IOSR Journal of Engineering (IOSRJEN) **www.iosrjen.org**
ISSN (e): 2250-3021, ISSN (p): 2278-8719
Vol. 13, Issue 1, January 2023, ||Series -II|| PP 24-37

A Comprehensive Review of Antenna Design using Metamaterial Techniques in 6G Wireless Communication System: Specifications and Challenges.

Danladi Agadi Tonga[1] and Salisu Umar[2]
[1]Department of Electrical Engineering
Hussaini Adamu Federal Polytechnic, Kazaure, Jigawa State Nigeria.

[2]Departmentof Mechatronics Engineering
Hussaini Adamu Federal Polytechnic, Kazaure, Jigawa State Nigeria.
Received 15 January 2023; Accepted 31 January 2023

Abstract: 6G wireless communication systems are expected to operate in terahertzfrequency bands ranging from 0.1-10Thz, with an equivalent wavelength of 3 mm up to 0.03 mm. The terahertz frequency band has high propagation loss, path loss, and atmospheric absorption of molecules.Furthermore, antenna design, fabrication, and measurement at terahertz frequency bands are other challenges for 6G wireless communication applications. Designing a highly directional antenna with a high gain using metamaterials for 6G wireless communication can mitigate the inherent impairments of current 6G wireless communication systems.Metamaterials are artificial shapes that expose electromagnetic possessions and are not regularly found in nature.The negative values attribute these structures to either permittivity or permeability.A plethora of studies have been conducted on the repercussions of the mitigation potentials of 6G wireless communication systems. Therefore, this worksystematically analyzesa sixth-generation (6G) plan antennawith performance enhancement techniques for 6G wireless communication systems. The article also discusses the 6G design challenges and metamaterials to improve the performance of antenna specifications such as bandwidth, gain, directivity,radiation efficiency,and return loss.

Keywords: 6G, Antenna Design, Metamaterial, Terahertz, and Antenna Parameter

I. INTRODUCTION

6Gnetwork technology is envisaged to offer more advanced applications,and from a broad perspective of accessibility,6G technology provides various access network opportunities, including mobile communication, spacecraft, communication, aircraft communication, submarine communication, and illumination ommunication[2]. In terms of network coverage, prospective 6G technology would have a coordinated and integrated coverage networkthat can cover all forms of communication to realize global network performance point of view,and 6G technology will considerably upgrade industrial requirements such as fidelity connection density,network efficiency, data transmission rate, spectrum efficiency, and end-to-end latency[3]. In May2018, the International Telecommunication Union (ITU) agreed to establish an IMT standard for 6G technology to achieve radical user involvement and develop the latest technological formation[4]. The International Telecommunication Union (ITU) targets 2030as a tentativeyear for launching6G wireless technologies. In addition, the United States Federal Communication Commission (FCC) suggested at the Mobile World Congress in September 2018 that 6G technology should be implemented in THz spectrum-based networks and spatial multiplexing technologies[3]. As a medium of frequency operation for 6G wireless technology, terahertz wavesoccupya radio frequency (RF) spectrum in the range of 0.1-10 THz band, and because of its high band frequency, the wavelength has a shorter range from 30 to 300µm[5].

The terahertz band lies between the microwave frequency band and a far-infrared light band of the electromagnetic spectrum.TheTHz band has two significant advantages. It has an abundant spectrum that can provide broadband communication and a high data transmission rate. The general issues limiting 6Gtechnology are high propagation losses, absorption, scattering by molecules, and tiny particles in the atmosphere, such as water vaporand oxygen, because their sizes are close to the natural wavelength. Path losses in the terahertz band are another significant limitation affecting communication-based on the distance range (coverage area up to 1 10m[6].However, the above general problems could be overcome by designing ahighlydirectional or omnidirectional antenna with a high gain to subdue the impairments. Manystudieshave been conducted to develop antennas for 6G wireless communication applicationsto enhanceantenna accomplishment possessions, such as bandwidth, antenna directivity,and gain[7].Performance enhancement techniques and coupling techniques such as choice of substrate, corrugation/corrosive resistance, multi-element, and dielectric lenses,and mutual coupling reduction techniques are neutralization on lines, decoupling networks,electromagnetic bandgap structures, defected ground structures,metamaterial structures, and slot elements [8].

II. CHALLENGES OF 6G WIRELESS COMMUNICATION SYSTEM

Numerous challenges are confronting 6G wireless communication at terahertz frequency bands, which require urgent attention to address practical and efficient services. Some of these challenges are categorized into four parts, as shown in Figure1.

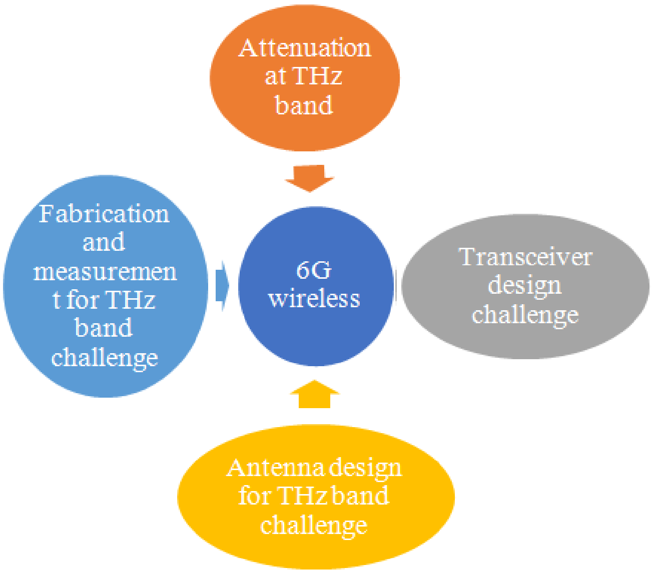

Figure 1. Some of the challenges of the 6G wireless communication system.

a) Attenuation in terahertz bands: The significance of terahertz cannot be overemphasized because it provides a high data rate. The major challenge in implementing the band for 6G wireless communication is the impairment encountered,such as high propagation loss, high path loss, multipath, and atmospheric absorption, which are very high[9].To achieve the desired result of using the terahertz band for 6G wireless communication, the transceiver and other related terminal devices must be redesigned to overcome the impairments mentioned earlier. Designing a modern transceiver that can operate at high power supports massive bandwidth, sharp sensitivity, and weak noise to subdue the high propagation and atmospheric losses.

b) **Transceiver design challenge:** Designing an efficient transceiver for the terahertz band is always a primary challenge for system engineers. The generation of the signal at THz is challenging because of the THz gap, which implies that the frequency band is too high for conventional oscillators and too low for optical photon emitters[10].Two methods were used to design an effective transceiver for the THz band for 6G wireless communication applications. Top-down and bottom-up are the two methods used to generate a signal for the transceiver in the THz bands. The multiplexer was applied to the bottom-up method to create a signal. At the same time,the photonic system is used for the top-down process to generate a signal, where laser simulation of the semiconductors provides continuous radiation, and the nonlinear crystal is operated at THz frequencies.

