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TOPICAL REVIEW

Review of Recent Advancement on Nature/Bio-Inspired Antenna Designs

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ABSTRACT This article presents an extensive examination of antennas rooted in nature and biology, showcasing their remarkable performance across a wide spectrum of frequencies—from microwave to terahertz. The limitations of traditional antenna design have become increasingly evident in the face of burgeoning demands for novel communication technologies. Conventional analytical-equation-based approaches struggle to deliver the combined performance characteristics – encompassing bandwidth, gain, radiation pattern, and miniaturization – that emerging technologies necessitate. This has fueled an interest in bio-inspired antenna designs, a paradigm shift drawing inspiration from the ingenious structural solutions found in the living and non-living world, from plant leaves to bird feathers. These bio-inspired designs offer distinct advantages such as broader bandwidth and reduced sizes, making them highly appealing alternatives to the limitations of conventional antenna designs. This review explores a diverse range of bio-inspired designs. Among them are fractal geometries, inspired by self-repeating patterns in nature, which achieve optimal performance. Numerous designs in this category draw inspiration from nature, incorporating patterns observed in snowflakes, tree branches, clouds, and butterflies. Furthermore, nano-antennas have attracted significant attention for their vast potential applications in microwave and optical frequencies, playing a pivotal role in high-resolution spectroscopy, biomedical diagnosis and sensing, quantum photonics, and solar cell applications. By examining design methodologies and potential benefits, this article highlights the transformative potential of nature-inspired antennas. The compelling advantages of bio-inspired approaches necessitate a thorough exploration of their potential, paving the way for the development of next-generation communication systems with unprecedented capabilities.

INDEX TERMS Bio-inspired antennas, nano antennas, wearable antennas, fractal antennas.

I. INTRODUCTION

The rapid development of wireless technologies has significantly influenced the performance requirements imposed on modern systems, necessitating a reevaluation of conventional antenna designs. The demands for increased bandwidth, reconfigurability, high directivity, customized radiation patterns, and multiband operation become challenging for conventional antenna designs due to physical space limitations. Consequently, there is a growing reliance on evolutionary strategies in antenna design to ensure compactness, higher performance, and enhanced functionality.

While traditional antenna designs based on basic geometric and alphabetic shapes (triangular, rectangular, circular,

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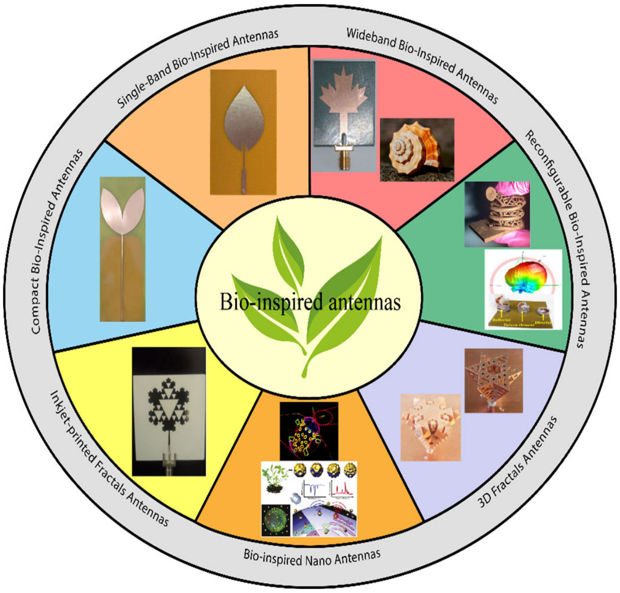

FIGURE 1. Nature/bio-inspired geometries for various antenna design applications.

E, H, U) have served us well, they are increasingly struggling to meet the demands of emerging technologies due to limitations in operating bands, bandwidth, directivity, and size. Researchers have been inspired by nature for technological development in various fields, and they have adopted a similar approach for antenna design [1], [2], [3], [4], [5]. Bio-inspired antenna designs utilize the structure of plants and animals to improve antenna performance, taking advantage of their diversity and evolutionary history. Over the last few years, bio-inspired solutions (Fig.1) have attracted considerable attention from the scientific community [6], [7].

The diversity found in nature, encompassing various forms, shapes, and sizes, inspires researchers to extend the limits of conventional designs toward more sophisticated and robust solutions. Furthermore, the presence of the golden ratio in nature, along with its manifestation in various modern architectures, arts, and designs, serves as additional inspiration for researchers [8], [9]. The golden ratio is a special number that appears in nature and art, creating a sense of beauty and balance when things are divided in a certain way. It is approximately equal to 1.618, represented by the Greek letter phi (Φ), and is derived through mathematical calculations. Additionally, the ratio between consecutive Fibonacci numbers (like 1/1, 2/1, 3/2, 5/3, and so on) approaches a value of 1.618 as one proceeds in taking the ratios of the Fibonacci series. If the ratio of the sum of two quantities to the larger of the two quantities is the same as the ratio of the larger to the smaller quantity, then the two quantities are said to be in the golden ratio. For example, if we add A and B together and then divide that sum by the larger of the two quantities, the result is equal to the ratio of the larger quantity to the smaller quantity, expressed as $(A+B)/A = A/B$ or $(A+B)/B = B/A$. The value that fulfills this condition is approximately 1.618, known as the golden ratio. This golden ratio is also used in many bio-inspired antenna designs. The value that fulfills this condition is approximately 1.618 (golden ratio). This golden ratio is also used in many bio-inspired antenna designs. Moreover, natural vegetation's leaves and branches are arranged efficiently (capture sunlight for photosynthesis), mirroring the Fibonacci number series: 0, 1, 1, 2, 3, 5, 8, 13, 21, and so forth. This series, starting with 0 and 1, generates subsequent numbers by adding the two before it. It is found in various natural phenomena, like flower petals and tree branching patterns. For instance, the trunk typically branches into two main branches, then each of those branches further divides into two more branches, and so on, following to match the numbers in the Fibonacci sequence.

Therefore, numerous design concepts have been proposed built upon this principle [10], [11].

Bio-inspired antenna designs offer several compelling advantages over traditional geometries, but their most striking feature is their significantly higher perimeter-to-area ratio. This allows for more compact antenna footprints, often achieving size reductions of up to 50% compared to conventional designs.

Fig. 2 shows categorization of bio-inspired antennas based on their operational characteristics.

Moreover, fractal geometries [12], [13], [14], inspired by natural occurrences like snowflakes, tree branches, clouds, and butterfly fractals, have been employed to boost gain and broaden bandwidth [1], [15]. These geometries provide a promising avenue for further improvement of antenna performance, particularly in the mm wave range [16].

Modern applications require antennas to operate in higher frequency ranges (5G and mm-wave) to showcase wider bandwidth, compact size, and higher gain. The operating frequency of a microstrip antenna is inversely related to the dimensions of the radiating element. The larger the size, the lower the operating frequency. Therefore, techniques employed for antenna miniaturization primarily focus on optimized geometries that maximize the patch dimension-to-area ratio. Such optimized geometries can be observed in both fauna (all animals) and flora (all plants).

Overall, diverse bio- and nature-inspired antennas, alongside nano antennas, are increasingly influencing the future of wireless communication across microwave, terahertz, and optical frequencies [17], [18], [19].

The utilization of fractal geometries and the integration of the golden ratio in antenna design underscore the potential for bio-inspired solutions to influence the future of wireless communication. As technology continues to evolve and the demand for high-performance systems increases, the prevalence of bio-inspired antennas is likely to grow even further.

