 15, pp. 919–932, Oct. 2022, https://doi.org/10.1049/mia2.12309

[89] V. G-G. Buend, S. Liberto, G. Goussetis and N. J. G. Fonseca, Review of antenna technologies for very high frequency Data Exchange Systems," *Int J Satell Commun Network.*, vol. 41, no. 2, pp. 122–133, Sept. 2023. https://doi.org/10.1002/sat.1428

[90] T. R. Kumar and M. Madhavan, "Design and optimization of wearable microstrip patch antenna using hybrid fuzzy flamingo swarm optimization algorithm for RF energy harvesting," *Iran J Sci Technol Trans Electr. Eng.,* vol. 48, 471, Feb. 2022. https://doi.org/10.1007/s40998-021-00470-5

[91] M. Boudjerda, A. Reddaf, A. Kacha, K. Hamdi-Cherif, T. E. A. Alharbi, M. S. Alzaidi, M. Alsharef and S. S. M. Ghoneim, "Design and optimization of miniaturized microstrip patch antennas using a genetic algorithm," *Electronics*, vol. 11, Art no. 2123, Jul. 2022. https://doi.org/10.3390/electronics11142123

[92] B. Nasiri and J. Zbitou, "A new design of stepped antenna loaded metamaterial for RFID applications," *Bull. Electr. Eng. Informat.*, vol. 10, no. 5, pp. 2661–2666, Oct. 2021, https://doi.org/10.11591/eei.v10i5.2675

[93] M. S. R. Bashri, M. I. Ibrahimy and S. M. A. Motakabber, "Design of a planar wideband patch antenna for UHF RFID tag," *Microw. Opt. Technol. Lett.,* vol. 56: pp. 1579–1584, Apr. 2014. https://doi.org/10.1002/mop.28389

[94] M. S. Grewal, A. P. Andrews, and C. Bartone, *Global navigation satellite systems, inertial navigation, and integration*, Fourth Edition. Hoboken: Wiley, 2020.

[95] T. Ali, N. Fatima and R. C. Biradar, "A miniaturized multiband reconfigurable fractal slot antenna for GPS/GNSS/Bluetooth/WiMAX/X-band applications," *AEU - Int. J. Electron. Commun.,* vol. 94, pp. 234–243, Sept. 2018, https://doi.org/10.1016/j.aeue.2018.07.017

[96] M. Ameen and R. K. Chaudhary, "Dual-layer and dual-polarized metamaterial inspired antenna using circular-complementary split ring resonator mushroom and metasurface for wireless applications," *AEU - Int. J. Electron. Commun.,* vol. 113, Art. no. 152977, Jan. 2019. https://doi.org/10.1016/j.aeue.2019.152977

[97] M.-S. Wang, X. -Q. Zhu, Y. -X. Guo and W. Wu, "Miniaturized dual-band circularly polarized quadruple inverted-F antenna for GPS applications," *IEEE Anten. Wirel. Propag. Lett.,* vol. 17, no. 6, pp. 1109–1113, Jun. 2018, https://doi.org/10.1109/LAWP.2018.2834484.

[98] A. Dejen, J. Jayasinghe, M. Ridwan, and J. Anguera, "Synthesis of quadband mm-wave microstrip antenna using genetic algorithm for wireless application," *Technologies*, vol. 11, no. 1, Jan. 2023. https://doi.org/10.3390/technologies11010014

[99] Z. D. Zaharis *et al.*, "Exponential log-periodic antenna design using improved particle swarm optimization with velocity mutation," *IEEE Trans. Magn.,* vol. 53, no. 6, pp. 1–4, Art no. 7204104, Jun. 2017, https://doi.org/10.1109/TMAG.2017.2660061.

[100] Y-M Cai, K. Li, Y. Yin and L. Zhao, "A multi-functional tri-mode patch antenna supporting dual-band GPS and wireless communication system," *Microw. Opt. Technol. Lett.,* vol. 59, pp. 2457–2462, Jul. 2017. https://doi.org/10.1002/mop.30750

[101] M. H. El Misilmani, T. Naous and S. K. Al Khatib, "A review on the design and optimization of antennas using machine learning algorithms and techniques," *Int. J. RF Microw. Comput. Aided Eng.,* vol. 30, no. 10, Art. no. 22356, Oct. 2020, .https://doi.org/10.1002/mmce.22356

[102] T. M. Neebha and M. Nesasudha, "Analysis of an ultra-miniature capsule antenna for gastrointestinal endoscopy*", Eng. Sci. Technol. Int. J.,* vol. 21, no. 5, pp. 938–944, Oct. 2018, https://doi.org/10.1016/j.jestch.2018.06.017