c) Notwithstanding the two methods involved in designing an effective transceiver, a massive number of multiplexers must be avoided in a bottom-up approach to maintain the spurious effects and inter-modulation losses at a low level. The optimum goal is to design a transceiver with a high path loss, propagation loss, and atmospheric absorption in the THz frequency band. The last aspect to consider when designing a transceiver for the THz band is the throughput of the transceiver, which hashigh power, high sensitivity, and low noise figure[10].

d) **Antenna design for THz band challenges:** The designedantenna for the THz band is more challenging. Designing an antenna for future 6G wireless communication in the THz band requires high-directional antennas covering short transmission distances because of the high propagation loss. Designing a highly directional antenna at the THz band challenges antenna design and market value (trade-off) for 6G wireless communication systems. In general, it is challenging to meet all the required specifications of antenna design; however, ultra-broadband antennas offer low directivity/gain, and narrowband antennas provide high gain/directivity. This is because of the effect of the intensity of the aerialparts on the gain/bandwidth. It always proves difficult for bandwidth and increases when the size of the antenna remains small[11]. To improve the antenna gain, the aperture of the antenna is a significant factor to consider, which may lead to another problem in practice.Wireless communications are required as many aerials will be produced for THz utilization in the sixth generation (6G). The components and appearance of the aerialparts may influence the production cost; thus, maintaining a low cost of antenna production should be considered. There is the problem of traditional failure to serve the THz frequency band because of drawbacks in fabrication and installation, primarily for small sizes [12]. New affordable materials and fabrication techniques for THz band antennas must meet the latest user requirements for 6G wireless communication systems.

e) Nevertheless, graphene is a promising material for the THz band; it also has a drawback of application owing to its cost and technological constraints in fabricating the antenna shape, such as a 3D antenna.Although metallic antennas are suitable as affordable antennas [13], they have the advantage of reducing production costs and complex fabrication[14]. Copper is a good conductor, making it suitable and favorable for affordable antenna fabrication[15]. It is challenging to use copper for antenna design in the THz frequency band because of the skin depth and conductivity of the copper material, which reduces the radiation efficiency of the antenna elements[15]. Din designing an antenna using copper at a low frequency of THz frequency bands and resonating at 4.65THz, the ohmic resistance contributes to the surface impedance of the copper material, which is a major challenge in antenna design using copper materials [15]. In addition, the use of a patch copper antenna for the THz bandexhibited an excellent result of greater bandwidth and good return loss compared to thin patch graphene[16]. This effect favorsthe considerationof copper material for antenna design in the THz bands for 6G wireless communication. However,metal surface lossisa challenge when designing an antenna for the THz band using copper.

f) Terahertz band antenna fabrication **and measurement:** The production of affordable, high-precision,and reliable antennas for terahertz band applications is required[14]. The antenna's small size for THz band applications facedwith challenges of fabrication andmeasurement. Fabricating an antenna for the THz band requires very high precision, tolerance, and smooth finishing[17]. Considerable surface roughness increases the insertion loss, affecting antenna performance[17]. The present fabrication technologies for THz band antennasarenarrow at 1THz only for the moment;the THz band is newly proposed,and fabrication technology for THz frequency for more than 1THz of the antenna is not yet available. A small antenna size makes inadequate fabrication technology for THz band antennas that are currently not readily available.The antenna measurement in the THz band is another challenging moment,and measurementequipment for the THz band is not now adequately available.Despite the availability of some review studies on 6G, to the author’s knowledge, none of these studiesachieved the contributions summarized below.The research contributed to reviewing 6Gintensee a design and further classifying the performance enhancement techniques for 6G at theantenna design. In addition, based on the assessment of the antenna parameters, the performance of different designed antennasfor 6G was evaluated. This review identified constraints and drawbacks while designing effective and efficient antennas for 6G wireless communication applications. Finally, some of the challenges facing the design of terminal devices for the smooth implementation of 6G wireless communication are highlighted in this review.The remainder of this paperorganized as follows. Section II presentsthe challenges of 6G antenna design, andSection III presents a review of metamaterial antenna designs for 6G applications. Section IV presents the performance enhancement techniques. Finally, Section V presents the conclusions of this study.

E.)ANTENNA DESIGN

A few years ago,graphene attracted the attention of researchers in both academia and industry because of its exceptional electronic,optical, and mechanical properties[18]. The structure of graphene can be used in nanoelectronics to realize novel high-speed devices such as antennas and transceivers[17].Graphene of micrometreintensity can be emitted in the terahertz band frequency of 0.1 -10THz. Broadband antenna design is required to achieve ultra-wideband transmission at terahertz frequency bands. Designing an antenna with high directivity is one of the criteria to be considered for solving transmission-distance problems owing to propagation loss and high path loss. Graphene-based and large antenna arrays have been proposed to fulfil these two requirements. Graphene helps propagate surface plasmon polariton (SPP) waves at terahertz frequencies.

Compared to copper and carbon nanotubes, graphene produces antennas with small sizes [19] and high directivity[20]. Plasmonic graphene antennas can be sized at the nanoscale, implying that they can be applied to nanodevices[21].Designinga 6G antenna for wireless communication using metamaterials to improve antenna performance requires systematic steps. The selection ofthe frequencyof operation of the desiredplanned antenna is fundamental to the antenna designer. The next step is designing and modeling the antenna and optimizing the antenna performance. Simulation, fabrication, and testing analysis of the modeled antenna are required. Subsequently, the measurement of the prototype was carried out in the laboratory using appropriate equipment to validate the simulated results obtained earlier.There has been a rapid decrease in the measurements of wireless communication devices; a succinct size, compact, and lightweight microstrip patch antenna needs to be designed. Researchers are currently working on the latest shapes and various substrates with different dielectric constants to improve the performance of 6G antennas using MTMs.

III. REVIEW OF RELATED LITERATURE

The need fora succinct size, high gain multi-band, and wideband antenna capable of upgrading channel capacity is receiving increasing attention from antenna designers to meet the prerequisites of sixth-generation (6G)network communications. Despite their low weight, simplicity of fabrication, low profile, and easeof incorporation, patch antennas have limitations such as narrow bandwidth, low gain, large size, and low power-handling capacity. Toaddress the problems mentioned above, a metamaterialcan be adopted to enhance the accomplishment of the antenna[21]. The circular polarizedmultiple-input multiple-output (MIMO) of a microstrip patch antenna incorporating a metamaterial superstrate yielded a gain of 13.6 dBi, and a bandwidth of 15.4% at 11GHz was realized[22]. A compact antipodal Vivaldi antenna with an epsilon-near-zero metamaterial (ENZ) unit cell exhibits an ultra-wide bandwidth, good reflection coefficient, and gain of 14 to 17.2 dBi[23]. The designed dipole antenna improved gain, bandwidth, and steady radiation efficiency[24]. A multilayer PCB antenna structure that easily excites the resonant modes can deliver multi-bandoperations with a wideband[25]. Using parasitic elements with different coupling techniques, a designed antenna can upgrade antenna parameters, such as bandwidth, isolation,and radiation pattern isolation[26]. The design of resonant capacity antennas (RCA) can deliver the gain, front-to-back ratio, and directivity[27].