In this review article, we delve into the realm of bio-inspired antennas, specifically focusing on the exploration of diverse geometries inspired by natural shapes found in living organisms, particularly plant leaves. Additionally, we categorize all these bio-designed antennas into seven groups based on their intended user requirements. These categories include single-band operation, wideband and multi-band behavior,

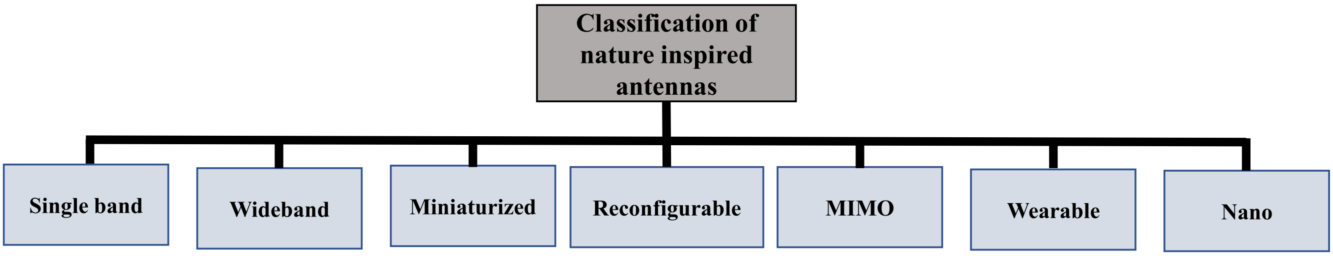

FIGURE 2. Classification of bio-inspired antenna based on operational characteristics.

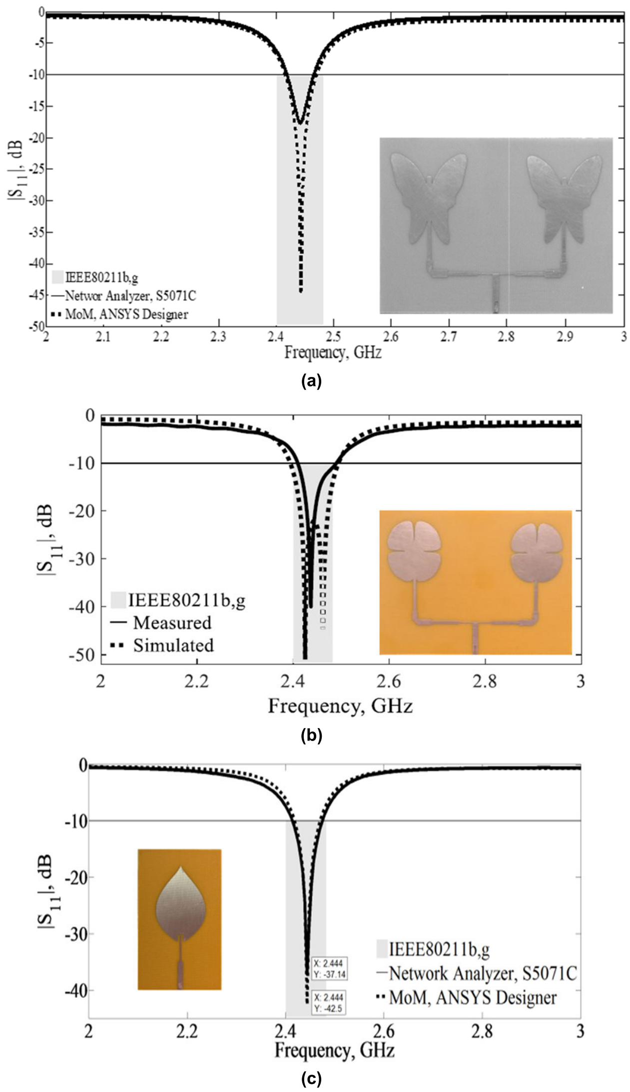

FIGURE 3. Single band and wideband bio-inspired antennas: (a) reflection response of a butterfly-shaped antenna array proposed in [20], (b) reflection coefficient of two element array presented in [21], (c) reflection response of a wayfaring-tree (Viburnum lantana) leaf-shaped antenna reported in [22].

nano antennas, reconfigurable performance, compact size, wearability, and MIMO specifications. We emphasize the advantages of these innovative designs and explore various design methodologies, encouraging further research in this exciting area to meet the growing demands of emerging technologies.

II. BIO-INSPIRED ANTENNAS

A. SINGLE-BAND BIO-INSPIRED ANTENNAS

Drawing inspiration from biological shapes can result in compact antenna designs with larger electrical perimeters, facilitating operation at lower frequencies. Additionally, incorporating dissimilar elements in an array configuration can generate multiple resonances. An example is a butterfly-shaped patch antenna array inspired by biological structures, created using polar transformations, as presented in [20]. This antenna covers the 2.4 GHz wireless local area network (WLAN) band, featuring both similar and dissimilar elements. With a bandwidth of 96 MHz covering the IEEE802.11b/g band, it achieves a maximum gain of 8.64 dBi, a half power beamwidth of 52°, and a front-to-back ratio of 15.21 dB. The reflection coefficient of the antenna is illustrated in Fig. 3(a). In [21], a bio-inspired patch antenna array generated by polar transformation was proposed for 2.4 GHz band applications. Polar transformation is a technique used to ensure accurate and repeatable antenna designs. Based on the four-leaf clover, a plant in the Fabaceae family, dissimilar elements were intentionally incorporated in the array configuration to enhance bandwidth. The prototype array demonstrated a gain of 8.24 dBi and an impedance bandwidth of 81 MHz, as depicted in Fig. 3(b).

The sunlight-capturing properties of leaves have inspired antenna designs that mimic shapes found in nature. In [22], these properties and techniques were employed to propose a bio-inspired patch antenna based on the leaf of the Wayfaring-tree (Viburnum lantana), a European native plant, designed for operation in the 2400-2483.5 MHz range of Wi-Fi and Bluetooth. The antenna was fabricated on a low-cost FR4 substrate, fed by a microstrip line using the hybrid technique with a matching impedance of 50 Ω. The reflection coefficient plot in Figure 3(c) indicates resonance at 2.4 GHz with a bandwidth of 2.5%.

This section has explored the versatility of bio-inspired designs for single-band antenna applications. Butterfly wings and plants have provided fertile ground for inspiration, demonstrating impressive performance parameters like bandwidth, gain, and radiation patterns. While examples presented here focused on the 2.4 GHz band, the principles can

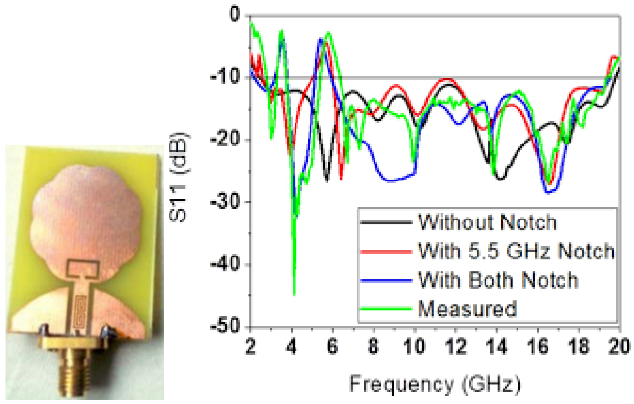

FIGURE 4. **Proposed nature inspired tree shaped antenna photograph, and its S11 graph showing UWB characteristics [28].**

be extended to other frequency ranges. Further research investigating diverse biological structures and incorporating optimization techniques holds immense potential for crafting even more compact and efficient single-band antennas, paving the way for miniaturized communication devices in various applications.

B. WIDEBAND AND MULTIBAND BIO-INSPIRED ANTENNAS

Basic microstrip antennas have inherent narrowband characteristics [23], [24]. However, a few modifications, such as using a thick substrate or adding etched slots, can enable the achievement of ultra-wideband (UWB) characteristics [25], [26], [27]. One approach is to modify the radiating patch, which is typically square, rectangular, or circular, to imitate shapes found in nature, such as those seen in trees or leaves. The modified radiating patch, inspired by natural structures, can excite the antenna within a wide band [7], [28], thus overcoming the narrowband limitations of basic microstrip antennas. Additionally, appropriate modifications of microstrip and printed monopole antennas to bio-inspired structures could result in UWB and multiband characteristics [24]. Multiband responses are valuable in applications where physical space is limited, and the integration of different wireless standards into a single wireless device is necessary. Bio-inspired antenna designs hold the potential for broad bandwidth coverage, resonating at multiple frequencies required by current and future standards. Furthermore, these designs can mitigate interference in UWB systems through notch bands, as demonstrated in [24] and [29], or through frequency reconfiguration [30].

