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Multiband Reconfigurable Antennas for 5G Wireless and CubeSat Applications: A Review

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ABSTRACT The rapid development of wireless technology has sparked interest in multi-band reconfigurable antennas as devices and satellites are innovating toward miniaturization. With limited space, reliable and efficient high bandwidth antenna systems are needed for current and next-generation wireless technology as well as for the revolutionary small satellites. The fifth generation of mobile communication technology promises high data rates, low latency and good spectrum efficiency. One of the key enablers of this technology is the integration of satellite technology-particularly CubeSats with terrestrial communication technologies. Next-generation antennas that can meet functional requirements for 5G and CubeSat applications are therefore of fundamental importance. These antenna systems should have large bandwidth, high gain and efficiency and be compact in size. Reconfigurable antennas can provide different configurations in terms of the operating frequency, radiation pattern and polarization. Tuning reconfigurable antennas can be done by changing the physical parameters of the antenna elements through electronic switches, optical switches and the use of meta-materials. The most popular implementation method for reconfigurable antennas for wireless and satellite communication is the electronic switching method due to its high reliability, efficiency, and ease of integration with microwave circuitry. In this article, different techniques for implementing reconfigurable and multi-band antennas are reviewed, with emphasis on two main application areas; 5G wireless communication and CubeSat application. Different reconfiguration techniques have been studied for application in various wireless communication systems such as satellite communication, multiple-input multiple-output (MIMO) systems, cognitive radio and 5G communication. It has been found that reconfigurable antennas have favourable properties for next-generation wireless technology and small satellites. These properties include low cost, less volume requirements and good isolation between wireless standards.

INDEX TERMS Microstrip antenna, multi-band, reconfigurable antenna, frequency reconfigurable, radiation pattern, CubeSat, nanosatellite, circular polarization, reflection coefficient, 5G, RF-switches.

NOMENCLATURE

4G	Fourth generation.	DCS	Digital cellular systems.
1U	One unit of a CubeSat.	DRA	Dielectric resonator antenna.
5G	Fifth generation.	EPS	Electrical power system.
S_{11}	Reflection coefficient.	GSM	Global System for mobile communications.
ADCS	Attitude determination and control system.	HFSS	High-frequency structure simulator.
COTS	Commercial off the shelf.	IoT	Internet of things.
CP	Circular polarization.	ISS	International space station.
CPW	Coplanar waveguide.	LEO	Low earth orbit.
CST	Computer simulation technology.	LHCP	Left hand circular polarization.
		LTE	Long term evolution of 4G.
		LWA	Leaky wave antenna.
		MEMS	Micro-electromechanical system.

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MIMO	Multiple input multiple output.
mMTC	Massive machine type communication.
PCS	Personal communication system.
PIFA	Planar inverted F-antenna.
QoS	Quality of service.
RF	Radio frequency.
RHCP	Right hand circular polarization.
RL	Return loss.
SAR	Synthetic aperture radar.
SDR	Software defined radio.
SIW	Substrate integrated waveguide.
TTC	Telemetry, tracking and control.
UHF	Ultra high frequency.
UMTS	Universal mobile telecommunication system.
VHF	Very high frequency.
VSWR	Voltage standing wave ratio.
WiMAX	Worldwide interoperability for microwave access.
WLAN	Wireless local area network.

I. INTRODUCTION

The fifth generation of wireless communication (5G) offers a significant improvement from 4G network as an effort to meet the ever-growing demand in data and connectivity of today's modern world [1], [2]. It also solves some of the problems brought about by the implementation of the previous network generations such as high energy consumption, spectrum scarcity, poor coverage and poor quality of service (QoS) by providing multi-Gbps data rates with low latency of about 1 ms, greater capacity, global coverage, increased availability and adaptability [3].

For 5G to meet the required performance which supports a broad range of use cases for addressing both local and global market needs, it has to integrate available communication technologies, taking advantage of their strengths to form a large heterogeneous network [4]. These technologies includes terrestrial mobile communication as well as satellite communications. Satellite communication networks are critical to the realization of the 5G vision of global connectivity as they provide highly efficient, effective and expedient network deployments, leveraging it's intrinsic advantages in broadcasting capabilities, global coverage, reduced reliance on terrestrial infrastructure and high security [5]. Integrating these features of satellite communications into the 5G network can lead to a wider range of improved use cases using an integrated 5G satellite-terrestrial network as opposed to relying only on terrestrial-based solutions [6]. These use cases include providing communication service to rural under-served, remote areas while also serving dense urban areas such as on-premise local networks, content acquisition and distribution, highly distributed IoT networks and private mobile and nomadic deployment [7], [8]. Some of the use cases are shown in figure 1.

Attributes that are unique to satellites, which support 5G includes; ubiquity (global coverage), mobility, broadcasting

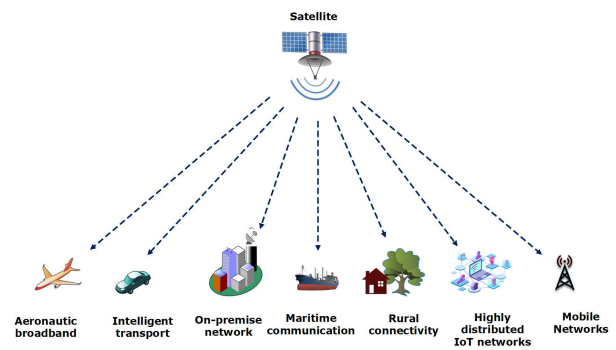


FIGURE 1. Some of the 5G use cases.

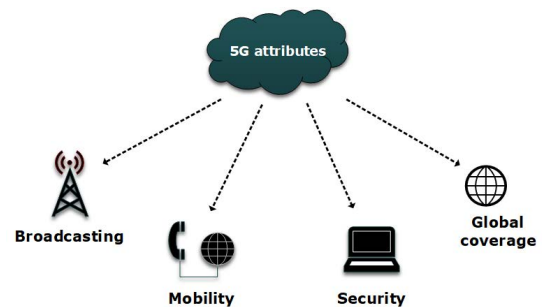


FIGURE 2. 5G network attributes.

as well as security [9]. These attributes are shown in figure 2. Their integration in 5G will help vendors and telecommunication operators to serve markets and communities that were previously hard to reach with conventional, terrestrial communication, thereby addressing some of the important 5G challenges. These includes; to extend service coverage in currently under-served areas, ensure service continuity, provide connectivity to massive machine type communication and IoT devices, as well as scaling up and scaling down of network capacity in response to the varying traffic demands [10].

The emergence of nanosatellites has proven that conventional satellite structures can be miniaturized into a very small form factor [11], [12]. The technological advances on miniaturization techniques for electrical and electronics components has also enabled that satellite systems which were once large, complex, time consuming and extremely high costs may now be developed in small, less costly satellite structures with less development time. These small miniaturized satellites are called nanosatellites, of which the Cube Satellite (CubeSat) is most common [13], [14]. CubeSats use a standardized form factor called one unit (1U) which is a cube-shaped structure measuring 10 cm × 10 cm × 10 cm [15]. This design concept is a modular design which can be scaled to other units such as 3U, 6U, 12U or even 24U. The design of the CubeSats is also made less complex due to the availability of commercial off the shelf (COTS) components.

The use of conventional satellites in the 5G communication network, has proven to be advantageous due to its coverage, ubiquity and security [10]. However, the downside to using

traditional satellites in 5G communication is the fact that they are very expensive and time consuming to develop, requiring specialized expertise and infrastructure for design, development and testing [16]. The use of satellites for IoT and massive machine type communication (mMTC) in the development of next generation communication systems including 5G and 6G communication necessitates that they be placed in low earth orbit (LEO) to achieve low latency [17], [18]. They must also be able to communicate with each other in constellations to ensure global coverage and mobility. These large, conventional satellite constellations take years to build at very high costs, which could delay the roll out of 6G which is expected to begin in 2030 [19].

Nanosatellites, due to their small structure and low development and launch cost can be used to meet the requirements of satellite-terrestrial 5G networks in LEO. Their launch is relatively low cost as they can be launched in ride sharing missions alongside a bigger satellite or can be launched from the international space station (ISS). Because they are much more convenient and cheaper to develop and launch than bigger conventional satellites, nanosatellite constellations can also be designed and launched as they offer improved performance in terms of low latency, robustness, security and global coverage [15], [20]. Furthermore, new-space companies like One Webb and SpaceX have invested billions of dollars to develop such small satellite-constellations for fast 5G internet as well as to connect the unconnected populations in rural areas all over the world.

One of the challenges in developing small satellites is that, the available, COTS components may not meet the design and performance requirements for specialized high speed and high data rate satellite missions. Subsystems of the nanosatellite system includes; communication antennas, electrical power system (EPS) module, onboard computer & transmitter and attitude determination and control system (ADCS) module [21], [22]. The antenna, which is part of the radio frequency (RF) front end, is of particular importance as it transmits RF waves between space and earth and also establish a connection to other satellites in a constellation. Satellite antennas are required to support communication bands that offer both high speed links (such as S-band, X-band, Ka- and Ku-bands) for data downlink as well as low data rate link for telemetry, telecommand and control data such as very high frequency and ultra high frequency (VHF/UHF) [23], [24]. The antenna structures are required to be small and align with CubeSat specifications while also meeting the requirements for the satellite mission.

The other challenge with the design of small nanosatellite antennas is the lack of hardware adaptability to keep up with the software updates and improvements. Software generally adapts quickly as companies or organizations focus on improving their product performance. Occasionally, software used onboard the satellite is updated to improve performance. On the other hand, most hardware components on the satellite are only limited to the current software release and may not meet the specifications for the update. Other actions while the

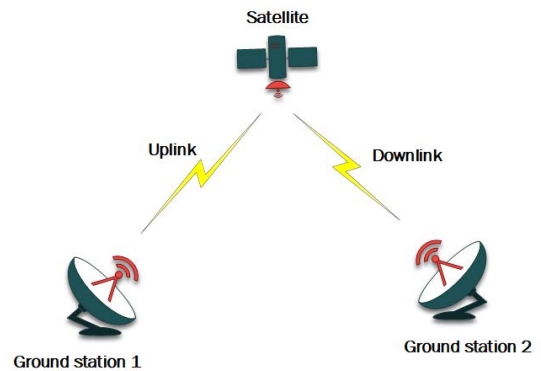


FIGURE 3. Satellite bent-pipe communication architecture.

satellite is in orbit include the transition from armature radio frequencies to commercial radio frequencies [25]. In some cases, commercial frequency license applications may take years before approval, the satellite may therefore have to operate first in the armature frequencies and later switch to commercial, following the approval. Hardware components especially antennas, that allows for switching of radio frequencies from armature to commercial, together with the ability to handle in-orbit software updates are of fundamental importance in nanosatellites [26]. This adaptability however is very limited especially in commercially available antennas.

A study of different antennas such as spiral antenna, wire antennas, parabolic reflectors, reflectarrays and microstrip antennas and also intelligent reflective surfaces in [27], has shown that the microstrip antenna provides better performance in terms of the gain, frequency adaptability and that it has a low volume with the ability to be flush mounted. Microstrip antenna also meets the adaptability requirements as its design can be tweaked to address each application need. Microstrip antennas can also be designed in an array form to increase the directivity, gain and efficiency as required in 5G communication. Other functionalities such as phased array structure reconfigurability, beamforming abilities and massive MIMO systems can also be achieved by microstrip antennas [28], [29].