The design of an antenna using corrugated structures in 6G applications energizesantenna performance, such as a reduction in size and front-to-back ratio. The inclusion of a corrugated structure in an antipodal Vivaldi antenna improves the antenna's gain [28]. Using Dolp Chebyshev's current distribution, a designed antenna array can minimizethe side lobes and enhance radiation characteristics[29].Researchers have noticed the design of antennas incorporating metamaterial-based 6G antennas owing to their unique features such as improved gain, bandwidth, and succinct size. A rigorous review of 6G antenna designs incorporating different metamaterial-based antenna structures and theutilizationin MIMO systems[30].A few years ago,6G antenna designs integrating artificial magnetic conductors, high-impedance surfaces, electromagnetic bandgaps, and meta surfaceswere investigated to obtain the overall antenna parameters. Antenna design structures incorporating multilayers, such asartificial magnetic conductors, and high impedance improve the gain and bandwidth requirements [30].The antenna design for 6G MIMO integrated with an electromagnetic bandgap-based structure delivers better isolation.

A. Categorization of Metamaterial Based on permittivity and Permeability

The permittivity and permeability of material control its electromagnetic properties. Veselego scientists were the first to propose metamaterial categorization based on the values of ε and μ. When both permittivity and permeability are negative,a unique paradox occurs, such as Snell’s law and Doppler shift reversal. The relationship between the permittivity, permeability, and refractive index (n) is given by

$$n \pm \qquad \sqrt{\varepsilon_r \mu_r \text{----------------------}_6}$$

Whereε_r and $\mu_r$are the medium's relative permittivity and permeability, respectively$_,$the sign metamaterials are categorized into four (4) classes. The Figure below shows the categorization of metamaterial structures [1].
9

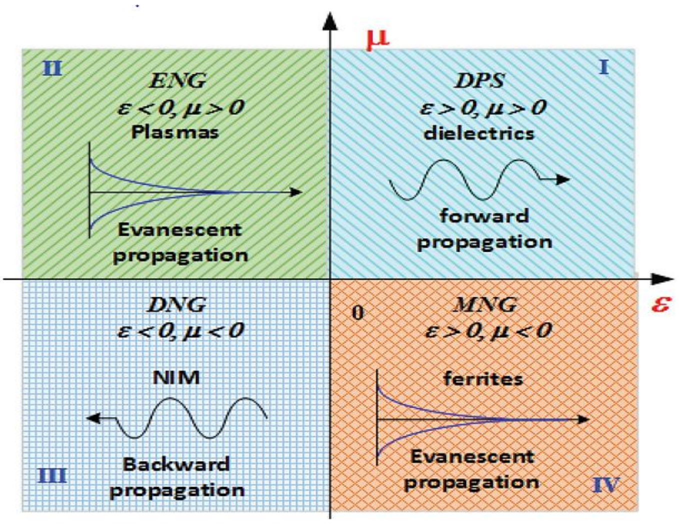

Figure 2.The Categorization of electromagnetic MTMs based on signs of the ε and μ[1].

The double-positive (DPS) permittivity and permeability are positive in the first quadrant and are referred toas the right-handmedium (RHM). These materials arelikely to befound in nature, such as dielectric materials that propagate electromagnetic waves. When the parameters $\varepsilon < 0$ negative and $\mu > 0$ positiveat the second quadrant, such material is referred to as epsilon negative medium (ENG) and is represented a plasma. When $\varepsilon < 0$ is negative and $\mu < 0$ is negative in the third quadrant, the region is referred to as a double-negative (DNG) or left-handed medium (LHM), and such material cannot be found in nature. When the parameters $\varepsilon > 0$positive and $\mu < 0$, in the fourth quadrant such a material is called as μ- negative (MNG) and represented by ferrite materials, a medium has plasma below frequency. The propagation of waves is mainly in two mediain regionsI and III.Nonpropagationevanescent waves are in regions II and IV[31]. At present,the two basic types of structures used for designing metamaterials are a dense array of thin wires (electricaldipoles) and an array of split-ring resonators (SRRs)(magnetic loops).

B. Metamaterials in antenna design

Electromagnetic metamaterials are primarily human-made materials found in nature with exceptional properties. Metamaterials are composed of microstructures referred to as unit cells. These structures can be antisymmetric or symmetric. The shape and unit cell size regulate permittivity, permeability, and resonant frequencies[32]. The unit cell size is a frequency task that differs concerning the resonant frequency f_r.Literature survey results indicate that the basic designs used in metamaterials are electric dipoles and split-ring resonators (SRRs). The figure below shows that the inclusion sizereduces as the order of the Hilbert fractal curve increases[33].

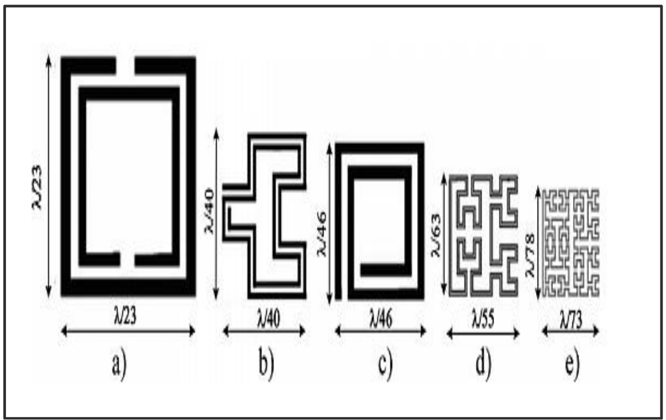

Figure 3. (a) SRR-based unit cell (b) 2nd order Hilbert fractal inclusion, (c) square spiral, (d) 3rd order Hilbert fractal inclusion, (e) 4th order Hilbert inclusion[33],[34].

The antenna parameter performance, such as high-gain multiband structures with beam steering, can be upgraded by integrating metamaterials based on the antenna design[31].A metamaterial-based antenna design for 5G mm-waves can delivera high gain performance[35]. The metamaterial antenna design of a shared aperture contributesto orthogonal pattern diversity and improvesmutual coupling. The designed antenna is a good candidate for 6G repeaters because it deliversa wide frequency band[36]. Design antennas incorporating negative refractive index metamaterials with dielectric resonators contribute to dual-polarization and augmented bandwidths [37]. The design of an AVA antenna integrated with metamaterial-based structures with and without corrugated structures shows that the design delivers better bandwidth and is suitable for 6Gapplications[38].