Bio-inspired radiators, featuring modified front and ground planes, hold the potential for ultra-wideband (UWB) applications. One method to generate notch bands at multiple frequencies involves incorporating a split-ring resonator in the bottom part of the radiator and a spiral-shaped defected ground structure. These techniques were applied in [28] o design a nature-inspired microstrip antenna with dual-band notch characteristics for UWB applications, as depicted in Fig. 4. The design concept drew inspiration from the growth pattern of trees and was implemented on a low-cost FR4 substrate with a dielectric constant of 4.4. For UWB

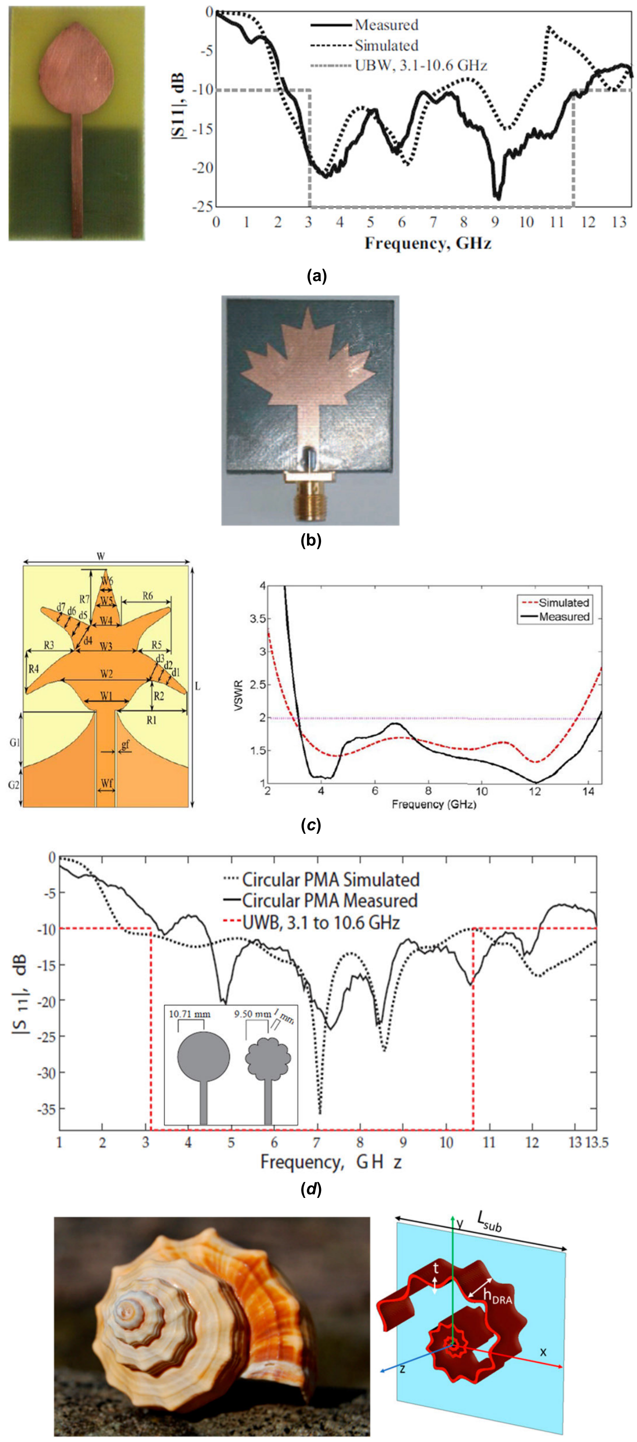

FIGURE 5. **(a) Orchid petal shaped UWB antenna and its simulated reflection coefficient [31], (b) prototype of a maple leaf shaped UWB antenna [32], (c) 5 Volume xx Palmate-leaf-shaped radiator and its VSWR graph [3], (d) Reflection coefficient of Jasmine flower shaped monopole antenna proposed in [33], and (e) Picture of a button snail modulus (spiral seashell), the basis for a bio-inspired spiral shell dielectric resonator antenna (DRA) at sub-6 GHZ, hDRA=29mm [37].**

TABLE 1. Summary of wide band bio inspired antennas with their respective parameters and adpted techniques.

Ref.	Design Approach	Antenna Type	•Operating Frequency (GHz)	Impedance Bandwidth (%)	Feeding Mechanism	Dimen. (mm)	Gain (dB)	Radiation Characteristics
[3]	Palmate leaf	Planar monopole antenna	3–14	129.4	Modified CPW	13.5×14.8 ×0.8	3	N/A
[7]	*Papaya* leaf	Microstrip patch antenna	1.9 –6.2 6.99–7.44 9.15–9.35	106.17/ 6.23/ 2.16	50-Ω microstrip feedline	59.25×35.7	2.60-10.22	Quasi-omnidirectional
[10]	Snail shell	Microstrip antenna.	1–35	188.9	Trapezoidal feedline	40×40×1.6	1.9–5.2	Directional for higher frequencies
[11]	Sneezewort plant	Planar antenna	8.2–16.5	67.2	50-Ω microstrip line	46×18×1.6	5.22	N/A
[28]	Tree shape	Microstrip patch antenna	2.2–19.5	158	Coplanar waveguide (CPW)	28.3×35.3 ×1.6	7.5	Omni-directional
[31]	Orchid petal-shape	Printed monopole antenna	3.1–10.6	109.5	Microstrip line	N/A	5.78	N/A
[32]	Maple leaf shaped	Planar monopole antenna	3–14	129.4	50-Ω microstrip line.	30.48×35.5	N/A	N/A
[33]	Jasmine flower	Printed monopole antenna	3.1–10.6	109.49	Microstrip line	N/A	5.99	Omni-directional
[37]	Spiral shell of a sea mollusk	Dielectric Resonator Antennas (DRAs)	3.5–5.8	44.4	Coaxial cable	100×100	3.7-5	N/A
[38]	Leaf shaped	Two element array	4.2–10.2	83.3	Tapered microstrip line T-junction	100×100	5.3–8.2	Uni-directional
[39]	sprout-leaf shaped	N/A	8.5–14.5	52.17	Broadband microstrip to coplanar stripline (CPS) balun	12.8×15.5	4–5	End-fire

•Operating frequency corresponds to the band where the magnitude of S_{11} is lower than -10 dB, for all the tables.

performance, the ground plane was modified to an elliptical shape, and a rectangular slot was introduced in the bottom ground plane. Notch bands for WiMAX (3.3–3.7 GHz) and WLAN (5.15–5.85 GHz) were introduced by incorporating a split-ring resonator in the bottom part of the radiator and a spiral-shaped defected ground structure in the feed line.

In [7], an innovative bio-inspired antenna design based on the shape of a Papaya leaf was proposed. The design incorporated perturbing a circular patch antenna with a radius of 13 mm to mimic the Papaya leaf structure, resulting in enhanced performance and reduced losses. The expanded bandwidth is attributed to the decrease in losses and the variation in surface current density distribution. Additionally, the perturbation reduces the area covered by the patch from 13 mm to 9.18 mm while optimizing the perimeter.

In [10], Gupta et al. proposed a novel bio-inspired super ultra-wideband spiral microstrip antenna based on the Fibonacci sequence. The antenna achieves super ultra-wideband operation by incorporating a truncated ground plane with semi-circles on both sides of the microstrip feed. The radiating patch, comprising a curved patch fed by a microstrip line, draws inspiration from the spiral patterns found in nature. The application of bio-inspired design techniques has contributed to achieving wideband characteristics while maintaining a compact antenna size. The designs of [7], [10], and [28] exhibit an improved performance, as indicated in Table 1.

Printed monopole antennas have demonstrated promising results for UWB applications with modifications in the patch, ground, or feed. Once again, by drawing inspiration from nature, it becomes possible to enhance the performance of antenna designs. For instance, certain designs have integrated flower shapes to achieve wideband operation while still maintaining a compact size. In particular, printed monopole antennas with bio-inspired shapes such as palmate leaf [3], orchid petal [31], maple leaf [32], and jasmine flower [33] have been proposed and investigated. These designs demonstrate a potential to achieve wideband operation and improve overall antenna performance.

Printed monopole antennas with UWB characteristics can be designed using petal shapes generated by applying the Gielis formula [6], [34], [35], [36], which involves polar transformation of structures like circles, squares, rectangles, or ellipses. An orchid petal-shaped printed monopole antenna was proposed for UWB indoor applications, targeting 4G and WLAN bands [31]. The prototype exhibits UWB characteristics from 3.1 to 10.6 GHz, as shown in Fig. 5(a). The design demonstrates a bandwidth of 9.65 GHz, a gain of 5.78 dBi, and a half-power beamwidth of 108°.