As shown in [27], microstrip patch antennas, especially array microstrip antennas offer better performance in terms of gain, circular polarization (CP), conformity to the structure, no deployment mechanical movements, reconfigurability, gain dynamics etc. Therefore, in this article, emphasis will be made to the microstrip patch antenna as used in nanosatellite and constellations for 5G communication and space to ground bent-pipe communication (figure 3). More attention will be given to the reconfigurable and multiband versions of these antennas. They are studied in detail to find out how exactly they operate for both terrestrial and nanosatellite communication.

The basic microstrip antenna consists of a ground plane and a patch separated by a substrate, as seen in figure 4 [30]. The patch antenna can take any geometrical shape. The most common ones however, are the rectangular, triangular and

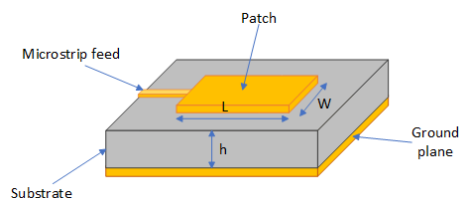


FIGURE 4. Basic structure of a microstrip patch antenna and microstrip line feed.

circular ring shapes. These shapes can be modified by adding slots, inserting stubs or arranging the patches to form arrays.

There are a number of substrates that can be used in the design of the microstrip antenna with dielectric constants ranging from $2.2 < \epsilon_r < 12$, where, ϵ_r represents the relative dielectric constant. Some of the commonly used substrates are the RT-duroid, rogers, FR-4, alumina, epoxy, etc. Research has shown that a thicker substrate leads to an increased radiation power, reduced conductor loss and improved bandwidth and efficiency which are some of the most important system requirements for 5G communication [30]. Radiation from microstrip antennas occurs from fringing fields between the open circuited edge of the microstrip antenna conductor and the ground plane [31].

Microstrip patch antennas can be fed using different feeding techniques such as; coaxial, microstrip line, aperture coupling, proximity coupling and coplanar waveguide (CPW) feed [32]. Coaxial feed and microstrip line feed methods are the most commonly used in microstrip patch antennas. Coaxial feed is widely used because of its advantages like; low spurious radiation and ease of matching. Other feeding methods like proximity and aperture coupled methods are not widely used because they require multilayer fabrication which leads to a complex fabrication process [33]. The microstrip line feeding technique is also shown in figure 4.

According to [34], some of the research outputs in microstrip antennas include; reconfigurable designs, improved bandwidth designs, miniaturization, as well as array designs [35]. Microstrip antennas are used in many different application areas like mobile and wireless communication, satellite communication, cognitive radio, radar systems and wireless local area networks [36]. The requirements for designing a basic microstrip antenna are; substrate, shape of patch, dimension of patch, feeding technique, resonant frequency and substrate thickness.

This paper studies multi-band and reconfigurable antenna designs for 5G and CubeSat applications. Design specifications for these antennas are closely looked into in order to evaluate the performance of such antennas for possible improvements in terms of gain, radiation pattern, efficiency as well as increasing the number of frequency bands covered. Different reconfiguration techniques are studied in this paper, with emphasis made particularly on electrical reconfigurability. Particular focus is given to frequency and radiation pattern reconfigurable antennas because of the need to increase coverage for applications such as 5G and small satellites,

by increasing the number of frequencies covered as well as a single antenna with multiple possible radiation pattern configuration.

A. RELATED WORKS

1) ANTENNAS FOR 5G WIRELESS COMMUNICATION

There is ongoing research work in the area of reconfigurable multi-band antennas for wireless communication for current and future communication systems. In [37], the concept of reconfigurable antennas is explained in detail and the authors also expand on the different methods used for implementing dynamic, reconfigurable antennas. These methods include electrical and mechanical switching which are also extended and looked into closely by the authors of [38]. As stated in [38], electrical reconfiguration through the use of PIN diode alters the flow of current in the antenna geometric structure, which modifies its electrical characteristics. Reconfigurable patch antenna design articles are reviewed in [32]. The antennas studied reduce the complexity and the antenna size through reconfigurability. A more detailed review of antennas for future wireless communication which provides information on the various types and approaches to reconfigurable antennas and antenna arrays as they can be used in future generation wireless communication systems is provided in [39]. In [40] a review of frequency reconfigurable microstrip antennas for 5G application is provided. Furthermore, a dedicated survey on switching techniques for reconfigurable antennas is outlined in [41]. Implementations of these techniques have been studied specifically to be used in the various wireless communication systems. Possible applications for the next generation antennas include cognitive radio, multiple-input multiple-output (MIMO) applications, mobile terminals, software defined radio (SDR) as well as CubeSat communication.

2) ANTENNAS FOR NANOSATELLITES

One of the most critical component of the CubeSat spacecraft that has attracted tremendous research attention is the antenna system, which is used to provide a strong communication link between the satellite and the ground station. In [42], a comprehensive review of antennas used for nanosatellites was provided. The paper details both currently operational antenna systems as well as those that are still under development for future missions. Planar antennas proposed for use in CubeSats were discussed further in [43]. The survey gives details of planar antennas (microstrip patch and slot antennas) used for picosatellite cross-link communication. A qualitative comparison of CubeSat antennas was also carried out in terms of their mass, gain, size, steerability, return loss, polarization and operating frequency. The paper further describes in detail the techniques for miniaturization, high gain and wide bandwidth, that are applied to microstrip and slot antennas as well as an evaluation of the effects of the CubeSat body on the antenna performance.

In [44], various types and applications of antennas for picosatellites are presented. Design challenges of such

antennas are considered together with possible innovative methods used to solve the space and power limitations in these compact satellites. Small satellites contain more than one antenna for different functions. Authors in [45] give details of some of the most advanced satellite antenna systems available so far in practice. Designs of antennas onboard satellites need to be optimized because they directly determine the performance of the spacecraft. One of the satellite application that needs innovative antenna design is the synthetic aperture radar (SAR) technology which requires antennas to have multiple operating frequency bands, dual polarization, electronic beam steering, high efficiency compact size as well as low mass and low power [46].

Despite the amount of literature on antennas for 5G communications and nanosatellites in general, there is still room for more research specifically on multi-band and reconfigurable antenna design. Reconfigurable antennas can be useful for limited space satellite designs and also for satellite missions that require more than one operating frequency or that require a dynamic radiation pattern. The next section discusses contributions of this paper.

B. CONTRIBUTIONS

This paper provides a comprehensive review of reconfigurable antennas for 5G wireless and CubeSat applications. Another paper that presents reconfigurable antennas for both wireless and space application is in [26]. The paper however does not exhaust the subject and also, it is not based specifically on 5G or CubeSat antennas. It is rather generalized to space and wireless applications of up to the fourth generation technology. Furthermore, it was published in 2012, which means that, current designs for CubeSat antennas that evolved between then and now were not covered. The contribution found in this research therefore explicitly gives details on the designs for both 5G wireless and CubeSat antennas together with some reproduced simulation results. This is to help prepare for the implementation of next generation technology (5G and 6G) which requires the integration of terrestrial technology with satellite technology, especially low earth orbiting (LEO) satellites. This paper therefore presents design techniques for multi-band, reconfigurable antennas which can be used for the design of 5G and CubeSat antennas. Different, novel designs for 5G reconfigurable antennas are also examined in detail, focusing on their design specifications and performance analysis. Antenna systems used on previous CubeSats missions are studied and their advantages and disadvantages analyzed in order to understand antenna requirements for successful CubeSat missions. Designs of dual- and multi-band antennas for CubeSats are also presented with their performance results. This paper therefore presents the missing link of multi-band and reconfigurable antennas for 5G and CubeSat application.

C. PAPER STRUCTURE

The rest of this paper is organized as follows; Section II discusses CubeSat antennas, section III discusses the basics

of reconfigurable antennas in detail, specifying different types of reconfiguration as applied to microstrip patch antennas. Section IV discusses reconfiguration techniques, from electrical reconfiguration to material change reconfiguration. Detailed literature survey then follows, with section V discussing designs of multi-band antennas for 5G technology and section VI describing dual- and multi-band reconfigurable antennas for CubeSats in detail with examples of some reproduced results. Section VII is the discussion section which expounds the similar and future trends in this area of research as well as the limitations and mitigating measures for reconfigurable antennas. Finally, section VIII gives the conclusion of the paper.

II. CUBESAT ANTENNAS

The rapid development of electronics technology has made the miniaturization of satellites possible. This means that complex systems like conventional satellites which are very large, about the size of a minibus weighing 500 to 1000 kg or more could be designed to fit into a small volume equivalent to a shoe-box at a lower cost such that, university students, research groups and enthusiasts could develop and launch them [47]. A class of small satellites called nanosatellites, mainly the CubeSat were born from this technological development. CubeSats are standardized nanosatellites which has a volume of 10 cm³ and mass not exceeding 1.33 kg for a single unit (1U). It is a modular design, based on a single unit, which means that more units can be added to form 2U, 3U, 6U, and 12U [48].

CubeSats are miniaturized satellites that can be used for scientific research, technology demonstration, space weather research as well as deep space exploration. This technological development however, produces a challenge to the design of the communication system, of which antennas are an integral part of. The efficiency of communication between the ground station and the satellite depends on the communication link budget estimate [49]. The communication link budget depends on the performance of the antenna. Antenna parameters that determines the efficiency of this link are; the gain, operating frequency, steerability, polarization, radiation pattern etc. The antenna should also occupy less real estate in the limited space of the CubeSat structure [50].

Antenna design generally determines the performance of all wireless systems including; telemetry, tracking and control (TTC), high-speed data downlink, navigation, intersatellite communications, intrasatellite communications, radars and sensors [51]. CubeSat antenna design is one of the most challenging tasks for design engineers as they have to design antennas with very strict constraints such as less space, less mass and less power.

1) REQUIREMENTS FOR CubeSat ANTENNAS

Antennas are needed primarily for two main functions in CubeSats; for telemetry, tracking and command (TTC), and for high data rate payload data downlink [51]. In case of a constellation, antennas may be used for inter-satellite

communication. Different types of antennas may be used for satellite communications [52]. These includes; dipole and monopole antennas, helical antennas, slot antennas, microstrip antennas, reflector antennas, reflectarray antennas etc. Some CubeSat missions may require large antennas like the RainCube mission which required a 0.5 m antenna. For these missions, the antennas must be stowed in a sufficient volume of the CubeSat and later be deployed when they reach the desired orbit [53], [54]. There are some important parameters that needs to be taken into consideration to ensure good communication link between the satellite and the ground station;

- Operating frequency: CubeSat antennas are required to operate at certain frequency bands as per the requirements; very high frequency (VHF) and ultra high frequency (UHF) bands are normally used for telemetry and tracking functions while higher frequency bands like S-band, X-band and Ka-band are used for payload data downlink as they allow for high data rate transmission in a short time [55], [56].
- Gain: Gain requirements vary depending on the satellite altitude and mission.
- Polarization: Circularly polarized (CP) antennas are typically used in satellite communication applications due to their ability to receive randomly polarized signals better than linearly polarized antennas [53]. They are capable of reducing losses in the long distance links between space and earth.
- Radiation pattern: Directional radiation pattern antennas are required in deep space CubeSat antennas to minimize the losses. For inter-satellite links, omni-directional pattern is preferred [57].
- Size compactness and deployability: The size of the antenna mainly determines the gain. CubeSat antennas often have to be stowed during launch, then deployed once they reach the intended orbit.