C. Metamaterial Promote Antenna Gain and Bandwidth Enhancement

An accessible literature survey features low-profile antenna structures with low gain and narrow bandwidth. Many techniques are available to upgrade the antenna parameters, such as gain and bandwidth[39]. Recently, 6G antenna designs that integrate metamaterial structures have been widely investigated by researchers. Antenna design incorporating a planar metamaterial-based can deliver impedance bandwidth of 3.08-11.7GHz and 13.6-36.4GHz with a peak gain of 8.02 dB[40]. A designed dual-band antenna integrating a double negative-ground metamaterial-based structure provides a gain of 7.45 dBi and a bandwidth of 6GHz[41]. A designed antenna using split-ring resonators (SRRs) with and without a corrugated structure contributes a gain of 7 dBi ana d bandwidth of 230–429 MHz [42]. A design of a Fabry Perot cavity antenna structure integrating a partially reflective surface can deliver a gain of 8.2 dBwith an impedance bandwidth of 2.2GHz[43]. Furthermore, the design of antennas incorporating EBG, FSS, and AMC metamaterial-based structure techniques in the 6G antenna design can upgrade bandwidth and gain[43],[44].The antenna's capability to enhance the power gain lies in the number of superstrates, the type of unit cell,and the distance between the radiate elementsand the superstrate, as shown in figure 4.

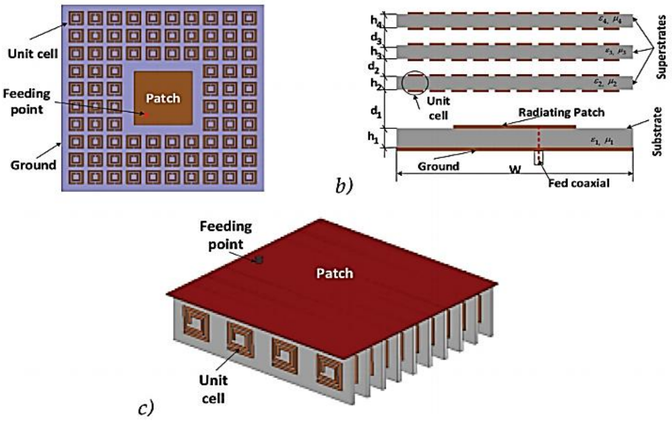

Figure4: showing metamaterials application models for enhancing the power gain of the aerial: unit cells surrounding the radiated patch (a) metamaterials as superstrate(b), using the metamaterials antenna loading (c)unit cell propagation[31],[45].

D. Metamaterial -Base Compact Antenna Designs

Antenna miniaturization demonstrateshowto minimizethe size of the antenna designsto achievethe desired gain and bandwidth. Conventional techniques for designing condensed antennas include materials with high permittivity and permeability. A compact antenna size of 23 mmx29mm with an SRR-based structure can deliver broadband of 3-12GHz[45]. A wearable antenna design incorporating an EBG structure as a metamaterial-based antenna showed a succinct size of 20 mmx25mm in the frequency band of 3.1-10.6GHz[46]. The designed antenna for biomedical applications integrating metamaterial-based antennas has a size of 7 mm × 6 mm [47].The design of a compact antenna incorporating metamaterials is suitable for 6G applications with a size of 31mmx31mm[36].

E. Metamaterials for multiband applications

There is a demand to integrate multiple functions (on single devices and multiband antennas). The application of metamaterials for antenna design is more attractive for minimizing size, upgrading power gain, improving bandwidth, and designing multifrequency antennas[48]. The intensity of a unit cell of metamaterials can be applied as radiation components or as a part or loaded part of the antenna's ground plane. The metamaterials support negative refraction indices at the resonant frequencies and unit cell structures of asymmetric pairs. It can be applied in designing multifrequency antennas with small measurements compared to conventional antennas [49]. It is possible to combine metamaterials with traditional or fractal microstrip antennas to establish multi-bands, and the lowest frequency regulates the size of the antenna. The antenna's resonant frequency can be fine-tuned by changingthe intensity of the antenna or the intensity of the unit cell's intensity[45].The figure belowshows the simulated model and S_{11} scattering matrix coefficient of the two antennas operating at multiband frequencies.

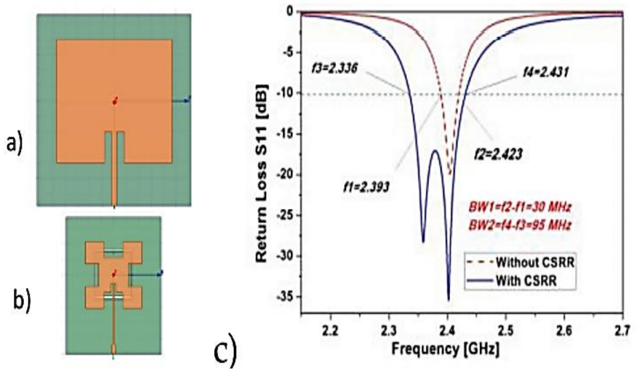

Figure 5:The configuration of microstrip

Figure 5 showsthe simulated antenna for the WLAN system without loaded (a),fractal antenna with loaded CSRR(b), and S11 parameters (c) frequency propagation[45],[50].

TABLE 1: 6G ANTENNA DESIGN WITH ANTENNA PARAMETERS PERFORMANCE.

No	*Reference*	*Antenna Type*	*Frequency band (THz)*	*Gain (dB)*	*Efficiency (%)*	*Radiation pattern (%)*	*Bandwidth (GHz/THz/%)*	*Return loss (dB)*	*Remark*
1	[51]	Dual polarized MPA	3.98	9.6	90	------	……..	-36	Radiation pattern and bandwidth require further investigation
2	[52]	Metamaterial based RMPA	1.02	5.75	……	…….	179.5	-65	Other parameters require to be explored
3	[30]	Multiband MPA	3.99- 6.06	7.54	54	------	6.8	-37	Radiation patterns need further findings.
4	[53]	Multiple THz PA	3.00-10.78	13.92	…..	85.8	85.77	-----	Return loss has no game.
5	[54]	Graphene-based Patch antenna	0.332019	2.995	90	------	22381	-48.58	Radiation requires investigation
6	[55]	Graphene circular PA	6.8-7.2	16.7	10.34	11.76	------	-34.69	Bandwidth is not reported.
7	[16]	Microstrip antenna	0.5-0.8	9.19	-----	90.84	230	-83.73	Efficiency is not reported.
8	[56]	Graphene-based patch antenna	1.0	5.0	66.71	66.72	79.1	-39.19	Antenna parameters result reported.
9	[57]	Graphene-based MPA	0.72	6.60	----	-----	0.3750	-59.87	Efficiency, and radiation patterns results not reported.
10	[58]	Graphene-based miniaturized THz antenna	2.67-2.92	5.0	----	87	270	-26.71	No result for efficiency was reported.
11	[59]	High-isolation high gain MIMO Antenna	0.33-10	19	------	70	187	----	Efficiency & return loss are absent.
12	[60]	UWB MPA for THZ	0.1-20	12-25	------	55.9	--------	-48	Efficiency and bandwidth nill
13	[61]	MPA designed	0.6152	7.94	-----	85.71	36.25	-44.71	Efficiency result nill
14	[62]	Dual-band fractal antenna	1-1.48	7.64	-----	-----	----	----	Other parameters require more findings
15	[63]	Yagi- antenna	0.884-1.06	10,0	-----	------	176	-20	Efficiency & return loss nil
16	[64]	On-chip antenna based on CRHL	0.350-385	8.15	60.85	65.71	38.71	----	Return loss nill
17	[65]	CW Fed Jasmine shaped	0.65	11.0	-----	------	197.42	----	Efficiency, return loss, and radiation patterns nill
18	[66]	High-performance Graphene patch antenna	7.32	6.338	-----	------	677	-50.78	Efficiency & radiation patterns nill
19	[67]	Graphene-based MF antenna	2.14-5.41	4.71	-----	-----	658		Efficiency & radiation patterns nill
20	[68]	High-performance GPA for THZ	7	7.236	----	97.21	419	-75.66	Efficiency result nill
21	[69]	Graphene on glass	1	5	68.71	75.72	77.01	----	Return loss nill
22	[58]	Analysis of graphene-based nano PA	0.75	5.09	-----	-----	6.67	-----	Other parameters need to investigate