The compact design (30.5 mm × 35.5 mm) was realized on a Rogers Duroid 5880 substrate (dielectric constant of 2.2, thickness of 1.575 mm), as shown in Fig. 5(b). This antenna exhibits an impedance bandwidth from 3 GHz to 14 GHz. To address interference with narrowband systems, two modified designs were proposed in [7], featuring band notches centered around 5 GHz.

Another compact planar monopole antenna, based on a palmate-leaf-shaped geometry, was proposed for UWB applications in [3]. The antenna was fabricated on a 0.8-mm-thick FR4 substrate and the CPW feed line was modified to excite the antenna, as shown in Fig. 5(c). The proposed cuttings in the radiator allowed for an enlarged antenna perimeter, which in turn affected the lower resonant frequency and increased the impedance bandwidth, measured to span from 3 to over 14 GHz (cf. Fig. 5(c)).

In recent years, bio-inspired geometries have seen growing use in wideband antenna design. In [33], a Jasmine flower-inspired geometry with ten petals was applied to circular printed monopole antennas, as depicted in Fig. 5(d), resulting in a size reduction of 11% compared to the circular-shaped antenna.. The measured results showed a –10 dB bandwidth of 9.75 GHz, omnidirectional radiation pattern with a gain of 5.99 dBi, and power spectral density below –41.3 dBm across the UWB band.

To achieve a wider bandwidth at sub-6 GHz, polymer-based 3D antennas have been explored for dual-frequency operation. In [37], a bio-inspired spiral shell dielectric resonator antenna (DRA) was proposed for sub-6 GHz wideband

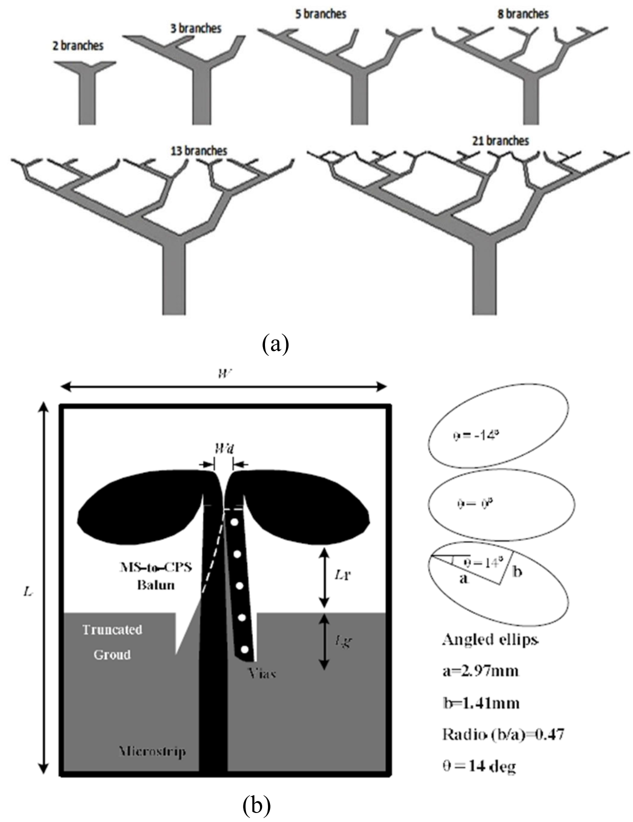

FIGURE 6. (a) Antenna geometry utilizing a pattern of a sneezewort plant [11], (b) prototype of wideband sprout-leaf-shaped antenna [39].

applications. Inspired by the button snail modulus (spiral seashell), as shown in Fig. 5(e), the DRA was positioned at the center of a ground plane, using a dielectric material with a permittivity (εr) of 2.7. The DRA provided a bandwidth of 2 GHz, with gains of 3.7 dBi and 5 dBi at frequencies of 3.5 GHz and 5.5 GHz, respectively. Compared with cylindrical DRA, rectangular DRA, and star-shaped DRA, the bio-inspired spiral shell DRA demonstrated a wider bandwidth and higher gain.

Another unique approach to achieving wideband operation has been reported in [11], which employs the growth pattern of a sneezewort plant with the Fibonacci sequence and golden ratio in branching and branch width respectively. The antenna prototype consists of a substrate sandwiched between a defective ground (defects or slots on the ground plane) and a plant-shaped patch. The full ground is altered to an asymmetric ground with a T-shaped slot. The antenna has a compact size of 46 × 18 mm^2. The radiation performance of the proposed geometry is significantly enhanced by increasing the number of branches to 21 as shown in Fig. 6(a). In general, a higher number of branches contributes to increased surface area. This expanded surface area enhances the radiation and reception of electromagnetic waves, facilitating a more effective transfer of electromagnetic energy. However, it is important to note that there is an upper limit to increasing branches, as the branches are progressively divided. For example, in the case of 21 branches, the branch width of the upper leftmost branch is approximately 0.2 mm, while the upper rightmost branch is approximately 0.3 mm, making further division challenging.

There is a growing demand for UWB antennas with unidirectional radiation characteristics and high directivity in various applications. Such antennas can be realized by utilizing bio-inspired designs. For instance, a bio-inspired leaf-shaped radiator, accompanied by a reflector, and its two-element array version, were reported to exhibit unidirectional UWB behavior [38]. The antenna is comprised of two pairs of leaf-shaped bowtie elements arranged on the upper and lower layers of a 0.76-mm-thick dielectric substrate of permittivity $\varepsilon_r = 2.17$. A copper reflector is used to realize the unidirectional radiation characteristics.

In [39], a sprout-leaf shaped antenna with a wideband and end-fire radiation pattern has been developed by taking inspiration from nature. The antenna's angled radiator was designed to generate radiation patterns with a wide beamwidth, making it appropriate for motion detection sensors. To achieve the end-fire radiation patterns, an extended and truncated ground plane was employed as a reflector. A broadband microstrip (MS) to coplanar stripline (CPS) balun was used to feed the balanced radiator, as depicted in Fig. 6(b). Table 1 summarizes the performance parameters of various bio-inspired wideband antennas, comparing key factors such as impedance bandwidth, dimensions, gain, and radiation pattern characteristics.

Bio-inspired designs have revolutionized the landscape of wideband and multiband antennas. Mimicking nature's ingenuity, these antennas offer several advantages over conventional designs, including enhanced bandwidth, smaller footprints, and the ability to resonate at multiple frequencies. However, this field is not without its challenges. Integrating dissimilar elements in array configurations for wider bands presents design complexities with regard to element optimization and mutual coupling. Addressing these challenges through advanced modeling techniques and innovative feeding methods will be crucial in optimizing the performance and maximizing the potential of bio-inspired antennas for diverse applications.

C. COMPACT BIO-INSPIRED ANTENNAS

An essential consideration in antenna design is ensuring a compact size. In environments with intricate circuitry, space limitations are common, emphasizing the importance of compact antennas. For certain bio-inspired antennas, size reduction is inherent, as demonstrated in [2], [40], and [41]. However, for other designs, additional miniaturization techniques are necessary. For instance, in [42], compact dimensions were achieved using an asymmetric microstrip feedline. Miniaturization of bio-inspired antennas has resulted in improvements in other performance parameters, as demonstrated in numerous studies, including [2], [29], [40], [42], and [43].