The following section discusses reconfigurable antennas, giving relevant examples as applied to wireless communications.

III. RECONFIGURABLE ANTENNAS

The use of reconfigurable antennas is extensively found in multi-band systems due to their dynamic spectrum restructuring. Conventional antennas cover only a single band, this means that with an increase in wireless communication services, more antennas will be needed [58]. This leads to a large device, complex circuitry and narrow bandwidth [59]. This is where reconfigurability comes in. Reconfigurable antennas aim to reduce the number of antennas in a given device by integrating the frequencies of those antennas into a single antenna [32]. In [58] two PIN diodes are used in a frequency reconfigurable antenna for WiMAX and WLAN applications.

Antenna reconfiguration is the ability to dynamically adjust antenna parameters to adapt to the changes in system requirements [60]. Antenna parameters that can be reconfigured include; frequency, polarization, and radiation pattern.

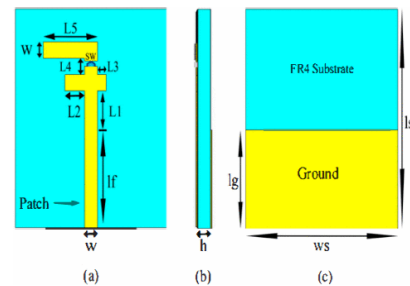


FIGURE 5. Reconfigurable antenna using switches [61].

Moreover, hybrid reconfigurable antennas have the capability of altering atleast two of its fundamental parameters. Frequency reconfigurable antennas are those which can operate at more than one frequency. This can be achieved using slots, stubs and radio frequency switches like PIN diode, varactor diode and radio frequency micro-electromechanical system (RF-MEMS). Figure 5 shows a reconfigurable antenna with one switch on its structure. The antenna operates at 2.45 GHz (Wi-Fi), 5.4 GHz (WLAN) and 3.4 GHz (WiMAX) when the switch is in ON and OFF states, respectively [61]. The PIN diode is most commonly used due to its fast-electronic switching ability and low loss rate [62].

In [63], a hexa-band frequency reconfigurable planar antenna was designed and fabricated on a 1.6 mm thick FR-4 substrate with a truncated ground plane. The frequency bands covered by this antenna are; WiFi (2.45 GHz), WiMAX (3.59 GHz), WLAN (5.2 GHz), Military/NATO (4.5 GHz) and C-Band (6.22 and 6.27 GHz) with a VSWR of less than 1.45 for all the six bands. A planar inverted F antenna (PIFA) for wireless wide area network (WWAN) mobile phones is proposed in [64]. The antenna uses a PIN diode to achieve reconfigurability. The antenna geometry can be seen in figure 6. It has the ability to operate at GSM850, GSM1800, GSM1900 and UMTS bands in the ON-state and GSM900 band in the OFF-state. More reconfigurable antennas are presented in [41], [65].

A. FREQUENCY RECONFIGURABLE ANTENNAS

Frequency reconfigurable antennas use RF-switches to switch between different frequencies as required. Some of the applications of frequency reconfigurable antennas include cognitive radio systems, satellite application, MIMO systems and biomedical applications [37], [66], [67]. The frequency reconfigurable antenna in [67] is designed for cognitive radio application. This antenna is able to reconfigure between a wide operating band of 3.0 GHz – 10 GHz and six different narrow band frequencies operating from 5 GHz to 10 GHz. The authors of [68] designed an antenna that can reconfigure between multi-band mode (2.4, 3.5, and 5.2 GHz) and wide-band mode (2 – 6 GHz) by adjusting the switch state.

B. RADIATION PATTERN RECONFIGURABLE ANTENNAS

Radiation pattern reconfigurable antennas can modify its radiation pattern while maintaining a fixed frequency

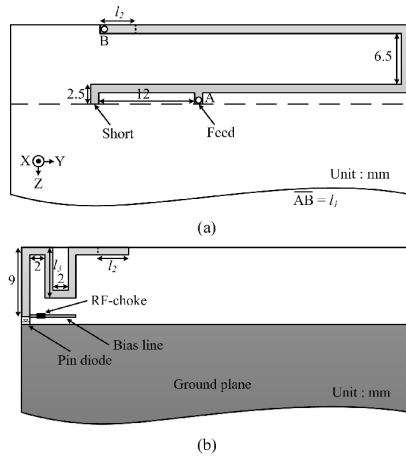


FIGURE 6. Geometry of the antenna proposed in [64] (a) top layer (b) bottom layer.

of operation. A novel design of pattern reconfigurable antenna was introduced in [69] for millimeter wave operation. The proposed antenna system can provide beam-steering capabilities covering the 360° azimuth plane with a maximum gain of 4.2 dBi. Other radiation pattern reconfigurable antennas are investigated in [70]–[72].

C. POLARIZATION RECONFIGURABLE ANTENNAS

These antennas have the capacity to change their polarization orientation while maintaining a fixed radiation pattern and frequency. In [73], a circular polarization technique is presented for operation in 5G wireless communication systems. It can operate in the right-hand and left-hand circular polarization mode using two PIN diodes. Authors of [74] presents a square patch antenna, fed by a microstrip line feed which uses two independently biased PIN diodes to switch polarization between right hand circular polarization (RHCP) and left hand circular polarization (LHCP). A coplanar waveguide fed antenna with the ability to switch between left-handed circular polarization and right handed circular polarization is presented in [75]. In [76], the antenna radiates in vertical and horizontal polarization modes depending on the feed being used.

D. HYBRID RECONFIGURATION ANTENNAS

Hybrid reconfigured antennas can change more than one characteristic at the same time e.g. radiation pattern and frequency to achieve a certain desired configuration [37]. In [77], PIN diodes are used to achieve frequency reconfiguration while truncated corners of the patch are for enabling linear to circular polarization reconfigurability. Using varactor diodes and orthogonal feed points, frequency and polarization reconfigurability is achieved in [78]. Other hybrid reconfigurable antennas are stated in [79].

There are many techniques used for achieving reconfigurability in antennas. The following section details these techniques as applied in the design of reconfigurable antennas.

IV. RECONFIGURATION TECHNIQUES

The antenna designer is responsible for choosing reconfiguration techniques (also called switching techniques) based on the design constraints. Reconfiguration techniques are the means through which reconfiguration in an antenna is achieved. Some of these techniques are; electrical reconfiguration, mechanical reconfiguration, material change reconfiguration as well as optical reconfiguration [80]. Electrical reconfiguration is the most popular among these because it uses switches, which are efficient, reliable, and relatively easy to integrate into microwave circuits [81].

A. ELECTRICAL RECONFIGURATION TECHNIQUE

RF-switches are used to alter the surface current distribution in the antenna patch which in turn changes its fundamental characteristics like frequency, polarization and radiation pattern. These switches include; PIN diodes, varactor diodes and RF-MEMS [41]. In [82], one RF MEMS switch was used in the design of a dual-band antenna. Two operating modes were achieved with central frequencies of 718 and 4960 MHz. Authors in [83] presents the design of a compact frequency reconfigurable antenna using PIN diodes. These radio frequency switches have different properties which make them suitable for different applications. Deciding factors for the switch – choice are the switching speed, insertion loss, reliability and power requirements. Table 1 outlines the advantages and disadvantages of the switches based on these factors.

B. OPTICAL RECONFIGURATION TECHNIQUE

Photo-conductive switches are used for optical reconfiguration. When a laser light comes in contact with a semiconductor material's surface (silicon, gallium arsenide), an optical switch forms. It has a very fast switching speed, which is a desirable feature for reconfigurable antenna [84]. Eight operational states have been achieved through the use of a photoconductive switch in [85]. Optical loading was varied in order to tune the frequency using <60 mW of power.

C. MECHANICAL RECONFIGURATION TECHNIQUE

The authors in [86] discuss physically reconfigurable antennas that use actuators to move the radiating elements of the antenna patch. A mechanically reconfigured antenna changes the antenna's physical composition to change the desired antenna characteristics. This method however, limits the flexibility of the antenna as compared to other switching methods. A rotatable circular conductor with five microstrip patches of different shapes radiating at different frequencies has been presented in [87] for use in cognitive radio applications.

D. MATERIAL CHANGE RECONFIGURATION TECHNIQUE

Smart tunable materials like ferrites and liquid crystals can be used to achieve reconfiguration in antennas for various applications. The authors of [58], presents a reconfigurable planar inverted F antenna (PIFA) which can be tuned using

TABLE 1. Comparison of the most commonly used RF switches.

Component	Advantages	Disadvantages
PIN diodes	Reliable Low cost Low Driving Voltage High tuning speed High power handling capacity	Poor quality factor Non-Linear High DC bias
Varactor diodes	Small current flow Continuous tuning Ease of integration	Non-linear Low dynamic range Complex bias circuitry
RF- MEMS	Low insertion loss High linearity Low power losses Good isolation Wide impedance bandwidth	Poor reliability High control voltage Slow switching speed Limited lifecycle

piezoelectric material (PZT) switched elements. The antenna can produce eight combinations of possible switching positions. The phase changing property of vanadium dioxide material was used in [88] to achieve reconfigurability for a frequency of 4.68 GHz and 4.58 GHz based on the temperature change of the material. Vanadium dioxide material was also used in [89], to design a frequency reconfigurable, fast switching antenna.

V. MULTI-BAND RECONFIGURABLE ANTENNAS FOR 5G TECHNOLOGY

There is already an immense literature in the area of reconfigurable antennas for current and next-generation wireless communication technology. In this section, design and implementation of dual- and multi-band reconfigurable antennas for 5G technology are discussed. The designs are categorized into two; frequency reconfigurable and radiation pattern reconfigurable.

1) FREQUENCY RECONFIGURABLE DESIGNS

Multi-band antennas for 5G technology operates with multi-band capabilities in frequency bands allocated for the fifth generation of mobile technology. These frequency bands include the sub-6 GHz bands as well as the millimeter wave frequency bands. The antennas designed for 5G may also have the ability to operate at other frequency bands and for other applications like 3G, LTE, UMTS, Wi-Fi, WLAN as well as satellite communication [90]. The following includes some of the designs that support multi-band and reconfigurability in wireless technology, with emphasis on 5G.

A frequency reconfigurable patch antenna with 3 operating modes is proposed in [91]. PIN diodes are placed between the inner and outer patches to achieve reconfigurability. In order to increase gain and directivity, six parasitic patches were added to the antenna structure. Simulation results show that the impedance bandwidth of the optimized antenna for mode-1, mode-2, and mode-3 are 0.7 GHz, 1.11 GHz, and 0.8 GHz, respectively. A 50 Ω coaxial cable is used to excite the antenna.

In [92], a frequency reconfigurable antenna for wireless applications is proposed. This antenna is printed on one

side of the substrate, uses 6 PIN diodes for reconfiguration and offers a selection choice between 36 operating frequencies. The observed operating frequencies range from 2.35 to 3.43 GHz with peak gain and efficiency of 4.3 dBi and 73%. The return loss is more than 10 dB at all the operating frequencies. Peak gain and efficiency of 4.26 dBi and 71% were measured at 2.35 GHz. Figure 7 shows the simulated and measured reflection coefficient for this antenna.