IV. PERFORMANCE ENHANCEMENT TECHNIQUES FOR 6G ANTENNA DESIGN

Various performance enhancement techniqueshave been used to upgrade antenna parameters, such as bandwidth, gain, directivity, radiation efficiency, total efficiency, return loss, and size. The enhancement techniques are discussed below.

i. **Choice of substrate**: The primary consideration and priority requirement of antenna implementation is selecting an appropriate substrate. Several substrates with permittivity and loss tangents are available for antenna fabrication. However, to enhance the gain and minimizethe power loss, it is necessary to select a substrate with lower relative permittivity and loss tangent [70].

ii. **Corrosion-resistant/corrugation**: This means shaping into parallel ridges or removing a metal part, for example, rectangular, square, or triangular, from the edge of a radiator. This technique helps enhance the bandwidth and front-to-back ratio of the antenna [71].

iii. **Multi-element:**This technique helps improve the gain of an antenna. This also enhances the bandwidth and efficiency of the antenna. It is applied where a single-element antenna cannot meet the requirements, such as an antenna with high gain and wide bandwidth employing the multi-element technique [70].

iv. **Dielectric lens:**Electrostatic emission is transmitted in one direction by the dielectric lens, improving the gain and directivity of the aerial part. Numerous dielectric lens structures exist. Designing the dielectric involves using various substrate materials with the same or different substrates[70].

V. MUTUAL COUPLING REDUCTION TECHNIQUE

In designing the multi-element aerial andaerial element consequences, researchers incorporate various mutual coupling methods in the MIMO aerial, named isolation or decoupling methods. These methods are discussed below, and their leverage and drawbacks are presented in table form.The various types of mutual coupling techniques are discussed below.

i. **Neutralization lines:**Applying metallic slit antithesis lines passes electromagnetic waves between the antennas to diminish mutual coupling. It also minimizes the antenna area and boosts the bandwidth when connected between ground planes. With the alteration in the location of a point on the antithesis lines, impedance changes limit the bandwidth[72].

ii. **Decoupling Network**: cross admittance is transformed to a purely imaginary value by adding a distinct component in the decoupling network that acts as a resonator to diminish mutual coupling. A decoupling network involves multiple elements, a dummy load, and coupled resonators. This technique is a less cost-effective solution for boosting isolation[73].

iii. **The electromagnetic bandgap structure (EBG)** wasexploited as a medium for transmitting electromagnetic waves. The EBG is made of a dielectric or metallic material with a continuous arrangement. Because of the independent consistency resonance, it can yield manyband gaps. The shape of the EBG provides weak mutual coupling and high efficiency[74].

iv. **Metamaterials:**This method accommodates electromagnetic features. Numerous types of metamaterials consist ofa single negative electromagnetic bandgap, double negative scattering, isotropic terahertz, chiral tunable photonic, frequency-selective surface-based, nonlinear, and tunable metamaterials — mutual design of metamaterials involving two or more materials[26]. The adoption of metamaterials enables aerialenhancement with weak mutual coupling to improve the gain and bandwidth with a succinctaerial size [26].

v. **Slot element:**This technique booststhe impedance bandwidth by applying the coupling method in the ground plane. A slot antenna is used to supply a wide bandwidth, high gain, efficiency, and high mutual coupling value[75].

TABLE 2: MERITS AND DRAWBACKS OF PERFORMANCE ENHANCEMENT TECHNIQUES.

	Reference	**Name of techniques**	**Merits**	**Drawbacks**
1	[23],[76]	Dielectric Lens	It improves the gain, enhances the front-to-back ratio, supplies a balanced emission pattern, and emits the peak energy in the front direction.	The technique has the limitation of the expands the magnitude of the antenna
2	[77],[78]	Multi-Element	It hances the gain, efficiency return loss, and bandwidth	Design the feeding network is challenging and increases the size of the antenna
3	[15],[79]	Corrosion-resistant/corrugation	It provides enhanced gain, return loss, and bandwidth, minimizes side and back lobe levels, and increases the front-to-back ratio.	It minimizes input impedance
4	[80],[81]	Choice of substrate	A substrate with low permittivity offers improved gain, efficiency, wide bandwidth, and a small antenna, while a	A substrate with weak permittivity is expensive and very scarce.

			return loss is enhanced with a substrate with high permittivity.	
5	[82]	Mutual coupling reduction (decoupling technique)	It improves gain, efficiency, andinput impedance matching;the mutual coupling method reduces an antenna's magnitude.	Complexity in design.

TABLE 3: MERITS AND DRAWBACKS OF ACCOMPLISHMENT ENHANCEMENT METHODS

	Reference	**Mutual-coupling reduction technique**	**Merits**	**Demerits**
1	[75]	Slot element	It improves heterogeneity gain, bandwidth, and efficiency	Design is very complicated and decides the position of the slot.
2	[72]	Neutralization lines.	A very small aerial offers wide bandwidth and improved efficiency.	It has a complex structure.
3	[83]	metamaterial	It boosts the heterogeneity gain, bandwidth, and Envelops correlation coefficient, and it is compatible with integration with other components	Complex in design and decide the position of metamaterial unit cells
4	[84],[59]	Electromagnetic bandgap structure	generates an excellent front-to-back ratio and impedance matching	A very complicated structure
5	[73]	Decoupling network	It boasts heterogeneity gain and impedance matching	It has weak gain and is very complex in design.

VI. CONCLUSION

The review paper mentioned the terahertz frequency band as the expected operating frequency for 6G wireless communication systems. The problems associated with the short-wavelength terahertz frequency bands include high propagation loss, path loss, and atmospheric absorptionof molecules as the impairments facing 6G wireless communication systems. This paper also highlights some of the antenna design challenges of 6G wireless communication systems. The use of metamaterials and performance enhancement techniques to improve antenna parameters such as bandwidth, gain, directivity, return loss radiation efficiency, and multiband antennas is discussed in this paper.