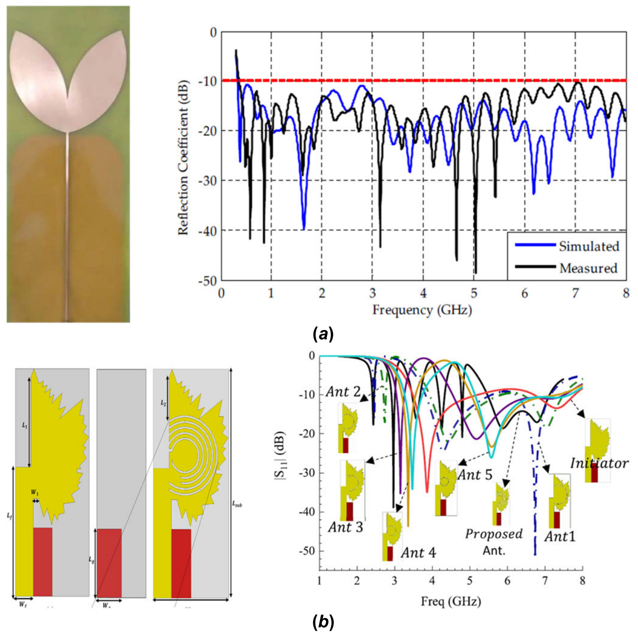

FIGURE 7. **(a) Patch geometry of Inga Marginata leaf with its measured and simulated reflection coefficients [40], and (b) semi-Vitis Vinifera leaf-shaped antenna and its reflection coefficient [42].**

In [40], researchers presented a bio-inspired printed monopole antenna (PMA) with improved performance characteristics in terms of bandwidth, size, gain, radiation pattern, and sensitivity, specifically for detecting partial discharge (PD) activity in high-voltage insulating systems. The use of a truncated ground plane enhanced the bandwidth, while the patch geometry, inspired by the Inga Marginata leaf shown in Fig. 7(a), resulted in a significant size reduction and gain increase. The results demonstrate that the antenna's bandwidth extends from 340 MHz to over 8 GHz. This bio-inspired PMA exhibits potential as a UHF sensor for PD detection, given its omnidirectional radiation pattern, wide bandwidth (300 MHz to 1500 MHz), and gain of over 2 dB.

In [2], a small-size patch antenna inspired by the crop leaf was proposed for wireless sensor network (WSN) applications. With resonant frequencies at 2.4 GHz and 4.1 GHz, this antenna offers 158.9 MHz and 145 MHz impedance bandwidths, making it suitable for agricultural monitoring applications.

The demand for compact size and multi-functionality has spurred exploration into various bio-inspired, such as the compact Hexa-band Bio-inspired antenna for Industrial, Scientific and Medical (ISM) Band, Radar, WiMAX, 5G mid-band, Bluetooth, WLAN, WiMAX, LTE, and Wi-Fi applications proposed in [42]. Illustrated in Fig. 7(b), this antenna, with overall dimensions of $0.35\lambda d \times 0.14\lambda d$, draws inspiration from a semi-Vine-leaf shape and incorporates five arc slits for band notches, enabling multiband performance and further miniaturization. The antenna operates at 2.37 GHz, 3.06 GHz, 3.52 GHz, 4.28 GHz, 4.88 GHz, and 6.0 GHz with a 10 dB fractional bandwidth of 11.97%,

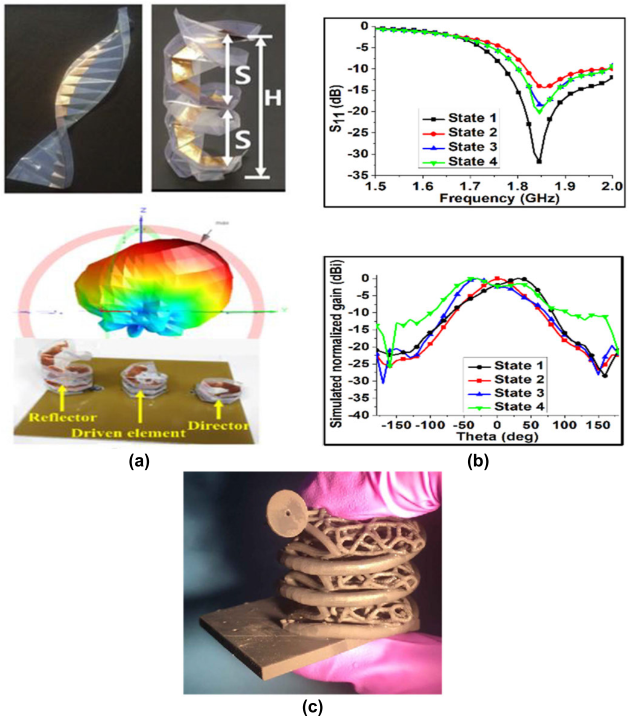

FIGURE 8. (a) Design concept of origami DNA antenna [48], (b) Reflection coefficient and gain plots [48], and (c) an example of origami antennas fabricated using 3D-printing: zigzag with matching circuit, and compressed zipper tube [30].

4.61%, 12.43%, 6.77%, 2.46%, and 11.55%, respectively, and a peak gain of 3.21 dBi.

In [43], a miniaturized monopole antenna with filtering properties was proposed using a leaf-shaped radiating patch. The design features two elliptic-shaped slots on the radiator and a parasitic circle patch on the ground plane to enable a band stop behavior. With a compact size of 20 × 20 × 1 mm^3, the antenna exhibits band rejection properties from 4.2 to 7.2 GHz.

Bio-inspired shapes generated by Gieli's formula result in compact size while maintaining greater perimeters. Utilization of such elements in antenna arrays leads to improved gain and bandwidth.

In [41], a flower-shaped bio-inspired aperture-coupled antenna array for on-chip applications was introduced. The shape is derived using Gielis's formula from a circular shape to enable antenna operation at 60 GHz. The bio-inspired geometry contributes to a compact size, and the two-element array design achieves a maximum gain of 8.82 dBi with a total bandwidth of 5.88 GHz.

Similarly, a compact coplanar waveguide (CPW) antenna resembling the shape of a three-leaf clover was proposed in [29]. With dimensions of 20 × 20 × 1 mm^3 on a 1-mm-thick FR4 substrate and the use of L-shaped slits in the ground plane, the antenna exhibits triple-band operation covering WiMAX, WLAN, and ITS bands.

In the face of ever-shrinking technological landscapes, bio-inspired antenna designs offer a beacon of hope for efficient and miniaturized communication solutions. These natural shapes inherently lend themselves to compactness, while additional techniques like asymmetric feeds and band notches further maximize size reduction. The benefits of this miniaturization are tangible, as evidenced by improved bandwidths, higher gains, and multi-band functionality. However, challenges like element optimization and mutual coupling in array configurations require continued research and development for the full potential of this technology to be unleashed.

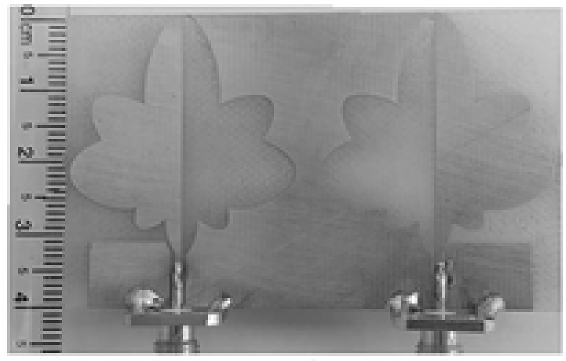

FIGURE 9. Prototype of the proposed two-element MIMO antenna [54].

Table 2 provides an overview of various miniaturized designs of bio-inspired antennas that feature compact sizes. The use of bio-inspired designs has resulted in improved performance, including wider bandwidths, increased gain, and better matching.

D. RECONFIGURABLE AND ORIGAMI BIO-INSPIRED ANTENNAS

Reconfigurable antennas are gaining popularity due to their adaptability to various operating conditions. These antennas can be categorized based on their switching abilities, encompassing frequency, radiation pattern, and polarization reconfigurability. Fundamental techniques like PIN diodes, RF-MEMS switches, and optical switches are employed for achieving reconfigurability [44], [45], [46], [47]. In addition to these conventional methods, there is a growing exploration of nature-inspired structures for designing reconfigurable antennas that offer stability, robustness, flexibility, foldability, and deployability.

One interesting approach to design of reconfigurable antennas is to use the principles of origami. Origami antennas have the unique ability to be folded and unfolded, which can be leveraged to achieve reconfigurability. For instance, a quasi-Yagi helical antenna featuring beam direction and beamwidth switching capability was presented in [48] based on the transformable origami DNA, which was inspired by the DNA of a living cell. The antenna structure comprises three origami DNA geometries, depicted in Fig. 8(a), and was fabricated using a copper film on a folded polyethylene terephthalate (PET) substrate with dimensions of 300 × 53 mm^2. By folding and unfolding the parasitic elements, the antenna's beam direction and beamwidth could

TABLE 2. Summary of miniaturized/compact bio inspired antennas with their respective parameters and adopted design techniques.