In [93], a compact frequency reconfigurable dielectric resonator antenna (DRA) able to operate at frequencies suitable for GSM, LTE and 5G applications is proposed. The proposed antenna structure consists of three rectangular dielectric resonators, DR1, DR2 and DR3. Reconfigurability is achieved by the use of two PIN diodes placed on the microstrip line. For the ON–ON state, the antenna is tuned to an operating frequency of 1.81 GHz for GSM application. For the ON–OFF state, the antenna operates at a frequency of 2.6 GHz for LTE application. The OFF–OFF state tunes the antenna to an operating frequency of 3.6 GHz for the lower 5G frequencies.

A coplanar waveguide (CPW) fed compact antenna of dimensions $0.22\lambda_0 \times 0.11\lambda_0 \times 0.012\lambda_0$ (where λ_0 is the free space wavelength) for portable devices is presented in [94]. Three PIN diodes have been used to achieve frequency reconfigurability for this antenna. The proposed antenna displays a maximum gain of 5.4 dBi and efficiency of 86% in the pass-band region while still maintaining its compactness, making it suitable for portable devices that require operation at different frequencies between 2 GHz and 10 GHz. Applications covered by these frequencies include; Wi-MAX, WLAN, 5G Sub-6 GHz, S- and X-band and it can be implemented in devices like laptops and cell phones.

HFSS software was used in [95] to design and simulate a compact ($44.09 \times 44.09 \times 3.2 \text{ mm}^3$) frequency reconfigurable antenna for wireless applications. The proposed antenna has an omnidirectional radiation pattern. It is proposed for smart phone application hence, the omnidirectional property of the antenna is desirable. The proposed antenna can reconfigure using PIN diodes at eight different frequency bands between 2.60 and 3.91 GHz with peak gain, efficiency and bandwidth of 7.4 dBi, 98% and 186 MHz respectively.

The triangular antenna designed in [96] is energized using a micro-strip feed line method. The antenna dimensions allows it to radiate at different, multi-band frequencies. The reflection coefficient at resonant frequencies of 43.9 GHz, 61.8 GHz, 75.8 GHz and 94 GHz is -19.2 dB , -28.202 dB , -41.89 dB and -19.035 dB with bandwidth of 3.255 GHz, 7.132 GHz, 7.721 GHz and 8.434 GHz respectively. This antenna provides a directivity of 7.31 dBi at 75.8 GHz of which the gain is 4.643 dB. The antenna exhibits a VSWR of less than 2 at the 5G operating frequencies.

Two multi-band antenna structures designed for fifth generation communication systems are investigated in [97]. One is a multi-band antenna for the 5G sub-6 GHz band, and the other one is a millimeter wave multi-band antenna. The authors used an insert feed method to excite both antennas in an FR-4 substrate. Slots in the patch are introduced in both

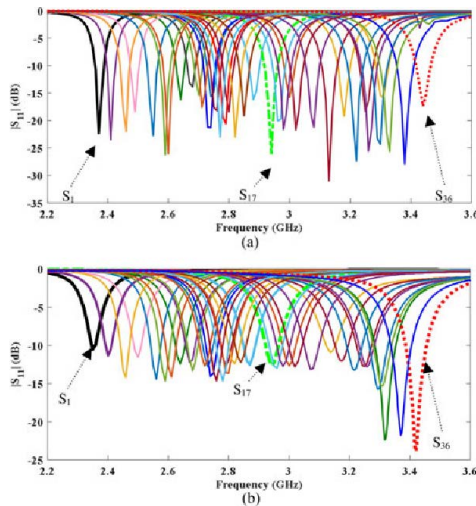


FIGURE 7. (a) Simulated and (b) measured reflection coefficient [92].

designs to achieve multi-band properties. The reflection coefficient of the antennas was found to be less than -10 dB with VSWR values ranging between 1 and 2 which demonstrates that this antenna has good impedance matching. Maximum gain of 6.28 dBi was observed for the sub-6 GHz multi-band antenna. Operating frequencies obtained for this antenna are; 2.48 GHz, 2.89 GHz, 4.19 GHz, and 5.5 GHz. The millimeter wave antenna has achieved three resonating frequencies at 14.6 GHz, 23.3 GHz and 28.9 GHz. The return loss at 14.6 GHz and 28.9 GHz frequencies are -37.82 and -30.44 respectively. Maximum gain for this antenna is 5.44 dBi which, according to the authors can be improved by using RT Duroid 5880 substrate instead of FR-4 because of its high dielectric constant of 10.

Sukanya Baruah *et al.* in [98], presents a CPW fed U-shaped antenna with the capability of operating in the band of 2.8 GHz to 6.1 GHz for cognitive radio applications. The novel antenna is proposed to operate using the interweave protocol for cognitive radio. Both the sensing and the reconfigurable antenna have omni-directional radiation properties. Two PIN diodes are used to achieve four cases of frequency reconfigurability depending on the states of the switches. S_{11} results for the four cases are shown in figure 8. These four frequencies are; 4.6 GHz, 2.3 GHz, 4.7 GHz and 5.7 GHz. The antenna can be used as a sensing antenna or a reconfigurable antenna according to the requirements.

In [99], Sonal and Anjali proposes a hook shaped frequency reconfigurable antenna for UMTS, WiMAX, WLAN and other wireless applications. For this antenna to achieve reconfiguration, two PIN diodes are used. The antenna structure is shown in figure 9. Two semicircular patches of distinct electrical length yield tri-band with reflection coefficient, $S_{11} < -10$ dB. The middle rectangular patch in the antenna offers 4.8 GHz – 8.6 GHz band, the right and left side of semicircular patches yield 1.9 GHz – 2.1 GHz (UMTS) and 2.7 GHz – 3.1 GHz (Wi-MAX) bands respectively. The hook shaped antenna is fed by a microstrip feed line. Resonant

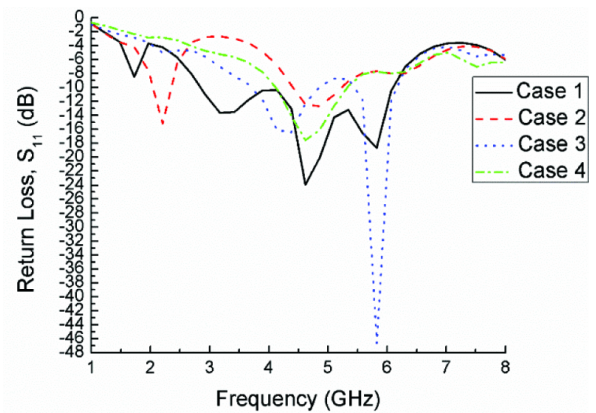


FIGURE 8. Reflection coefficient results for all the four cases (1-4) considered in [98].

frequencies for the tri-band; UMTS, WiMAX and WLAN are 2 GHz, 2.9 GHz and 6 GHz respectively. Reflection coefficient, S_{11} of < -10 dB were observed.

A wide-band printed bow-tie antenna which can operate at frequencies from 1.4 GHz to 6.2 GHz is investigated in [100]. The proposed antenna can switch between wide-band as well as lower frequency narrow-band. Parasitic elements and PIN diodes are used for the design of the proposed bow-tie antenna. The antenna is printed on an FR-4 substrate of dielectric constant, 4.34 and thickness of 1.6 mm. An insertion loss of -10 dB over 2 to 5.5 GHz frequencies is observed from simulation results with gain varying between 2 dB and 4 dB over the same frequency band.

The authors of [101] present a coplanar waveguide fed T-shaped antenna with a dual beam of $\pm 30^\circ$. Two variable resistors connected between the ground plane and the stub enables reconfigurability. Rogers RT Duroid substrate is used for this design. In the band of 23 GHz – 29 GHz, frequency reconfiguration is achieved by varying the resistance of the variable resistors. The 3 dB beam-width remains conserved for this range of operation. The resonant frequency increases as the value of the resistance is gradually changed from 100 Ω to 10 k Ω . While this is the case, at resistance values above 5 k Ω , there is no considerable frequency change in the return loss graph. Along the end-fire direction, the radiation pattern is a symmetrical distribution of two beams. At the resistance value of 250 Ω , the 3 dB beam-width remains the same for the whole operating range. The gain of each beam is suitable for short range communication which is why this antenna can be used for indoor 5G wireless communication networks [101].

The frequency reconfigurable antenna designed in [102], finds application in the Indian regional navigation satellite System (IRNSS) and it has the ability to switch between L5 band and the S-band. Three PIN diodes are used together with a slot to attain reconfigurability. A directional radiation pattern with gain of 8.51 dB is obtained by this antenna at 2.49 GHz. A 50 Ω coaxial connector is used for feeding this antenna and simulation is carried out using HFSS

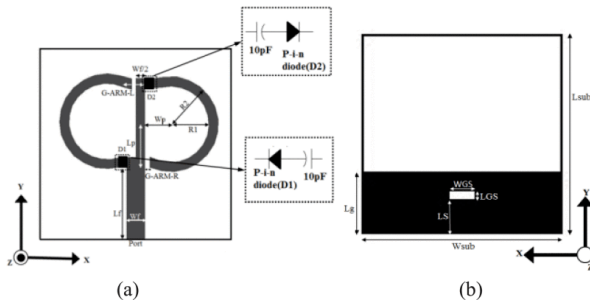


FIGURE 9. Proposed antenna structure (a) front view (b) back view [99].

simulation software. For the reflection coefficient of less than -10 dB, resonating frequencies of 2.49 GHz and 1.18 GHz are observed.

A differential frequency reconfigurable antenna based on dipoles is presented in [103]. Four PIN diodes are used for reconfigurability. Simulated gain is between 1.5 and 4.2 dBi with an average gain of 2.85 dBi for operational state 1, and simulated gain is between 2.2 and 3.7 dBi with an average gain of 2.95 dBi for operational state 2. Measured gain is between 1.5 and 3.5 dBi with an average gain of 2.5 dBi for state 1, and measured gain is between 1.8 and 3.4 dBi with an average gain of 2.6 dBi for state 2. The slight difference between simulated and measured values is due to the losses from PIN diodes, the substrate as well as the metal. This antenna is suited for operation at frequencies; 3.5 GHz, 5.25 GHz and 5.80 GHz for WLAN as well as the 5G sub-6 GHz band applications.

A Ka-band antenna operating at frequencies of 28 and 38 GHz proposed for use in 5G wireless communication systems is designed in [104]. An omni-directional radiation pattern has been observed from the simulation results. The maximum gain at 38.75 GHz frequency is observed to be 8.2 dBi. The overall gain observed shows that the antenna is suited for short range communication.

A 30 mm \times 30 mm compact multi-band frequency reconfigurable antenna for 5G application is proposed in [105]. The substrate used has a high permittivity of 10.2 and a thickness of 1.9 mm. A microstrip transmission line feed method is used to feed the triangular shaped antenna. Two slots were utilized to achieve on-demand frequency reconfigurability from wide-band mode to tri-band mode. When both the PIN diodes are in the ON state, the antenna operates as a tri-band antenna and when the diodes are both in the OFF state, the antenna operates in the dual band mode. The antenna shows good impedance bandwidth of 2.11 GHz with a high efficiency of more than 90%. Figure 10 shows the 2D radiation pattern simulation results for the proposed reconfigurable antenna.