[103] S. Azzaz-Rahmani, H. Zerrouki and L. Dekkiche, "Novel microstrip patch antenna for implantable medical telemetry devices," *J. Appl. Eng. Sci.,* vol. 24, no. 6, pp. 853–860, Jun. 2021, https://doi.org/10.6180/jase.20211224(6).0005

[104] G. K. Das, S. Basu, B. Mandal, D. Mitra, R. Augustine and M. Mitra, "Gain-enhancement technique for wearable patch antenna using grounded metamaterial," *IET Microw. Antennas Propag.*, vol. 14, no. 15, pp. 2045-2052, Dec. 2020, https://doi.org/10.1049/iet-map.2020.0083

[105] L. Luo, B. Hu, J. Wu, T. Yan and L-J. Xu, "Compact dual-band antenna with slotted ground for implantable applications," *Microw. Opt. Technol. Lett.*, vol. 61, no. 5, pp. 1314–1319, May 2019. https://doi.org/10.1002/mop.31718

[106] K. Jairath, N. Singh, M. Shabaz, V. Jagota, and B. K. Singh, "Performance Analysis of Metamaterial-Inspired Structure Loaded Antennas for Narrow Range Wireless Communication," *Sci. Program.,* vol. 2022, pp. 1–17, May 2022, https://doi.org/10.1155/2022/7940319

[107] E. Fernandes, M. Silva, L. Briggs and A. Campos, "2.4-5.8 GHz dual-band patch antenna with FSS reflector for radiation parameters enhancement," *AEU - Int. J. Electron. Commun.,* vol. 108, pp. 235–241, Aug. 2019. https://doi.org/10.1016/j.aeue.2019.06.021

[108] S. N. Nafea, "Compact multilayer patch antenna for wireless sensing network applications at 5.8 GHz," *in Conf. Mathem, Sci. Applic. Engin.: CMSAE-2021*, Chennai, India, 2023, Art. no. 050021. doi: 10.1063/5.0148093.

[109] M. Chinnasamy, E. F. Sundarsingh and P. Sankaran, "Design of a novel compact modified-circular printed antenna for high data rate wireless sensor networks," *Int. J. RF Microw. Comput. Aided Eng.,* vol. 30, no. 10, Art. no. e22375, Oct. 2020. https://doi.org/10.1002/mmce.22375

[110] K. Anim, P. Danuor, S.-O. Park, Y.-B. Jung, "High-efficiency broadband planar array antenna with suspended microstrip slab for X-band SAR On board Small Satellites. *Sensors*, vol. 22, Art. no. 252, Nov. 2022.https://doi.org/10.3390/s22010252

[111] K. Mahendran, D. R. Gayathri, and H. Sudarsan, "Design of multi band triangular microstrip patch antenna with triangular split ring resonator for S band, C band and X band applications," *Microprocess. Microsyst.*, vol. 80, Art. no. 103400, Feb. 2021, https://doi.org/10.1016/j.micpro.2020.103400

[112] A. Wa'il, R. M. Shaaban and A. Tahir, "Design, simulation and measurement of triple band annular ring microstrip antenna based on shape of crescent moon," *AEU - Int. J. Electron. Commun.,* vol. 117, Art. no. 153133, Apr. 2020, https://doi.org/10.1016/j.aeue.2020.153133

[113] S. Punith, S. K. Praveenkumar, A. A. Jugale and M. R. Ahmed, "A novel multiband microstrip patch antenna for 5G communications", *Procedia Comput. Sci.,* vol. 171, no. 2019, pp.

2080–2086, Jun. 2020, https://doi.org/10.1016/j.procs.2020.04.224

[114] J. Simon, H. Perez-Guerrero, J. Sosa-Pedroza, F. Mart´ınez-Z´u˜niga, J. Villanueva-Maldonado, J. Flores-Troncoso, M. Cardenas-Juarez," Design of an ultrawideband circularly polarized printed crossed-dipole antenna based on genetic algorithms for S-band cube-sat applications", *Int. J. Anten. Propag.,* vol. 2021, Art. no. 8733427, Sept. 2021. https://doi.org/10.1155/2021/8733427

[115] S. K. Patel, J. Surve, V. Katkar and J. Parmar, "Machine learning assisted metamaterial-based reconfigurable antenna for low-cost portable electronic devices," S*ci. Rep*., vol. 12, Art. no. 12354, Jul. 2022. https://doi.org/10.1038/s41598-022-16678-2