Ref.	Design Approach	Antenna Type	Feeding Mechanism	Operating Frequency (MHz/GHz)	Fractal BW (%)	Dimensions (mm)	Electrical length	Gain (dB)	Radiation Characteristics
[2]	Crops leaf	Printed monopole antenna	Microstrip feed line	2.3–2.5 & 4.03–4.3	8.33 & 6.59	57×47	$0.95\lambda_d \times 0.78\lambda_d$	15.8	Directional pattern
[29]	Three leaf clover	Co-planer wave guide antenna	Compact coplanar waveguide	3.3–3.6, 5.15–5.825, 5.795–6.400, 7.725–8.5	8.7, 12.29, 9.92, 9.55	20×20×1	$0.48\lambda_d \times 0.48\lambda_d$	N/A	H-plane: omnidirectionally, E-plane: Approximately bi-directional
[40]	*Inga Marginata* Leaf	Printed monopole antenna	Microstrip line	340 MHz– above 8 GHz	183.69	360×140	$0.81\lambda_d \times 0.33\lambda_d$	3.58	omni directional radiation pattern
[41]	Flower-shape	Aperture-coupled antenna array	NA	57–64	11.6	NA	$0.85\lambda_d \times 1.09\lambda_d$	8.82	Omni-directional
[42]	Semi-Vine-leaf shape,	Microstrip antenna	Asymmetric microstrip feedline	2.37, 3.06 3.52, 4.28 4.88, 6.0	11.97,4.61, 12.43,6.77, 2.46, 11.55 respectively	30×12	$0.35\lambda_d \times 0.14\lambda_d$	3.21	Bi-directional Omnidirectional
[43]	Leaf shaped radiating patch	Monopole antenna	Microstrip feed line	3.5–10	96.3	20×20×1	$0.49\lambda_d \times 0.49\lambda_d$	3.05	Omni-directional

be controlled, enabling the beam to switch from −40° to +30° in four states. The first three states provide a narrow beamwidth, while the fourth state offers a wide beamwidth at the fixed resonant frequency of 1.85 GHz, as illustrated in Fig. 8(b). This origami antenna design serves as an innovative example of how nature-inspired structures can be harnessed to create reconfigurable antennas with unique properties.

In [49], a novel DNA-inspired origami antenna design has been proposed for frequency reconfigurability, exploring the unique folding/unfolding property of origami structures. This design utilizes low-cost substrates such as PET and 1.6-mm-thick FR4, and has a wide frequency range of operation from 0.395 GHz to 2.5 GHz. The antenna could be deployed in three states: completely folded, partially folded, and unfolded segments, allowing for a tuning range of 145%. The design features compactness, low profile, flexibility, conformity, and robustness for deployment in any mechanical design. The antenna provided good realized gain for the three states, except for the unfolded state due to the small electrical length of the ground.

In [30], a 3D compressible and foldable antenna has been proposed using flexible 3D printing, cf. Fig. 8(c). The reconfigurable origami antenna tree utilizes liquid metal alloy microfluidics and Voronoi origami structures to integrate zigzag and helical 3D antennas. This design offers radiation polarization, and frequency reconfigurability, with minimal interference.

Bio-inspired origami antennas present a compelling alternative to conventional reconfigurable designs. Leveraging nature's ingenuity and the simplicity of folding, these antennas offer unique advantages like adaptability, flexibility, and miniaturization. Origami DNA enable beam switching, while 3D-printed origami structures allow for frequency and polarization reconfigurability. However, challenges remain in optimizing switching mechanisms, addressing parasitic coupling, and ensuring signal integrity across different configurations. Addressing these challenges through advanced modeling techniques and material innovations will be crucial in unlocking the full potential of bio-inspired origami antennas for diverse, real-world applications.

E. MIMO BIO-INSPIRED ANTENNAS

For better performance and space utilization in mm-Wave 5G applications, various geometrical and nature-inspired designs are explored. Generally, MIMO technology has been widely incorporated into various designs, particularly in the context of Sub-6 GHz and higher frequencies (millimeter-wave), showcasing its prevalence and versatility across a spectrum of applications [50], [51]. Wide impedance bandwidth and considerable gain are necessary for smooth communication

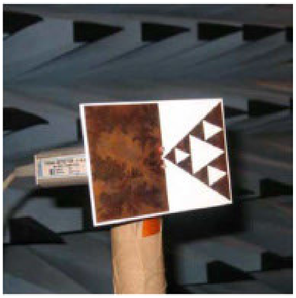

FIGURE 10. **Modified Sierpinski Fractal Gasket physical model [60].**

FIGURE 11. **Cotton leaf-shaped printed monopole antenna (a) The top side and (b) Lower side of the fabricated antenna [61].**

due to high losses at mm-wave band [52], [53]. One example of a flower-shaped MIMO antenna system inspired by nature was proposed in [16]. This antenna was developed on an RT5880 substrate and features a radiating structure with five circular petals and a circular hub connected through a rectangular branch. For achieving a wide bandwidth and optimal gain, a truncated ground plane with a semi-circular shell was incorporated into the design. The MIMO version of this antenna was specifically designed to ensure low mutual coupling and interference between the antenna elements, achieved by utilizing a common ground plane with four semi-circular shells. The overall dimensions of the antenna were 30 mm $\times$ 30 mm.

Another design, a single-sided MIMO antenna inspired by a castor leaf geometry, was proposed in [54]. This design consists of two castor-leaf-shaped quasi self-complementary antennas arranged side by side in a mirror configuration, as shown in Fig. 9. It was fabricated on 0.8-mm-thick FR4 substrate. The antenna exhibits a measured impedance bandwidth of 133.3% (2.6-13 GHz).

Bio-inspired MIMO antennas offer several compelling advantages over conventional designs. Their inherent wide bandwidth and high gain make them ideal for mm-Wave applications, while the use of natural shapes helps optimize space utilization. Additionally, biomimicry techniques can enhance efficiency and diversity gain, leading to improved signal quality and reduced interference. However, challenges remain in achieving optimal isolation between elements and minimizing mutual coupling, particularly in compact MIMO configurations. Addressing these challenges through innovative ground plane designs, advanced feeding methods, and computational optimization will be crucial in unlocking the full potential of bio-inspired MIMO antennas for robust and reliable communication in the mm-Wave era.

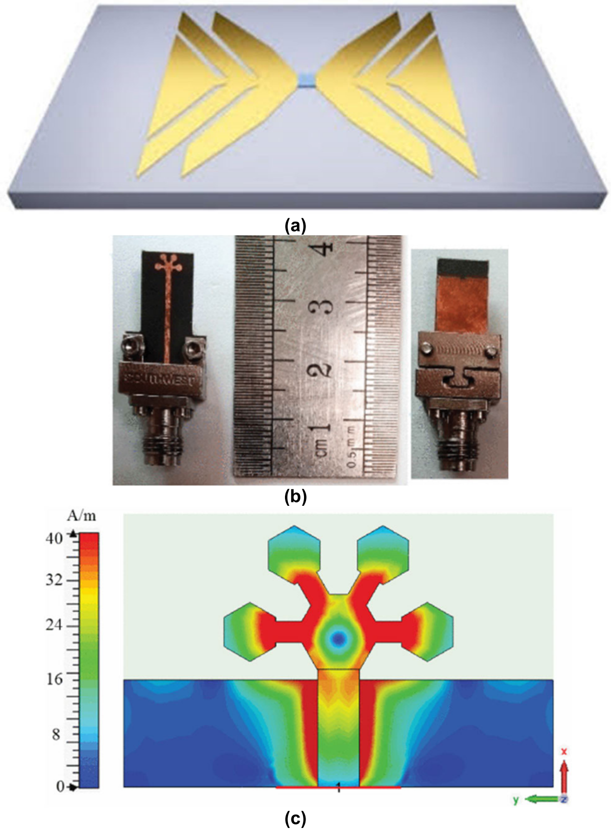

FIGURE 12. **(a) Protype of fractal butterfly antenna [1], (b) snowflake-shaped dual-beam wideband antenna prototype, and (c) snowflake-shaped dualbeam antenna surface current distribution [15].**

III. BIO-INSPIRED FRACTAL ANTENNAS

Fractal antennas belong to a class of nature-inspired geometries that take inspiration from the irregular shapes found in nature, such as leaves, mountains, and blood vessels. These shapes, which defy easy description using classical geometries like lines and polygons, find representation through the concept of fractals. Fractals exhibit self-similarity and space-filling properties, allowing for the exploration and design of antennas with superior radiation characteristics and space utilization. In contrast to Euclidean-shaped antennas, fractal antennas excel in multi-frequency applications and can be designed to be compact for deployment in confined spaces. Their intricate structures are crafted by replicating a base shape, facilitating the design of multiband antennas by leveraging one or more of these properties. Fractal antennas have undergone extensive research, leading to the proposal of various designs optimized for specific operating frequencies and utilizing diverse fractal geometries [55], [56], [57].