An advanced multi-band antenna covering frequency bands of Wi-Fi, WiMAX and 5G is designed and tested in [106]. The antenna designed using CST microwave studio shows three distinct multi-band frequencies (2.4 GHz, 7.8 GHz and 33.5 GHz). At these frequencies, the S_{11} parameters plot shows a value less than -10 dB, which

is suitable for a properly functioning communication system. At the Wi-Fi frequency of 2.4 GHz, S_{11} value is -22.37 dB. This antenna can accommodate multiple channels. For the 7.8 GHz WiMAX application, the reflection coefficient observed is about -26 dB with bandwidth of 235 MHz. This enables the antenna to be used in wide-band WiMAX applications. Lastly, at 33.5 GHz millimeter wave frequency for 5G applications, the bandwidth is 4.5 GHz, which has capacity to cover more channels having a large bandwidth. At this frequency, the reflection coefficient is -29 dB. The VSWR for the Wi-Fi, WiMAX and 5G frequencies is less than 1.3 which is within the accepted range for a communication system which is an indication of good impedance matching. Table 2 summarises the VSWR results at different operating frequencies. Reflection coefficient, S_{11} results for the antenna are displayed in figure 11.

2) RADIATION PATTERN RECONFIGURABLE DESIGNS

Yihua Zhou et al in [107], proposed a multi-beam antenna array fed by planar reconfigurable feeding network which operates at 28 GHz millimeter wave frequency. The proposed antenna is designed such that it can switch between one-beam, two-beams and four-beam states using RF switches. This design does not use phase shifters, making it less costly.

A tri-PRA (polarization reconfigurable antenna) based on crossed dipole and parasitic elements with an impedance bandwidth of 48.6% at frequencies of 2.04–3.94 GHz and maximum gain of 8.2 dBi is proposed in [108]. The proposed antenna is able to switch between three states; linear polarization (LP), left hand circular polarization (LHCP) and right hand circular polarization (RHCP). The simulated impedance bandwidth has a good agreement with the measured results, reaching 63.5% from 2.04 to 3.94 GHz. In particular, the measured CP and LP impedance bandwidth are about 80.4% (1.68–3.94 GHz) and 63.5% (2.04–3.94 GHz), respectively.

A pattern reconfigurable antenna was considered in [109]. At 2.53 GHz, the following observations are made; by exciting port-1, the maximum gain of 2.74 dB is obtained at $\theta = 225^\circ$ degrees in the yz plane. By exciting port-2, the maximum gain obtained at $\theta = 225^\circ$ degrees is 2.73 dB in the xz plane. At 3.55 GHz, exciting port-1 of the antenna system, gives maximum gain of 1.92 dB at $\phi = 0^\circ$ and $\theta = 215^\circ$. By exciting port-2, a maximum gain of 1.52 dB at $\phi = 90^\circ$ and $\theta = 215^\circ$ is obtained. The structure of this pattern reconfigurable antenna is shown in figure 12. The MIMO system antenna gives a good isolation, good pattern radiation and high efficiency and is therefore suited for 5G wireless communication systems.

In [110], a tunable feeding network is used to achieve broadside and conical radiation beams through in-phase and out of phase excitation. A two-port symmetrically fed microstrip antenna can radiate in two distinct patterns when the feeds are out of phase or in-phase. At broad-side, with reflection coefficient less than -10 dB, impedance bandwidth of 60.7% is observed while the measured radiation gain varies from 7.5 to 10.2 dBi. For the case of conical

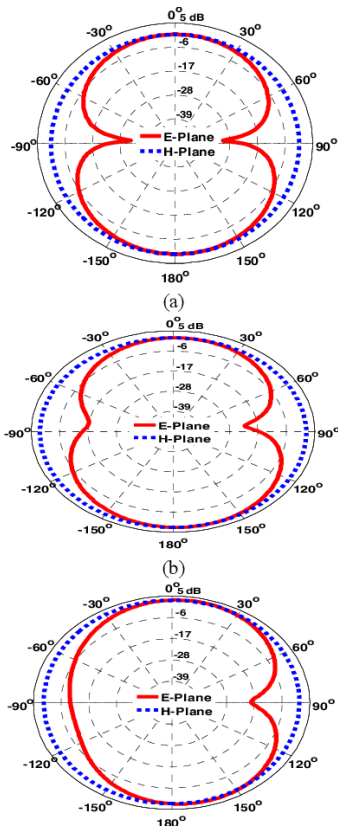


FIGURE 10. Simulated 2D radiation pattern at (a) 2.4 GHz (b) 3.5 GHz and (c) 4.2 GHz respectively for the antenna in [105].

TABLE 2. Simulated VSWR results for Wi-Fi, WiMAX and 5G [106].

Systems	Operating Frequency (GHz)	VSWR
Wi-Fi	2.4	1.27
WiMAX	7.8	1.11
5G	33.5	1.07

mode, at S_{11} less than -10 dB, an impedance bandwidth of 72.7% is observed with a realized gain of up to 7.7 dBi for frequencies, 1.75 to 3.75 GHz. For broad-side and conical beams, efficiencies of 80% and 76% are recorded respectively. This antenna can properly reconfigure between conical and broadside radiation with satisfying gain and efficiency.

A radiation pattern reconfigurable antenna is proposed for 5G mobile radio communication systems at 5.6 GHz frequency in [111]. This is a directive, high gain antenna for point-to-point communication. The fabry-perot cavity technique is used to create a radiation pattern reconfigurable antenna. This technique uses two substrates; a Rogers RO 4730 substrate with 2.7 permittivity as a high impedance surface and an FR-4 substrate of 4.4 permittivity as a partially reflective surface. The partially reflective surface consists of a central patch and other small patches around it which have been added to it in order to have a directional behaviour. PIN diodes are used on the high impedance surface to achieve reconfigurability. At frequency of 5.6 GHz, the main-lobe direction is 19° with a gain of 15.3 dBi.

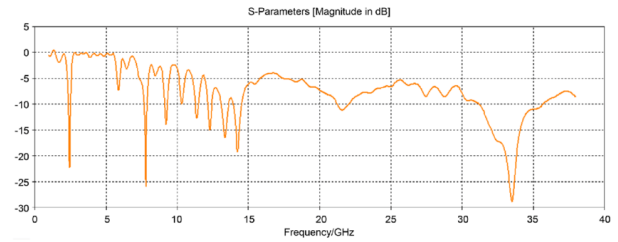


FIGURE 11. Reflection coefficient results for the antenna in [106].

In [112], a novel radiation pattern reconfigurable substrate integrated waveguide (SIW) antenna is presented. The proposed antenna is a leaky wave antenna (LWA) based on a SIW structure which achieves beam scanning at a fixed frequency of 27 GHz. The beam scanning ability is made possible by exciting the slot configuration electrically. The SIW is designed with two slots fed by plated-through holes (PTH) technology, with two PIN diodes connecting the ground plane and the top wall. By switching the PIN diode states, the array configuration and the corresponding beam direction can be changed electronically. The radiation pattern of this antenna is shown in figure 13.

In [113], two PIN diodes are inserted between the radiator and the stubs to achieve reconfigurability as seen in figure 14. The antenna radiates at four frequency bands with a wide bandwidth, high gain and good efficiencies. It resonates at 32 GHz with an impedance bandwidth of 6.75 GHz with respect to $S_{11} < -10$ dB when diodes are in the OFF state. When diode 1 (D1) is ON, the antenna resonates at 30 GHz with 6.42 GHz impedance bandwidth. When D1 is in the OFF state and D2 ON, the antenna resonates at 32 GHz with a bandwidth of 4.93 GHz. Finally, when D1 and D2 are both ON, the antenna starts to resonate at 28.7 GHz with bandwidth of 6.3 GHz. The antenna demonstrates broad-side radiation pattern in the H-plane and a slightly tilted pattern in the E-plane. The antenna shows a maximum gain greater than 6 dBi over the targeted frequency band with a 97% efficiency. This is a high gain and high efficiency antenna suitable for 5G millimeter wave (mm-wave) communication.

A hybrid antenna model to achieve spherical beam steering coverage is considered with the intended use in cellular devices [114]. One of the pressing challenges caused by the inherent mobile device restrictions is integrating millimeter wave into the user equipment (UE) because of limited power capacity and physical space. In an effort to combat loss factors like propagation loss and polarization mismatch loss caused by the mobility of terminals, adaptive beam-forming is used. The proposed solution is mm-wave 5G antenna for future non standalone antenna (NSA) smartphones.

The measured input reflection coefficient achieves impedance bandwidth of 1.67 GHz required to cover the 28 GHz 5G band spectrum. Peak gain of 9.2 dBi is noted at 28 GHz when $\theta = 0^\circ$. The simulated and measured results show that the optically transparent array antenna achieves impedance bandwidth of 850 MHz. The compact end-fire array (antenna in package) and the optical array (antenna on

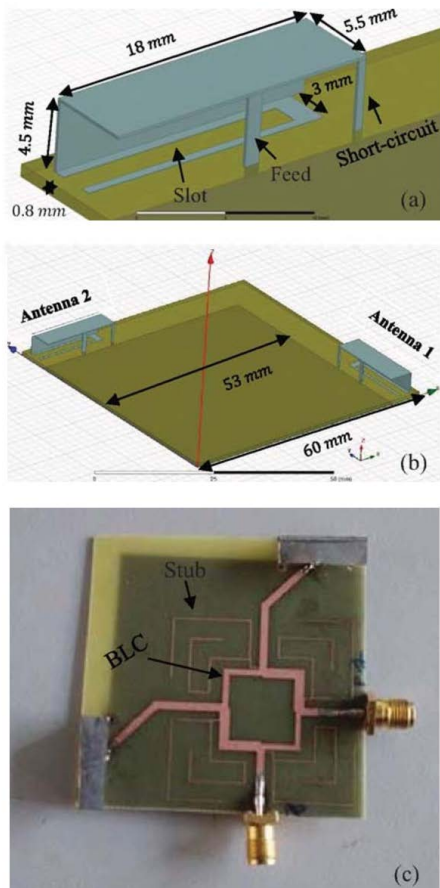


FIGURE 12. Structure of the pattern reconfigurable antenna [109].

display) displays an impedance bandwidth of 1.67 GHz and 0.85 GHz respectively with a 2 : 1 VSWR at 28 GHz. The radiation pattern of the antenna is shown in figure 15.

In [115], a beam-width reconfigurable antenna with high gain and wide bandwidth designed for 5G high frequency application is proposed. The design is made on a Rogers RT Duroid 5880 substrate. For operating frequencies ranging from 26 GHz to 31 GHz, a reflection coefficient of -10 dB is observed. The proposed reconfigurable antenna is designed using three PIN diodes and an added slot. Analysis of the antenna was made before and after inseting the slot with emphasis made on the gain. Before inserting the slot, the antenna radiation pattern shows a 6.2 dBi gain.

After the rectangular slot has been added, it is then rotated and simulations done at different slot positions. Impedance bandwidth is enhanced as the slot is rotated. Figures 16, 17 and 18 show the antenna radiation pattern and gain without a slot, with a slot cut at the center as well as with the slot rotated by -35° respectively. At first without the inset slot, a dual-beam radiation pattern with 6.2 dBi gain is obtained, as shown in figure 16. When the slot is inserted at the center, gain is slightly increased to 6.64 dBi as seen in figure 17. Lastly, when the slot is rotated by -35° , gain of 7.64 dBi is obtained as shown in figure 18.