[116] A. Srivastava, H. Gupta, A. K. Gupta, K. K. V. Penmatsa, P. Ranjan and A. Sharma, "Aperture coupled dielectric resonator antenna optimization using machine learning techniques," *AEU - Int. J. Electron. Commun.*, vol. 154, Art. no. 154302, Sept. 2022, https://doi.org/10.1016/j.aeue.2022.154302

[117] R. Kumar and R. K. Chaudhary, "Stacked rectangular dielectric resonator antenna with different volumes for wideband circular polarization coupled with step-shaped conformal strip," *Int. J. RF Microw. Comput. Aided Eng.,* vol. 29, no. 6, Art. no. e21667, Jun. 2019. https://doi.org/10.1002/mmce.21667

[118] H. Ahmad, M. H. Jamaluddin, F. C. Seman, and M. Rahman, "MIMO dielectric resonator antennas for 5G applications: A review," *Electronics*, vol. 12, no. 16, Art no. 3469, Aug. 2023. https://doi.org/10.3390/electronics12163469

[119] H. Attia, A. Abdalrazik, M. S. Sharawi and A. A. Kishk, "Wideband circularly polarized millimeter-wave DRA array for internet of things," *IEEE Intern. Things J.*, vol. 10, no. 11, pp. 9597–9606, Jun. 2023, https://doi.org/10.1109/JIOT.2023.3235344

[120] Y. Zhang, S. Ogurtsov, V. Vasilev, A. A. Kishk and D. Caratelli, "Advanced dielectric resonator antenna technology for 5G and 6G applications," *Sensors*, vol. 24, no. 5, Art. no. 1413, Feb. 2024. https://doi.org/10.3390/s24051413

[121] R. K. Chaudhary, R. Kumar, and R. Chowdhury, *Circularly polarized dielectric resonator antennas*. in Artech House antennas and propagation library. Boston: Artech, 2021.

[122] C. Wang, W. Hu, X. Jiang, Q. Fan, J. Huang and H. Huang, "A wideband circularly polarized dielectric resonator antenna with flat gain response within the passband," *AEU - Int. J. Electron. Commun.,* vol. 177, Art. no. 155224, Apr. 2024. https://doi.org/10.1016/j.aeue.2024.155224

[123] W. -W. Yang, W. -J. Sun, H. Tang and J. -X. Chen, "Design of a circularly polarized dielectric resonator antenna with wide bandwidth and low axial ratio values," *IEEE Trans. Anten. Propag.,* vol. 67, no. 3, pp. 1963–1968, Mar. 2019, https://doi.org/10.1109/TAP.2019.2891219

[124] T. Huang, H. Liu, H. Xu, and L. Geng, "3-D printed dual-band, dual-sense circularly polarized dielectric resonator antenna with a band stop filtering response using planar via-free D-CRLH feeding network," AEU - Int. J. Electron. Commun., vol. 169, Art. no. 154760, Sept. 2023, https://doi.org/10.1016/j.aeue.2023.154760

[125] A. Kesavan, M. Al-Hassan, I. Ben Mabrouk, and T. Denidni, "Wideband circular polarized dielectric resonator antenna array for millimeter-wave applications," *Sensors*, vol. 21, no. 11, Art. no. 3614, May 2021, https://doi.org/10.3390/s21113614

[126] B. Mukherjee, P. Patel and J. Mukherjee, "A review of the recent advances in dielectric resonator antennas," *J. Electromagn. Waves Appl.,* vol. 34, no. 9, pp. 1095–1158, Apr. 2020, https://doi.org/10.1080/09205071.2020.1744484

[127] S. Bhattacharya (Mitra) and S. C. Ray, "Broadbanding and multi-frequency in dielectric resonator antennas: a comprehensive review," *Int. J. Microw. Wireless Technol.*, vol. 15, no. 4, pp. 709–725, 2023, https://doi.org/10.1017/S1759078722000769

[128] R. Kumar and R. K. Chaudhary, "Compact asymmetric cross shaped rectangular dielectric resonator antenna for wideband circular polarization," *Microw. Opt. Technol. Lett.*, vol. 61, no. 7, pp. 1863–1873, Jul. 2019, https://doi.org/10.1002/mop.31808

[129] R. C. Hadarig, M. E. de Cos and F. Las-Heras, "High-performance computational electromagnetic methods applied to the design of patch antenna with EBG structure", *Int. J. Anten. Propag.,* vol. 2012, pp. 1–5, 2012.https://doi.org/10.1155/2012/435890

[130] K. Han, X. Feng, G. Wei, M. Wang and S. Lei, "A simple design of reconfigurable feeding network for antenna array beam scanning," *AEU - Int. J. Electron. Commun.,* vol. 169, Art. no. 154751, Sept. 2023, https://doi.org/10.1016/j.aeue.2023.154751