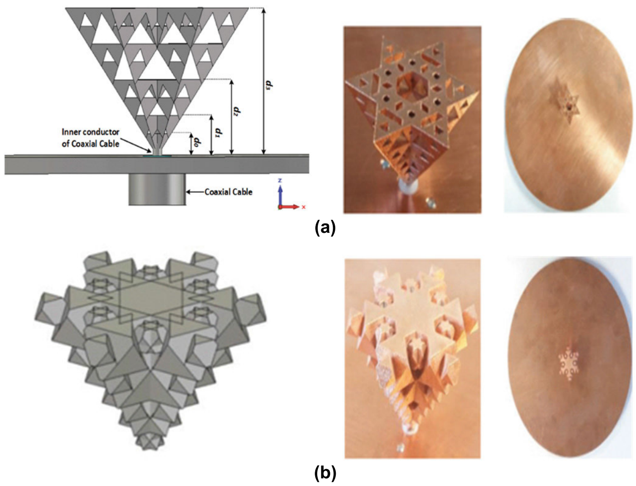

FIGURE 13. Example of 3D printed fractal antennas [69]: (a) fabricated 3D dual-band fractal antenna, 3D view and top view, and (b) fabricated inverse 3D dual fractal antenna, 3D view and top view.

In [58] a comprehensive analysis of various fractal antenna designs has been conducted, exploring the potential of these structures to improve antenna performance. The application of fractals in Frequency Selective Surface (FSS) design was also investigated. Furthermore, various fractal geometries have been compared to Euclidean geometries, concluding that fractal designs are superior in terms of compactness, low profile, and wideband operation.

In [59], a miniaturized Koch monopole antenna was designed using a fractal geometry. The authors conducted numerous iterations and analyzed various parameters associated with the fractals to achieve the optimum design. They also performed parameter tuning to approach the fundamental limit for small antennas. By manipulating complex fractal loops and Koch fractal geometries, it was possible to further reduce the antenna volume. The empirical evidence demonstrated that fractal antennas outperform Euclidean-shaped antennas in terms of radiation characteristics and space utilization.

In [60], a modified Sierpinski fractal monopole antenna, intended for the 2.4 GHz and 5.2 GHz ISM bands, was introduced. The design entails a series of iterations where triangles are etched onto the metallic surface, creating a solid metal part and a hollow etched part, as illustrated in Fig. 10. Through careful control of the space factor between the first two resonances, the proposed design achieves size reduction compared to a traditional Sierpinski antenna. The proposed monopole is shown to be an efficient radiator even without a matching network.

In [61], a fractal bioinspired cotton leaf antenna designed for the UWB band (3 GHz to 13 GHz) has been presented. The antenna features a simple geometry, as shown in Fig. 11, and is designed on a low-cost FR4 substrate. The antenna's matching is improved substantially by etching a rectangular slit in the ground plane, resulting in a better radiation efficiency. The truncated ground helps achieve a wider bandwidth and an omnidirectional radiation pattern due to the reduced current distribution.

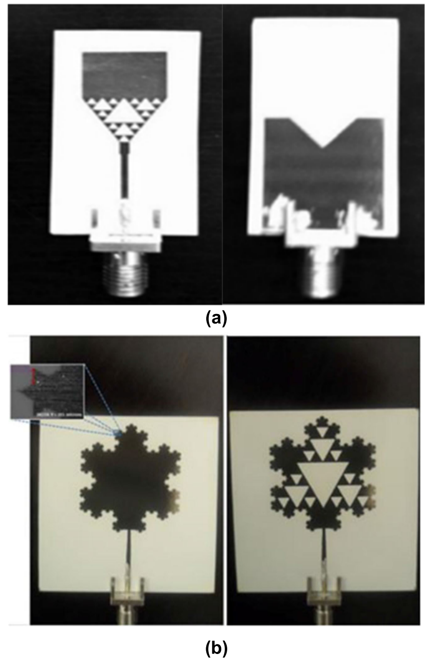

FIGURE 14. Design of the UWB printed monopole antenna [70] (a) top and bottom view, and (b) Koch Snowflake only (left) and Koch Snowflake combined with Sierpinski triangle (right).

A miniaturized butterfly-shaped antenna with wider impedance bandwidth and high gain has been designed in [1] using Koch fractal units. The antenna is designed symmetrically from the center to achieve multiband operation and improved space utilization.

Symmetric fractal geometries constitute a promising approach to achieve dual-beam radiation characteristics in antenna design. By utilizing self-similarity and space-filling fractal properties, compact and wideband antennas can be realized. In a recent study [15], the authors presented a snowflake-shaped dual-beam wideband antenna with impressive wideband characteristics (25 GHz to 28 GHz), illustrated in Fig, 12(a). To achieve dual-beam stability, an inherently symmetric geometry was implemented, featuring a central hexagon and six radiators placed at 60° angular distance from each other. The proposed two-stage fractal design and truncated ground plane enabled wider impedance bandwidth and compactness. The central symmetric design ensured that the current on each radiator is a mirror image of the other. It can be seen from Fig. 12(b), that the left- and right-hand side current distributions are mirror images of each other, thereby allowing an antenna to have a balanced dual-beam property.

Bio-inspired fractal antennas present a compelling alternative to conventional designs, offering a unique blend of performance and miniaturization. Their space-filling nature allows for compact antennas with wideband functionality and improved radiation efficiency. Additionally, the ability to tailor fractal shapes enables multi-band operation and customization for specific applications. However, challenges remain in accurately predicting the properties of complex fractal geometries and optimizing them for desired performance. Addressing these challenges through advanced modeling techniques, and computational tools will be crucial in unlocking the full potential of bio-inspired fractal antennas for robust and reliable communication across diverse frequency bands.

A. THREE-DIMENSIONAL (3D) FRACTAL ANTENNAS

Additive manufacturing (AM), commonly known as 3D printing, has gained widespread adoption in various industries [62], [63], [64], and the antenna community is no exception to this trend [65], [66], [67], [68]. Fractal geometries such as Sierpinski, Koch, Hilbert, or Peano curves can be readily manufactured using 3D printing. The AM technique enables the reduction of overall antenna volume, as less material is utilized, leading to cost savings without compromising the electrical properties of the antenna. Moreover, 3D printing is well-suited for the fabrication of bio-inspired structures with complex geometries that are difficult to manufacture using conventional techniques.

An example of a dual-band 3D fractal monopole antenna designed using AM technique is presented in [69], as shown in Fig. 13(a) and Fig. 13(b). The 3D fractal and inverse fractal cover both 2.4 GHz and 5.5 GHz WLAN frequencies. By utilizing AM, the design offers greater flexibility, maneuverability, and mechanical strength compared to subtractive techniques. The 3D fractal design exhibits better impedance matching and overall design flexibility, enabling the antenna to achieve monopole-like radiation patterns at both frequency bands. 3D fractal antennas are suitable for a range of commercial and military applications due to their compact size, design flexibility, and excellent electrical performance.