This section has presented reconfigurable and multi-band wireless communication antennas focusing especially on 5G

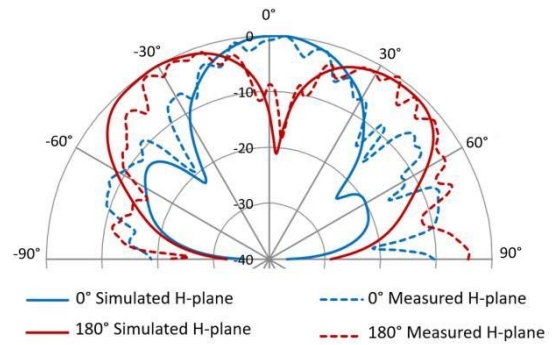


FIGURE 13. Radiation pattern results for the proposed SIW antenna [112].

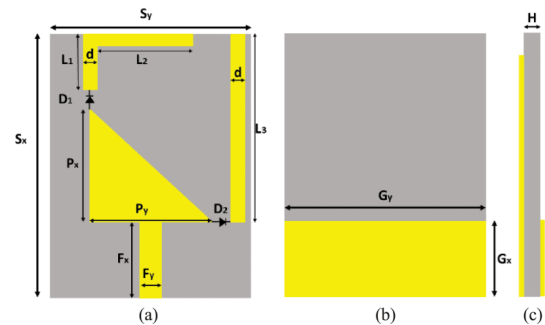


FIGURE 14. Geometry of antenna proposed in [113].

technology. However, some of these reconfigurable antennas can also be adopted for use in other wireless communication bands as well as for CubeSat application. These includes antennas with good performance attributes such as gain, efficiency, reflection coefficients as well as those which can operate on approved satellite frequencies. These antennas are summarized in table 3. The table shows that the maximum gain for wireless communication applications ranges from 1.92 dBi to 15.3 dBi depending on the application. Most of the designs included can reconfigure their frequency which eliminates the need for multiple antennas. The following section is dedicated to presenting antenna designs for CubeSats.

VI. DUAL- AND MULTI-BAND RECONFIGURABLE ANTENNAS FOR CubeSats

Dual- and multi-band reconfigurable antenna designs for CubeSat application are presented in this section. A summary of these designs is given in table 4.

A circularly polarized dual-band (operating at L- and S-band) and dual-feed patch antenna for a 3U form factor was proposed in [116]. The proposed antenna is a three layer stack with two different views shown in figure 19, which consists of a lower band GPS antenna of 1575 MHz resonant frequency on the top layer, an S-band antenna which operates at 2200 MHz for transmitting satellite downlink data to earth as well as a metallic ground plane embedded with the feed network on the bottom layer. The antenna system has a low profile of 11 mm and 120g weight. It is mounted on the nadir facing side of the CubeSat. Two independent

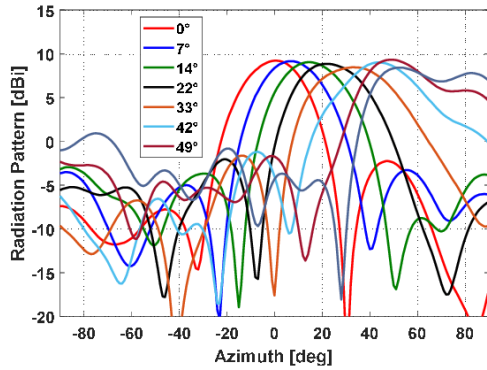


FIGURE 15. Radiation pattern of the 28 GHz end-fire phased arrays at different scanning angles [114].

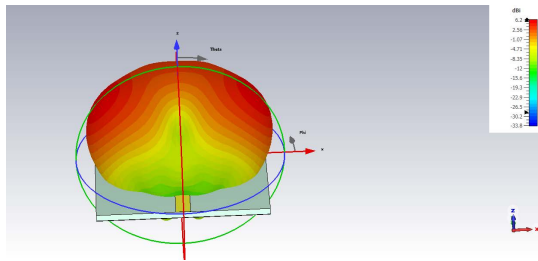


FIGURE 16. Antenna radiation pattern results without the slot in [115].

3-dB branch-line hybrid couplers have been used to feed the upper and lower band antennas. Two couplers have been used because they provide an improved axial ratio (2 dB in this case) compared to the single feed method. Simulated and measured return loss is less than -15 dB while the axial ratio is 2 dB at both operating frequency bands which means that the antenna achieves a good circular polarization.

In [117], a frequency reconfigurable antenna is proposed for satellite applications. The proposed circularly polarized multi-band antenna can operate at a single L-band frequency and dual S-band frequencies through electronic switching of four PIN diodes loaded in the feeding branches. Aperture coupling feed is used for feeding the structure such that the antenna achieves circular polarization. At L-band, the antenna resonates in the 1570–1650 MHz range and at 2.145 GHz and 2.660 GHz for S-band. The stacked radiators exhibit an impedance matching of $S_{11} < -10$ dB and an axial ratio of less than 3 dB in all three operating frequencies.

In [118], a compact-sized (40 mm × 30 mm) metamaterial-based antenna with dual circular polarization and double negative feed is proposed for a 1U nanosatellite application. The antenna is fed at two places to achieve dual circular polarization. It's structure was simulated using the Zeland IE3D software. Simulated and measured antenna efficiency of 90% have been obtained. The operating frequency of the antenna ranges from 2.3 GHz to 2.7 GHz with reflection coefficient of -30 dB at 2.4 GHz. The gain at the operating frequency of 2.4 GHz is 3 dBi.

The famous Japanese paper folding techniques called Origami theory has been adopted for use in the design of

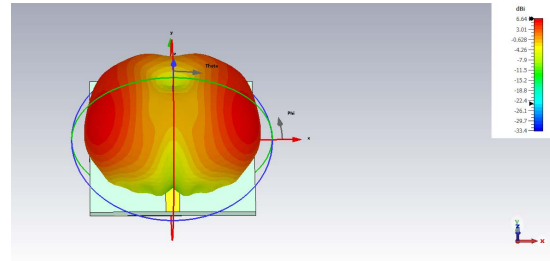


FIGURE 17. Antenna radiation pattern results with slot cut at the center.

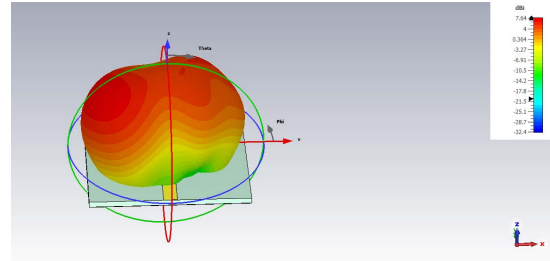


FIGURE 18. Radiation pattern results of the antenna when the cut slot is rotated by -35° .

reconfigurable antennas for CubeSats in [119]. The antenna presented in [120] uses adhesive polyimide tapes and folding to achieve its design goals. It is a radiation pattern and polarization reconfigurable patch/monopole hybrid that shares the same microstrip ground plane and feed. Reflection coefficient of less than -10 dB has been obtained in the design with a maximum gain of 7.7 dBi at 2.4GHz. The antenna can be used in CubeSats for next generation communication systems such as 6G.

Another pattern reconfigurable antenna for CubeSat application based on Origami technique has been studied in [121] for operation at C-band. The antenna is pattern and polarization reconfigurable designed specifically for CubeSat application based on spatial mapping origami theory. The pattern reconfigurable antenna can be used for satellite to ground link as well as for inter-satellite link. A maximum circularly polarized gain of 8.07 dBi has been observed at broadside radiation pattern. Axial ratio value of 1.13 dB has been achieved in this design.

The design and simulation of an S- and X-band shared aperture antenna for nanosatellite applications is carried out in [122]. The antenna measures 82 mm × 82 mm with a height of 4 mm. It operates at two frequency ranges; an S-band frequency range of 2.025 – 2.07 GHz shown in figure 20 and an X-band frequency range of 7.75 – 8.75 GHz shown in figure 21. This design has a realized RHCP gain of 6 dBi in the S-band and 12 dBi at X-band. The antenna has an impedance bandwidth of 85 MHz and 2.4 GHz at S- and X-band respectively, and has ≤ -25 dB cross coupling between the two antenna ports.

In [123], a single layer S- and X-band series-fed, shared aperture antenna for synthetic aperture radar (SAR) applications is presented. The overall size of the S and X dual-band

TABLE 3. Summary of existing literature of reconfigurable antennas for general wireless communication as well as 5G communication applications.

Reference	Antenna size (in mm ³)	Reconfiguration type	Frequency Range	Reflection Coefficient	Maximum Gain	Device
[91]	16.3 × 12.57 × 0.8	Frequency	9.57 GHz to 5.6 GHz	−40 dB and −30 dB	N/A	PIN diodes
[92]	0.31λ ₀ × 0.31λ ₀ × 0.015	Frequency	2.35 GHz to 3.43 GHz	< −10 dB	4.3 dBi	PIN diodes
[94]	0.22λ ₀ × 0.11λ ₀ × 0.012λ ₀	Frequency	2 GHz to 10 GHz	< −10 dB	5.4 dBi	PIN diodes
[95]	44.09 × 44.09 × 3.2	Frequency	2.60 GHz to 3.91 GHz	< −10 dB	7.4 dBi	PIN diodes
[96]	6.22 × 3.80 × 0.5	Frequency	43.9 GHz to 94 GHz	−19.2 dB to −41.89 dB	4.64 dBi	Structural modifications (Slots and stubs)
[97]	50 × 45 × 1.6	Frequency	6 GHz to 29 GHz	< −10 dB	5.44 dBi	Structural modifications (Slots)
[98]	50 × 50 × 0.6	Frequency	2.8 GHz to 6.1 GHz	−24 dB	10 dBi	PIN diodes
[99]	20 × 20 × 1	Frequency	2 GHz to 6 GHz	< −10 dB	N/A	PIN diodes
[100]	54.4 × 41.07 × 1.6	Frequency	1.4 GHz to 6.2 GHz	< −10 dB	4 dBi	PIN diodes and parasitic elements
[102]	120 × 120 × 1.575	Frequency	1.18 GHz and 2.49 GHz	< −10 dB	8.51 dBi	PIN diodes and slot
[103]	50 × 50 × 1.6	Frequency	3.5 GHz to 5.80 GHz	< −10 dB	4.2 dBi	PIN diodes
[104]	16 × 16 × 0.0135	Frequency	22 GHz to 40 GHz	< −10 dB	8.2 dBi	PIN diodes
[105]	30 × 30 × 1.9	Frequency	2.31 GHz to 4.44 GHz	−34 dB	N/A	PIN diodes
[106]	62 × 50 × 1	Frequency	2.4 GHz to 33.5 GHz	−22.37 dB	5.06 dBi	Structural modification (Slot)
[108]	60 × 60 × 0.03	Polarization	2.04 GHz to 3.94 GHz	< −10 dB	8.2 dBi	Structural modifications (stub)
[109]	18 × 5.5 × 4.5	Radiation pattern	2.53 GHz	< −10 dB	1.92 dBi	Slot and stubs
[110]	140 × 140 × 0.787	Radiation pattern	1.75 GHz to 3.75 GHz	< −10 dB	7.7 dBi	PIN diodes and slot
[111]	291 × 91 × 1.4	Radiation pattern	5.6 GHz	< −10 dB	15.3 dBi	PIN diodes
[112]	100 × 6 × 0.5	Radiation pattern	27 GHz	−23 dB	7 dBi	PIN diodes and slot
[113]	7.5 × 5 × 0.762	Frequency and radiation pattern	32 GHz	< −10 dB	6 dBi	PIN diodes and stub
[115]	20 × 20 × 0.787	Beam-width	26 GHz to 31 GHz	< −10 dB	7.64 dBi	PIN diodes and slot

dual-polarized shared aperture antenna is 100 × 100 × 1.6 mm³. The antenna operates at an X-band center frequency of 9.3 GHz and S-band frequency of 3.2 GHz, which are both well-suited for the intended operation in SAR mission. The impedance bandwidth covers a range of 3.12 – 3.42 GHz frequencies for S₁₁ < −10 dB and has an isolation of S₂₁ < −20 dB in the entire band.