The6G antenna design using a patch antenna has limitations such as narrowbandwidth, low gain,large size, and low power handling capacity for future communication technologies that can be improved with performance enhancement techniques. Reconfigurable and metamaterial-basedantennatechniques can boost the performance of antenna parameters. Other methods used in different designed antennas, including the choice of substrate, corrosive-resistant/corrugation, multi-elements, anddifferent mutual coupling reduction techniques,alsoimprove the antenna parameters. These methods have remarkable effects on antennas' corporeal and electrical properties,enhancingtheir performance. Finally, designing an antenna for 6G applications, antenna parameters such as directivity and high gain attention of antenna designers should be the focus because of the terahertz band frequencies, which range from 0.1THz – 10 THz to overcome high propagation losses, pathloss, and atmospheric absorption, suchas raindrops, dust, and molecular particles.

Author contributions: Conceptualization and writing of the original manuscript.

Conflict of Interest: The author declared no conflict of interest.

Ethics Statement: The author confirms that all the ethical standards are fulfilled.

REFERENCES

[1] J. B. Pendry, A. Holden, W. Stewart, and I. Youngs, "Extremely low-frequency plasmons in metallic mesostructures," Physical review letters, vol. 76, p. 4773, 1996.

[2] T. Huang, W. Yang, J. Wu, J. Ma, X. Zhang, and D. Zhang, "A survey on green 6G network: Architecture and technologies," IEEE Access, vol. 7, pp. 175758-175768, 2019.

[3] Y. Lu and X. Zheng, "6G: A survey on technologies, scenarios, challenges, and the related issues," Journal of Industrial Information Integration, p. 100158, 2020.

[4] S. J. Nawaz, S. K. Sharma, S. Wyne, M. N. Patwary, and M. Asaduzzaman, "Quantum machine learning for 6G communication networks: State-of-the-art and vision for the future," IEEE Access, vol. 7, pp. 46317-46350, 2019.

[5] I. Malhotra, K. R. Jha, and G. Singh, "Terahertz antenna technology for imaging applications: A technical review," International Journal of Microwave and Wireless Technologies, vol. 10, pp. 271-290, 2018.

[6] A. Saeed, O. Gurbuz, and M. A. Akkas, "Terahertz communications at various atmospheric altitudes," Physical Communication, vol. 41, p. 101113, 2020.

[7] C.-X. Wang, J. Huang, H. Wang, X. Gao, X. You, and Y. Hao, "6G wireless channel measurements and models: Trends and challenges," IEEE Vehicular Technology Magazine, vol. 15, pp. 22-32, 2020.

[8] M. Alibakhshikenari, B. S. Virdee, C. H. See, R. Abd- Alhameed, A. Hussein Ali, F. Falcone, et al., "Study on isolation improvement between closely- packed patch antenna arrays based on fractal metamaterial electromagnetic bandgap structures," IET Microwaves, Antennas & Propagation, vol. 12, pp. 2241-2247, 2018.

[9] T. S. Rappaport, Y. Xing, O. Kanhere, S. Ju, A. Madanayake, S. Mandal, et al., "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond," IEEE Access, vol. 7, pp. 78729-78757, 2019.

[10] K. Tekbıyık, A. R. Ekti, G. K. Kurt, and A. Görçin, "Terahertz band communication systems: Challenges, novelties and standardization efforts," Physical Communication, vol. 35, p. 100700, 2019.

[11] E. Zhou, Y. Cheng, F. Chen, and H. Luo, "Wideband and high-gain patch antenna with reflective focusing metasurface," AEU-International Journal of Electronics and Communications, vol. 134, p. 153709, 2021.

[12] S. N. H. Sa'don, M. H. Jamaluddin, M. R. Kamarudin, F. Ahmad, Y. Yamada, K. Kamardin, et al., "Analysis of graphene antenna properties for 5G applications," Sensors, vol. 19, p. 4835, 2019.

[13] Y. He, Y. Chen, L. Zhang, S. Wong, and Z. Chen, "An overview of terahertz antennas. China Commun. 17 (7), 124–165 (2020)," ed.

[14] M. STEER, "2004 IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium (IMS)," IEEE transactions on microwave theory and techniques, vol. 53, pp. 3-300, 2005.

[15] M. A. Jamshed, A. Nauman, M. A. B. Abbasi, and S. W. Kim, "Antenna selection and designing for THz applications: suitability and performance evaluation: a survey," IEEE Access, vol. 8, pp. 113246-113261, 2020.

[16] A. Hocini, M. Temmar, D. Khedrouche, and M. Zamani, "Novel approach for the design and analysis of a terahertz microstrip patch antenna based on photonic crystals," Photonics and Nanostructures-Fundamentals and Applications, vol. 36, p. 100723, 2019.

[17] B. Zhang, W. Chen, Y. Wu, K. Ding, and R. Li, "Review of 3D printed millimeter-wave and terahertz passive devices," International Journal of Antennas and Propagation, vol. 2017, 2017.

[18] A. K. Geim and K. S. Novoselov, "The rise of graphene," in Nanoscience and technology: a collection of reviews from nature journals, ed: World Scientific, 2010, pp. 11-19.

[19] S. Abadal, S. E. Hosseininejad, A. Cabellos-Aparicio, and E. Alarcón, "Graphene-based terahertz antennas for area-constrained applications," in 2017 40th International Conference on Telecommunications and Signal Processing (TSP), 2017, pp. 817-820.

[20] S. W. Kim, I. K. Cho, and S. Y. Hong, "Design of transmitting coil for the wireless charging system to expand charging area for drone applications," Microwave and Optical Technology Letters, vol. 60, pp. 1179-1183, 2018.

[21] S. A. Naghdehforushha and G. Moradi, "High directivity plasmonic graphene-based patch array antennas with tunable THz band communications," Optik, vol. 168, pp. 440-445, 2018.

[22] A. Kumar and T. Agrawal, "High-Performance Circularly Polarized MIMO Antenna with Polarization Independent Metamaterial," Wireless Personal Communications, vol. 116, pp. 3205-3216, 2021.

[23] S. El-Nady, H. M. Zamel, M. Hendy, A. A. Zekry, and A. Attiya, "Gain enhancement of a millimeter wave antipodal Vivaldi antenna by epsilon-near-zero metamaterial," Progress In Electromagnetics Research C, vol. 85, pp. 105-116, 2018.

[24] J. Yin, Q. Wu, C. Yu, H. Wang, and W. Hong, "Broadband endfire magnetoelectric dipole antenna array using SICL feeding network for 5G millimeter-wave applications," IEEE Transactions on Antennas and Propagation, vol. 67, pp. 4895-4900, 2019.

[25] H. Huang, X. Li, and Y. Liu, "A novel vector synthetic dipole antenna and its common aperture array," IEEE Transactions on Antennas and Propagation, vol. 66, pp. 3183-3188, 2018.

[26] Z. He, J. Jin, Y. Zhang, and Y. Duan, "Design of a two-dimensional "T" shaped metamaterial with wideband, low loss," IEEE Transactions on Applied Superconductivity, vol. 29, pp. 1-4, 2018.

[27] Y. Liang, J. Zhang, Q. Liu, and X. Li, "High-power dual-branch helical antenna," IEEE Antennas and Wireless Propagation Letters, vol. 17, pp. 472-475, 2018.