A hybrid reconfigurable S-band antenna for CubeSat application is proposed in [124]. The antenna system can achieve radiation pattern and polarization reconfiguration through port-excitation. By reconfiguring its polarization and radiation pattern, different missions can be satisfied with a single design. Arlon DiClad 870 substrate has been used for this design due to its high reliability characteristics for aerospace applications. Patch dimensions have been optimized for operation at 2.45 GHz with measured and simulated S-parameter results as shown in figure 22. The antenna has four rectangular patches which are fed using four different feeding ports. These ports are excited differently through the feed network to achieve the required radiation pattern and polarization. The antenna achieves circular polarization when φ₁ = 0, φ₂ = 90°, φ₃ = 180°, φ₄ = 270° and linear polarization

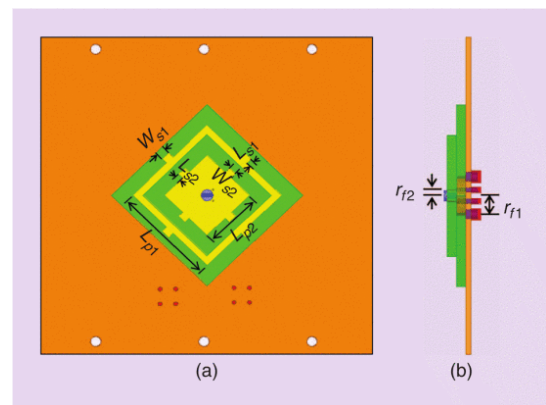


FIGURE 19. (a) Top view and (b) bottom view of the dual-band antenna in [116].

when φ₁ = 0, φ₂ = 90°, φ₃ = 180°, φ₄ = 90°, with a radiation pattern maximum in the yz plane at 134°. The antenna reconfigures between circular polarization and linear polarization when the patches are 90° out of phase to each other. The radiation pattern is 57.7° when the antenna is circularly polarized and 134° when linearly polarized.

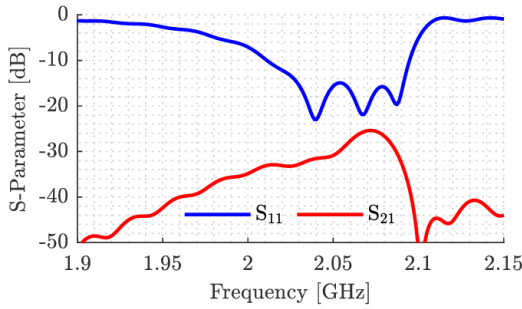


FIGURE 20. S-parameter results for the S-band part of the antenna in [122].

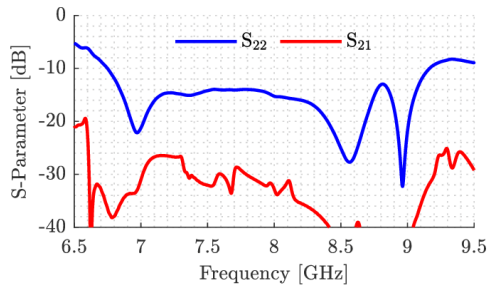


FIGURE 21. S-parameter results for the X-band part of the antenna in [122].

An 8-element array antenna has been designed, fabricated and analyzed in [125]. RT/Duroid 5880 substrate was used for the array fabrication due to its low loss as compared to other materials like FR-4 and GML1000. Simulation and measured results were compared in terms of the S-parameters, gain, directivity and radiation efficiency. S-parameter results of -12.492 dB, gain of 14.6 dBi and VSWR of 1.6 were measured at 10 GHz frequency. The antenna has a beam-width of 18° degrees at 10 GHz. As shown in figure 23, the designed antenna has a gain of 11 dBi at 10 GHz working frequency. The high-gain antenna in this design is for satellite application.

In [126], the authors present a four by one (4×1) microstrip antenna array for use in radar and satellite applications. The antenna operates in the X-band frequency range ($8-12$) GHz. An inset feed method optimized to increase performance is used to feed and match the antenna. The antenna has a maximum gain of 10.1 dBi at 11.8 GHz frequency as shown in figure 24. An S-parameter plot for the antenna is shown in figure 25. At all frequencies, the S-parameter values are well below the minimum required -10 dB value. Furthermore, the VSWR values of less than 1.5 are recorded, as shown in figure 26, which indicate good matching at multi-band frequencies of 10.3 GHz, 11.15 GHz and 11.8 GHz frequencies.

Authors of [127], presents a 2×2 corner truncated antenna array for wireless applications which includes satellite communication. The patch antennas are truncated at opposite corners to achieve circular polarization. It has a dual-band radiation at two fundamental frequencies of 10.85 GHz and 12.95 GHz. Figure 27 displays the S-parameter values of -21 dB and -19.9 dB at 10.85 GHz and 12.95 GHz

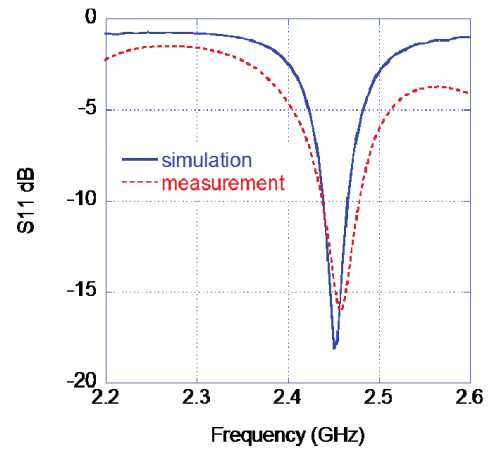


FIGURE 22. Comparison of measured and simulated results of the antenna in [124] at 2.45 GHz.

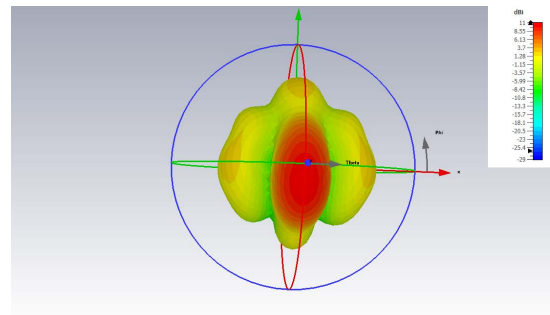


FIGURE 23. Reproduced realized gain pattern for the 8-element array in [125].

frequencies, respectively. The antenna achieves a realized circularly polarized gain of 10.1 dBi. The realized 3D gain plot of this antenna has been shown in figure 28. This 3D radiation plot shows that the antenna has some side-lobes even though they are not too significant. A better visualization of the side-lobes is shown in the 2D polar plot in figure 29.

As can be observed in table 4 summary, the most common operational frequency bands for CubeSat antennas are L-band, C-band, S-band and X-band. The majority of antennas used for CubeSat applications have circular polarization to maximize the probability for signal reception. This can be noticed from the axial ratio of 3 dB or less. Gain results for operational CubeSat antennas for good signal transmission and reception ranges from 3 dBi to 14.6 dBi. Furthermore, the antenna physical sizes are also very small to ensure conformity to the CubeSat body. The antennas can be mounted on any side or face of the CubeSat, whether it's a 1U, 3U or 6U CubeSat.

VII. DISCUSSION

A. ADVANCEMENTS AND FUTURE TRENDS

The technology of reconfigurable antennas in the field of wireless communications is still up-and-coming. The future of this technology will be driven by the emerging diverse application areas in wireless as well as in CubeSat

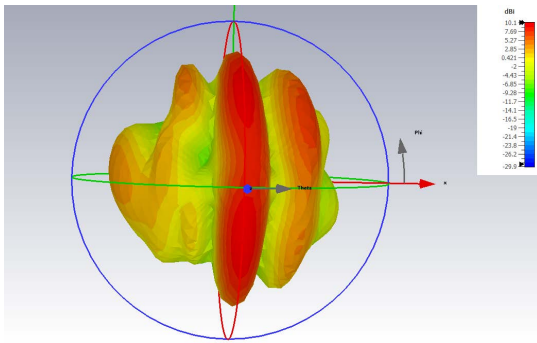


FIGURE 24. 3D radiation pattern for the antenna in [126].

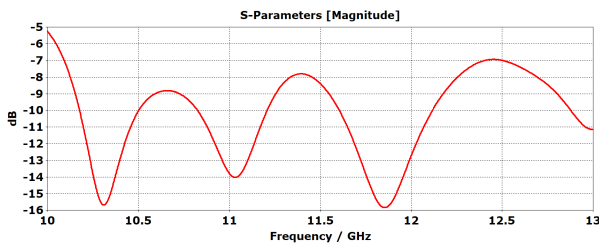


FIGURE 25. S-parameter results for the 4 by 1 array antenna.

communications [27]. These applications include hybrid 5G satellite-terrestrial architectures, internet of space things (IoST), remote sensing applications as well as deep space interplanetary exploration. To continue meeting the communication requirements for the mission as well as adhering to the CubeSat standards of a small form factor, low weight and low mass, future reconfigurable antennas must work in higher frequency bands such as the mm-Wave, sub-mm-Wave as well as the Terahertz frequencies [128]. Operating at these frequencies introduces more functionalities in the CubeSat such as multibeam, as well as beam steering. Furthermore, reconfigurable metasurface based antennas at these high frequencies (e.g. Ka-band, W-band) can also be designed and implemented in Silicone-based substrates. Moreover, as shown in [129], a metal-only (all metal) reconfigurable metasurface antenna is another candidate for future CubeSat missions, particularly in deep space. The absence of a dielectric material makes the antenna immune to dielectric losses; hence it can survive the harsh deep space environment. In [130], the authors discuss a metasurface antenna for CubeSat deep space exploration missions. According to the authors, metasurface antennas could potentially also be a good solution for high gain antennas because they provide the ability to deploy a large aperture antenna without deploying a feed at a focal distance from the antenna aperture.

Reconfigurable antennas of the future, whether frequency, radiation pattern or polarization pattern reconfigurable must have the ability to accurately adapt to their ever-changing environmental properties as well as achieving a well-defined and energy efficient communication link. Reconfigurable antennas for futuristic nanosatellites should be multi-functional and software-controlled (i.e with

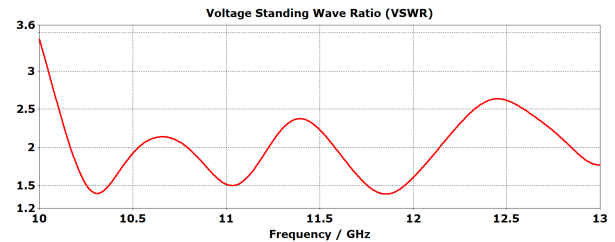


FIGURE 26. VSWR for the antenna design in [126].

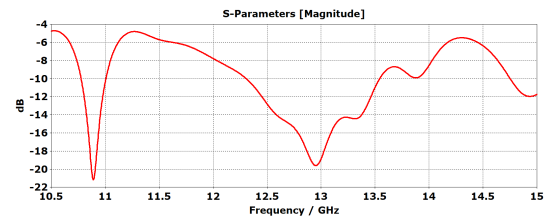


FIGURE 27. S-parameter plot for the antenna in [127].

the ability to be software-defined) to detect and react to their changing RF environment. Applications of the future reconfigurable antenna should be implemented based on a new generation of wireless systems and communication protocols [131].

As stated in the article, [45], future trends for antennas in small satellites includes making them smaller, smarter cheaper as well as faster. This can be implemented in part by using antenna reconfiguration technology and employing software defined radio to make the antennas smarter and faster. Another option to make antennas small is to move to higher frequencies such as Ka- band, V-band and the THz band. Shared aperture multiband antennas also saves on space and includes multi-functional properties. Another technique is to develop reconfigurable antennas with multiple functions integrated. To make the antennas smarter, the antenna needs to be electronically reconfigurable in radiation pattern, polarization, and frequency bands of operation. It is also necessary to investigate low loss tunable materials (ferroelectric thin films, piezoelectric materials, liquid crystals etc.) and their integration with antennas for forming low-cost beam-steerable antennas. Besides the above-mentioned reconfigurable concepts, other emerging research areas includes the exploitation of microfluidics [132], optical controls, and graphene [133], [134] in reconfigurable antennas.

Researchers are working on miniaturization using reconfigurable antennas for CubeSat applications. These includes operating at higher frequencies, making the antennas smarter by integrating software defined control so that they can adapt to changing environments. Reconfigurable antennas can also be developed using special materials such as graphene and ferroelectric materials which can also be adapted and employed in use for deep space CubeSat applications.

B. SIMILAR TRENDS

In spite of the ongoing research and innovation in reconfigurable antennas for 5G wireless communication and for

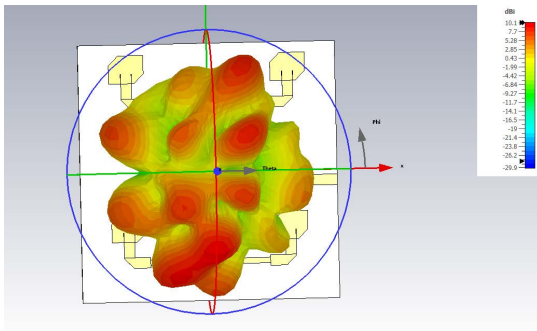


FIGURE 28. The antenna 3D radiation pattern representation.

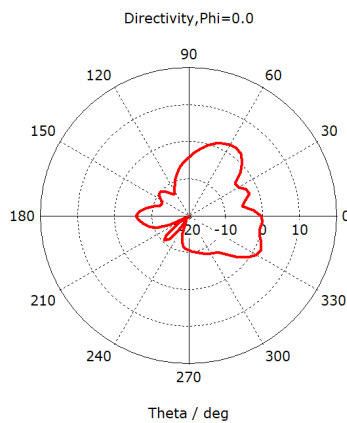


FIGURE 29. 2D polar plot representation of the antenna radiation pattern.

CubeSat applications using RF switches, tunable materials and the geometrical structure of the antenna, there are other antenna designs that can also achieve reconfiguration. These antenna designs have attractive properties that are attractive and are similar to properties of reconfigurable antennas such as beam shifting and scanning. These includes phased array antennas, reflect array antenna, as well as massive MIMO designs in which beam shifting and switching techniques can be done in their structures to reconfigure the performance.

1) PHASED ARRAY ANTENNAS

Phased array antennas have found a wide application area due to their high gain and beamforming capabilities. By shifting the phase of individual elements, antenna arrays can direct their main beam from one direction to another. Phased arrays can open a wide variety of new possibilities by allowing for electrical beam steering [135], [136]. They can also be employed in pattern reconfiguration of satellite communication antennas. An example of a phased array antenna that achieves this function is outlined in [137]. The antenna in this article is proposed to work in Ka-band designed for two-dimensional scanning. In the area of polarization reconfigurable antennas, a phased array antenna integrated into the solar panel of the CubeSat has been designed in [138].

A pattern reconfigurability phased array antenna designed in [139] demonstrates the ability to steer the beam direction by applying specific phases across the elements of the array.

As seen in [140], phased array antennas can also be used to achieve frequency reconfigurability. The antenna being studied operates in L and S band for satellite communication.

2) REFLECT ARRAY ANTENNAS

Reflect array antennas leverage on the advantages of phased arrays and reflectors to implement high gain antennas. They can be classified into fixed beam reflect arrays as well as reconfigurable reflect arrays. In reconfigurable reflect arrays, the beam can be dynamically reconfigured or scanned by introducing controllable mechanisms at the element level to change the phase shift and to reconfigure the beam [141]. The reflect array antenna has been adopted for use in CubeSats for remote sensing missions such as the Integrated Solar Array and Reflect Array (ISARA) CubeSat and the RainCube CubeSat. They can also be used for deep space applications as previously demonstrated by the Mars-bound twin 6U CubeSats called Mars Cube One (MarCO) mission [142], [143]. One of the reasons why this antenna has gained popularity in CubeSats is because it offers an increase in bandwidth and the possibility to be integrated with the solar array [144]. Reconfigurable reflect arrays have also been targeted for use in space communication for the new-generation satellite mega constellation [145].

3) MASSIVE MIMO

Massive MIMO technology is used in conventional satellites and 5G networks to mitigate the lossy nature of millimeter waves. Thanks to the small wavelength at mm-wave and THz frequencies, the size of antenna arrays can be significantly reduced. More antenna elements can fit per unit area of the array, enabling new massive and ultra-massive MIMO communication schemes [146]. Massive MIMO increases throughput and capacity in a communication channel and provides beam shifting, beamforming and beam-steering capabilities. Some of the examples of using massive MIMO in satellite communication is for the 5G satellite-terrestrial network in [147] to improve throughput and solve the coverage and availability problem. Because the massive MIMO consists of multiple antennas and radios, it consumes more power and demands more space on the CubeSat structure which would otherwise be used for other components on the CubeSat.

C. CRITICAL LIMITATIONS AND MITIGATING MEASURES

The techniques used in reconfiguration have both positive and negative effects on the overall antenna design and performance. Negative effects introduces a limitation in some performance characteristics. Cutting slots, adding stubs and adding switches in the antenna structure affects the electrical distribution and hence the antenna performance. Switches require a biasing network; therefore, this increases the complexity of the system and at times adds to the amount of losses in the circuit.

While reconfigurability in antennas increases system functionality and performance, there are some limitations and

TABLE 4. Summary of antenna designs for CubeSat application.

Reference	Antenna size (mm ³)	Frequencies	Axial ratio	Reflection Coefficients	Gain	Polarization	Application
[116]	110 × 110 × 3.18	1.575 GHz (L-band) & 2.2 GHz (S-band)	< 2 dB	< -15 dB	5.4 dBi (L-band) & 6 dBi (S-band)	Right Hand Circular Polarization (RHCP)	Satellite to Earth link and GPS
[117]	124 × 124 × 10	1.570 to 1.650 (L-band) GHz & 2.145 to 2.660 GHz (S-band)	< 3 dB	< -10 dB	5 dBi	Circular	Navigation and Earth to spacecraft receiving link
[118]	40 × 30 × 4	2.3 GHz to 2.7 GHz (S-band)	< 3 dB	-30 dB	3 dBi	Circular	Satellite GPS application
[120]	159 × 152 × 3.175	2.4 GHz (S-band)	Infinite	< -10 dB	7.7 dBi	Linear	Satellite to ground link
[121]	100 × 100 × 0.5	5.8 GHz (C-band)	1.13 dB	< -10 dB	8.07 dBi	Circular	Satellite to ground link and inter-satellite link
[122]	82 × 82 × 4	2.025 to 2.075 GHz (S-band) & 7.75 to 8.75 GHz (X-band)	< 2 dB	< -20 dB	6 dBi & (S-band) and 12 dBi at (X-band)	Right Hand Circular Polarization (RHCP)	Earth to satellite link
[123]	100 × 100 × 1.6	3.2 GHz (S-band) & 9.3 GHz (X-band)	Infinite	< -10 dB	8.5 dBi (S-band) & 11 dBi (X-band) dB	Horizontal and Vertical	SAR Satellite to Earth link
[124]	39.7 × 12 × 1.52	2.45 GHz (S-band)	< 3 dB	< -10 dB	3.7 dBi	Circular	Satellite to ground link
[125]	90 × 69 × 1.575	10 GHz (X-band)	Infinite	-12.492 dB	14.6 dBi	Linear	Satellite to ground communication
[126]	110 × 40 × 1.575	10.3 GHz to 11.8 GHz (X-band)	< 3 dB	< -10 dB	10.1 dBi	Circular	Satellite to ground link
[127]	79 × 79 × 1.575	10.48 GHz to 12.55 GHz (X-band)	0.17 dB	< -10 dB	11 dBi	Circular	Satellite to ground link

drawbacks to using methods such as tuning antennas using shifting physical structures as well as reconfigurability using radio frequency switches such as PIN diodes, varactor diodes and MEMS switches. Switches in the antenna structure tend to increase the cost and the power loss. An example of this is shown in the pixel antenna in [148] which allows for switching in frequency band and also polarization reconfigurability. The use of switches like PIN diodes in real time often necessitates biasing circuits [83] which increases system complexity. Another limitation in having a biasing network is that any uncontrolled electromagnetic coupling or RF signal leakage to the biasing parts from the radiating parts can reduce the antenna functionality or overall performance. The bias line can also become resonant structures if strongly coupled, which can cause problems in the antenna impedance matching [149].

Some of the mitigating measures for dealing with the challenges and limitations of reconfiguration techniques, especially using switches and biasing circuits, includes the following: using low insertion loss switches, small and very narrow high impedance biasing lines, improving RF isolation by using RF chokes or high value resistors and putting them away from the near field of the radiating part [150].

VIII. CONCLUSION

Dual and multi-band antennas have been presented in this paper. Previous designs and implementations of reconfigurable antennas for operation in 5G communication have also been discussed. Frequency reconfigurable antennas,

polarization reconfigurable antennas and radiation pattern reconfigurable antennas have been examined in detail. Improvements to already existing designs can be made, some of which include; adding more switches to the antenna structure to increase radiation at more frequencies to accommodate more wireless applications without using more weight or occupying additional space. Furthermore, high dielectric constant materials like Rogers substrate can be used to enable operation at high frequency millimeter wave frequencies. Hybrid reconfigurable antennas can also be further investigated in order to increase operational possibilities. Following the observation that there is still a gap in the application of reconfigurability to antennas in CubeSat communications, this paper has presented designs of reconfigurable antennas which are well qualified for use in satellite communications by providing reconfigurable frequencies, polarizations and radiating patterns. This research has also provided literature on 5G reconfigurable antennas in detail which can also be scaled for satellite communications, particularly for use in the nanosatellite application. Future designs include scaling the reconfigurable antennas into arrays as well as using their feeding networks to achieve reconfigurability. Based on the concepts and design examples in this article, high gain, directive antennas providing a large bandwidth for high speed link between a CubeSat in orbit and the ground station are required for maximum performance of the CubeSat communication downlink. Therefore, a design of reconfigurable antennas array for CubeSat communication will be designed and analyzed following this survey. The antenna

will be reconfigurable in frequency, covering the S- and X-bands.

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