[28] A. S. Dixit and S. Kumar, "The enhanced gain and cost- effective antipodal Vivaldi antenna for 5G communication applications," Microwave and Optical Technology Letters, vol. 62, pp. 2365-2374, 2020.

[29] B. Bhadoria and S. Kumar, "A novel omnidirectional triangular patch antenna array using Dolph Chebyshev current distribution for C-band applications," Progress In Electromagnetics Research M, vol. 71, pp. 75-84, 2018.

[30] S. Ghosh, S. Das, D. Samantaray, and S. Bhattacharyya, "Meander- line- based defected ground microstrip antenna slotted with split- ring resonator for terahertz range," Engineering Reports, vol. 2, p. e12088, 2020.

[31] W. J. Krzysztofik and T. N. Cao, "Metamaterials in application to improve antenna parameters," Metamaterials and Metasurfaces, vol. 12, pp. 63-85, 2018.

[32] P. D. Tung, P. H. Lam, and N. T. Q. Hoa, "A MINIATURIZATION OF MICROSTRIP ANTENNA USING NEGATIVE PERMITIVITY METAMATERIAL BASED ON CSRR-LOADED GROUND FOR WLAN APPLICATIONS," Vietnam Journal of Science and Technology, vol. 54, p. 689, 2016.

[33] W. J. Krzysztofik, "Antenna properties improvement using modern technology," in 2014 20th International Conference on Microwaves, Radar and Wireless Communications (MIKON), 2014, pp. 1-4.

[34] W. J. Krzysztofik, "Fractal Geometry in Electromagnetics Applications-from Antenna to Metamaterials," Microwave Review, vol. 19, 2013.

[35] H. Jiang, L.-M. Si, W. Hu, and X. Lv, "A symmetrical dual-beam bowtie antenna with gain enhancement using metamaterial for 5G MIMO applications," IEEE Photonics Journal, vol. 11, pp. 1-9, 2019.

[36] K. G. Sadananda, M. P. Abegaonkar, and S. K. Koul, "Gain equalized shared-aperture antenna using dual-polarized ZIM for mmWave 5G base stations," IEEE Antennas and Wireless Propagation Letters, vol. 18, pp. 1100-1104, 2019.

[37] J. Li, Q. Zeng, R. Liu, and T. A. Denidni, "Beam-tilting antenna with negative refractive index metamaterial loading," IEEE Antennas and Wireless Propagation Letters, vol. 16, pp. 2030-2033, 2017.

[38] S. Kumar, A. S. Dixit, R. R. Malekar, H. D. Raut, and L. K. Shevada, "Fifth generation antennas: A comprehensive review of design and performance enhancement techniques," IEEE Access, vol. 8, pp. 163568-163593, 2020.

[39] L. Shevada, H. D. Raut, R. Malekar, and S. Kumar, "Comparative Study of different beamforming techniques for 5G: A Review," Inventive Communication and Computational Technologies, pp. 589-595, 2021.

[40] B. Yuan, Y. H. Zheng, X. H. Zhang, B. You, and G. Q. Luo, "A bandwidth and gain enhancement for microstrip antenna based on metamaterial," Microwave and Optical Technology Letters, vol. 59, pp. 3088-3093, 2017.

[41] B. Urul, "Gain enhancement of microstrip antenna with a novel DNG material," Microwave and Optical Technology Letters, vol. 62, pp. 1824-1829, 2020.

[42] S. K. Patel and C. Argyropoulos, "Enhanced bandwidth and gain of compact microstrip antennas loaded with multiple corrugated split ring resonators," Journal of Electromagnetic WWavesand applications, vol. 30, pp. 945-961, 2016.

[43] Z. Wang, C. Pang, Y. Li, and X. Wang, "A method for radiation pattern reconstruction of phased-array antenna," IEEE Antennas and Wireless Propagation Letters, vol. 19, pp. 168-172, 2019.

[44] A. Verma, A. K. Singh, N. Srivastava, S. Patil, and B. K. Kanaujia, "Hexagonal ring electromagnetic band gap- based slot antenna for circular polarization and performance enhancement," Microwave and Optical Technology Letters, vol. 62, pp. 2576-2587, 2020.

[45] K. Yu, Y. Li, and Y. Wang, "Multi-band metamaterial-based microstrip antenna for WLAN and WiMAX applications," in 2017 International Applied Computational Electromagnetics Society Symposium-Italy (ACES), 2017, pp. 1-2.

[46] P. Sambandam, M. Kanagasabai, S. Ramadoss, R. Natarajan, M. G. N. Alsath, S. Shanmuganathan, et al., "Compact monopole antenna backed with fork-slotted EBG for wearable applications," IEEE Antennas and Wireless Propagation Letters, vol. 19, pp. 228-232, 2019.

[47] M. Zada, I. A. Shah, and H. Yoo, "Metamaterial-loaded compact high-gain dual-band circularly polarized implantable antenna system for multiple biomedical applications," IEEE Transactions on Antennas and Propagation, vol. 68, pp. 1140-1144, 2019.

[48] R. Rajkumar and K. U. Kiran, "A compact metamaterial multiband antenna for WLAN/WiMAX/ITU band applications," AEU-International Journal of Electronics and Communications, vol. 70, pp. 599-604, 2016.

[49] S. Dakhla, H. Rmili, J. M. Floc'h, M. Sheikh, A. Dobie, K. Mahdjoubi, et al., "Printed multiband metamaterial- inspired antennas," Microwave and Optical Technology Letters, vol. 58, pp. 1281-1289, 2016.

[50] T. N. Cao and W. J. Krzysztofik, "Fractal antenna of MIMO system WLAN," 2018.

[51] M. Shalini and M. G. Madhan, "Design and analysis of a dual-polarized graphene-based microstrip patch antenna for terahertz applications," Optik, vol. 194, p. 163050, 2019.

[52] H. Tao, W. J. Padilla, X. Zhang, and R. D. Averitt, "Recent progress in electromagnetic metamaterial devices for terahertz applications," IEEE Journal of Selected Topics in Quantum Electronics, vol. 17, pp. 92-101, 2010.

[53] V. Kotov, V. Shavrov, M. Vasiliev, K. Alameh, M. Nur-E-Alam, and D. Balabanov, "Properties of magnetic photonic crystals in the visible spectral region and their performance limitations," Photonics and Nanostructures-Fundamentals and Applications, vol. 28, pp. 12-19, 2018.

[54] T. Khajawal, Q. Rubin, A. Rajawat, and S. H. Gupta, "Performance Analysis and Optimization of Band Gap of Terahertz Antenna for WBAN Applications," Optik, p. 167387, 2021.

[55] S. Azam, M. A. K. Khan, T. A. Shame, and A. Z. Khan, "GGraphene-based circular patch terahertz antenna using novel substrate materials," in 2017 6th International Conference on Informatics, Electronics and Vision & 2017 7th International Symposium in Computational Medical and Health Technology (ICIEV-ISCMHT), 2017, pp. 1-6.

[56] R. Goyal and D. K. Vishwakarma, "Design of a graphene‐ based patch antenna on glass substrate for high‐ speed terahertz communications," Microwave and Optical Technology Letters, vol. 60, pp. 1594-1600, 2018.

[57] S. Shamim, M. S. Uddin, M. R. Hasan, and M. Samad, "Design and implementation of miniaturized wideband microstrip patch antenna for high-speed terahertz applications," Journal of Computational Electronics, vol. 20, pp. 604-610, 2021.

[58] R. Bala and A. Marwaha, "Investigation of graphene-based miniaturized terahertz antenna for novel substrate materials," Engineering Science and Technology, an International Journal, vol. 19, pp. 531-537, 2016.

[59] S. Gotra, G. Varshney, R. S. Yaduvanshi, and V. S. Pandey, "Dual‐ band circular polarisation generation technique with the miniaturization of a rectangular dielectric resonator antenna," IET Microwaves, Antennas & Propagation, vol. 13, pp. 1742-1748, 2019.

[60] H. A. Abdulnabi, M. A. Shuriji, and S. Ahmed, "UWB THz plasmonic microstrip antenna based on graphene," Telkomnika, vol. 18, pp. 30-36, 2020.

[61] R. K. Kushwaha, P. Karuppanan, and L. Malviya, "Design and analysis of novel microstrip patch antenna on the photonic crystal in THz," Physica B: Condensed Matter, vol. 545, pp. 107-112, 2018.

[62] F. Kazemi, "Dual-band compact fractal THz antenna based on CRLH-TL and graphene loads," Optik, vol. 206, p. 164369, 2020.

[63] G. Varshney, "Ultra-wideband antenna using graphite disk resonator for THz applications," Superlattices and Microstructures, vol. 141, p. 106480, 2020.

[64] F. B. Zarrabi, M. M. Seyedsharbaty, Z. Ahmed, A. S. Arezoomand, and S. Heydari, "Wideband yagi antenna for terahertz application with graphene control," Optik, vol. 140, pp. 866-872, 2017.

[65] S. Singhal, "CPW Fed Jasmine shaped super wideband Terahertz antenna for pattern diversity applications," Optik, vol. 231, p. 166356, 2021.

[66] G. B. Wu, Y.-S. Zeng, K. F. Chan, S.-W. Qu, and C. H. Chan, "High-gain circularly polarized lens antenna for terahertz applications," IEEE Antennas and Wireless Propagation Letters, vol. 18, pp. 921-925, 2019.

[67] M. Alibakhshikenari, B. S. Virdee, C. H. See, R. A. Abd-Alhameed, F. Falcone, and E. Limit, "High-Gain Metasurface in polyimide on-chip Antenna Based on cRLH-tL for Sub-terahertz integrated circuits," Scientific reports, vol. 10, pp. 1-9, 2020.

[68] M. A. K. Khan, M. I. Ullah, R. Kabir, and M. A. Alim, "High-performance graphene patch antenna with superstrate cover for terahertz band application," Plasmonics, vol. 15, pp. 1719-1727, 2020.

[69] N. S. Badr and G. Moradi, "Graphene-Based microstrip-fed hexagonal shape dual band antenna," Optik, vol. 202, p. 163608, 2020.

[70] I. Nadeem and D.-Y. Choi, "Study on mutual coupling reduction technique for MIMO antennas," IEEE Access, vol. 7, pp. 563-586, 2018.

[71] A. S. Dixit and S. Kumar, "A survey of performance enhancement techniques of antipodal Vivaldi antenna," IEEE Access, vol. 8, pp. 45774-45796, 2020.

[72] W. A. Ali and A. A. Ibrahim, "A compact double-sided MIMO antenna with an improved isolation for UWB applications," AEU-International Journal of Electronics and Communications, vol. 82, pp. 7-13, 2017.

[73] M. Li, L. Jiang, and K. L. Yeung, "Novel and efficient parasitic decoupling network for closely coupled antennas," IEEE Transactions on Antennas and Propagation, vol. 67, pp. 3574-3585, 2019.

[74] X. Shen, Y. Liu, L. Zhao, G.-L. Huang, X. Shi, and Q. Huang, "A miniaturized microstrip antenna array at 5G millimeter-wave band," IEEE Antennas and Wireless Propagation Letters, vol. 18, pp. 1671-1675, 2019.

[75] N. O. Parchin, Y. I. A. Al-Yasir, A. H. Ali, I. Elfergani, J. M. Noras, J. Rodriguez, et al., "Eight-element dual-polarized MIMO slot antenna system for 5G smartphone applications," IEEE Access, vol. 7, pp. 15612-15622, 2019.

[76] A. Dadgarpour, M. S. Sorkherizi, and A. A. Kishk, "High-efficient circularly polarized magnetoelectric dipole antenna for 5G applications using dual-polarized split-ring resonator lens," IEEE Transactions on Antennas and Propagation, vol. 65, pp. 4263-4267, 2017.
[77] P. A. Dzagbletey and Y.-B. Jung, "Stacked microstrip linear array for millimeter-wave 5G baseband communication," IEEE Antennas and Wireless Propagation Letters, vol. 17, pp. 780-783, 2018.
[78] Q. Zhu, K. B. Ng, C. H. Chan, and K.-M. Luk, "Substrate-integrated-waveguide-fed array antenna covering 57–71 GHz band for 5G applications," IEEE Transactions on Antennas and Propagation, vol. 65, pp. 6298-6306, 2017.
[79] D. Q. Liu, M. Zhang, H. J. Luo, H. L. Wen, and J. Wang, "Dual-band platform-free PIFA for 5G MIMO application of mobile devices," IEEE Transactions on Antennas and Propagation, vol. 66, pp. 6328-6333, 2018.
[80] L. Xi, "A wideband planar filtering dipole antenna for 5G communication applications," Microwave and Optical Technology Letters, vol. 61, pp. 2746-2751, 2019.
[81] J. Park, M. Jeong, N. Hussain, S. Rhee, S. Park, and N. Kim, "A low- profile high- gain filtering antenna for fifth generation systems based on nonuniform metasurface," Microwave and Optical Technology Letters, vol. 61, pp. 2513-2519, 2019.
[82] M. S. Sharawi, S. K. Podilchak, M. U. Khan, and Y. M. Antar, "Dual- frequency DRA- based MIMO antenna system for wireless access points," IET Microwaves, Antennas & Propagation, vol. 11, pp. 1174-1182, 2017.
[83] A. K. Vallappil, M. K. A. Rahim, B. A. Khawaja, and M. N. Iqbal, "Compact Metamaterial Based $4\times4 $ Butler Matrix with Improved Bandwidth for 5G Applications," IEEE Access, vol. 8, pp. 13573-13583, 2020.
[84] Z. Yang, J. Xiao, and Q. Ye, "Enhancing MIMO antenna isolation characteristic by manipulating the propagation of the surface wave," IEEE Access, vol. 8, pp. 115572-115581, 2020.

Danladi Agadi Tonga, et. al. "A Comprehensive Review of Antenna Design using Metamaterial Techniques in 6G Wireless Communication System: Specifications and Challenges." *IOSR Journal of Engineering (IOSRJEN),* 13(1), 2023, pp. 24-37.