B. INKJET-PRINTED FRACTALS ANTENNAS

Inkjet printing technology provides an effective means to fabricate complex geometries that are difficult to produce using conventional fabrication methods, including fractal antennas. In [70], a paper-based inkjet printed fractal antenna with ultra-wideband (UWB) capability was proposed and developed through a series of steps. Initially, a small UWB monopole with a fractal-tapered matching network was designed, as illustrated in Fig. 14(a). Subsequently, two fractal geometries, namely a fourth-order Koch snowflake and a third-order Sierpinski gasket, were amalgamated into a single monopole design, as shown in Fig. 14(b). The resulting combined fractal design proved to be cost-effective, robust, and compact due to the implementation of fractal geometries. The design exhibited wide impedance bandwidth and stable radiation characteristics, positioning it as an ideal candidate for UWB applications. The inkjet printing technique offers significant advantages over traditional fabrication methods, enabling the realization of intricate designs with ease and cost-efficiency.

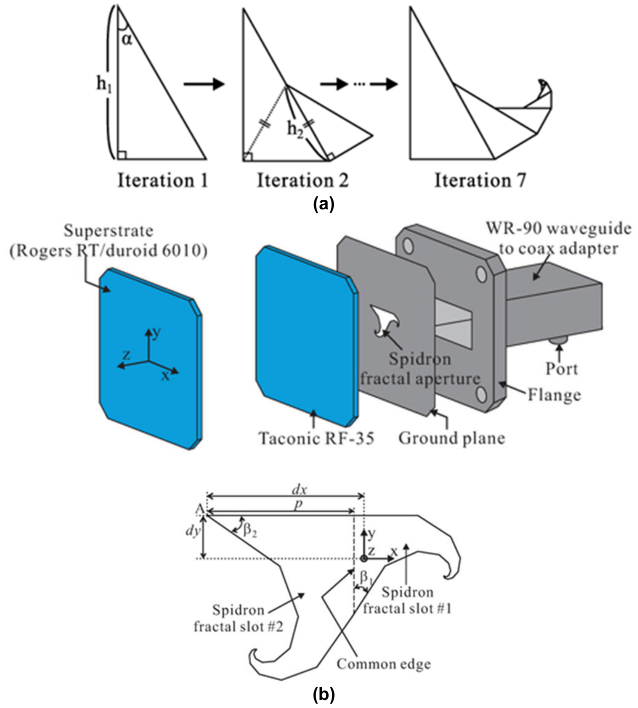

FIGURE 15. (a) Semi-spidron fractal system [72], and (b) antenna's 3-D view and spidron fractal aperture [73].

C. CIRCULARLY POLARIZED FRACTAL ANTENNAS

Combining two fractal geometries can enhance antenna performance, and this concept has been successfully demonstrated for simple microstrip antennas in [71]. Specifically, the authors proposed a proximity-fed dual-layer microstrip antenna incorporating the square and Giuseppe-Peano-shape fractal geometries. The amalgamation of these two fractal patches resulted in multiband operation at 1.5 GHz, 2.5 GHz, and 4.9 GHz, circular polarization and miniaturization of the overall design. Circular polarization is induced by generating two orthogonal modes with a 90° phase difference. The Giuseppe Peano teeth fractal with fewer iterations yields a broader 10 dB return loss bandwidth, good circular polarization, and miniaturization compared to conventional geometries.

The proximity-coupled circular polarized antenna resulting from this combination of fractal geometries features three resonant frequencies, a maximum gain of 4.3 dBi, and a 3-dB axial ratio bandwidth at the first, second, and third bands of 30, 40, and 50 MHz, respectively. These results demonstrate a potential of combining fractal geometries to improve multiband operation, circular polarization, and miniaturization in microstrip antennas, making this design promising for various wireless communication applications.

Antennas designed using the semi-spidron fractal system are easy to fabricate and have shown promising performance. The design consists of equilateral and isosceles triangles, where one side of a regular triangle coincides with one of the sides of an isosceles triangle, whereas another side coincides with the hypotenuse of another semi-spidron fractal system,

TABLE 3. Summary of CP fractal antennas with their respective parameters and adopted techniques.

Ref.	Design Approach	Antenna Type	Feeding Mechanism	Operating Frequency (GHz)	Impedance Bandwidth (%)	Dimensions (mm)	Gain (dB)	CP BW for an axial ratio of 3 dB
[71]	Using the Square and Giuseppe Peano Fractals	Microstrip Antenna	Electromagnetic coupling through a microstrip line	1.5, 2.5, 4.9	2.67, 36, 6.33	70×70	2.2-4.3	30, 40 and 50 MHz,
[72]	Fractal slot	Fractal slot antenna	microstrip line	2.58–5.9	78.3	40×40×1.52	4.3	15.2%
[73]	Spidron fractal aperture etched on the ground plane	Aperture Antenna	WR-90 waveguide-to-coax adapter	9.89–11.58	15.74	N/A	8.73-9.59	2.95%

as shown in Fig. 15(a). In [72], the semi-spidron fractal system was utilized to develop a circularly polarized spidron fractal slot antenna that exhibits broadband characteristics. The antenna was implemented on an RF-35 substrate and fed by a 50 Ω microstrip transmission line. The circular polarization bandwidth for an axial ratio less than 3 dB was 15.2% of the antenna in the desired band, and the simulated gain was approximately 4.5 dBi.

In another study [73], a high-gain circularly polarized spidron fractal aperture antenna fed by waveguide was reported. The antenna boasts a wide bandwidth ranging from 9.89 GHz to 11.58 GHz, achieved by merging two spidron fractal slots etched on the ground plane of a Taconic RF-35 dielectric substrate, as depicted in Fig. 15(b). The antenna showed maximum right-hand circular polarization (RHCP) gain of 9.59 dBi and a 3 dB axial ratio bandwidth of 2.9 GHz.

Overall, these results highlight the potential of utilizing semi-spidron fractal systems for designing circularly polarized antennas with broadband characteristics. These antennas are not only easy to fabricate but also find applications in various wireless communication scenarios.

Table 3 presents a comprehensive summary of circular polarized fractal antennas along with the feeding techniques employed to achieve circular polarization.

IV. WEARABLE BIO-INSPIRED ANTENNAS

The use of wearable antennas is becoming increasingly popular due to ubiquity and ever-shrinking size of wireless devices [74]. Wearable antennas are designed to be integrated into everyday clothing for communication purposes, making them an ideal choice for military use and many other sectors [75]. Bio-inspired antennas are a promising option for wearable applications due to their innovative geometries and low profile, particularly those based on plant shapes that offer a large perimeters-to-area ratio for size reduction at low frequencies [76].

One of the main concerns associated with wearable electronics is the leakage caused by direct contact of the radiator with the body. This contributes to the total losses of the antenna and affects its overall performance. To mitigate this concern, a compact bio-inspired electromagnetic bandgap integrated wearable antenna has been proposed [77]. Fabricated on textile material, it measured 22 mm × 12 mm × 0.7 mm at 2.45 GHz. A 2 by 2 uniplanar compact electromagnetic bandgap (UC-EBG) was integrated for isolation from human tissue. The antenna resonated at 2.45 and 5.7 GHz with maximum gain of 5.9 dBi at 2.45 GHz and 10.7 dBi at 5.7 GHz, respectively.

Another study [78] proposed a bio-inspired antenna based on the Gieli's formula and featuring the shape of a ginkgo biloba leaf, see Fig. 16. The antenna was made of a flexible substrate [79] designed for wireless body area networks (WBAN) and provides coverage for 2G, 3G, and 4G systems with an omnidirectional pattern and gain of 3.10 dBi. The impedance bandwidth was 2.7 GHz.

Bio-inspired wearable antennas offer several compelling advantages over conventional designs. Their low profile and adaptability to flexible substrates make them ideal for integration into clothing and accessories. Additionally, the utilization of nature-inspired shapes can facilitate size reduction at low frequencies, crucial for wearable applications. However, challenges remain in minimizing body leakage and optimizing antenna performance while maintaining comfort and flexibility. Addressing these challenges through advanced electromagnetic simulation tools, biocompatible materials, and novel feeding techniques will be crucial in unlocking the full potential of bio-inspired wearable antennas for real-world applications.

V. BIO-INSPIRED NANO ANTENNAS

The demand for high data rates has spurred the evolution of wireless communication into the millimeter and terahertz spectrum, offering potential operating bands from 0.1 to 10 THz [80]. To further enhance communication capabilities, researchers have turned to nano-antennas (Fig. 17(a)), also known as n-antennas, which are nanoscopic rectifier antennas designed to absorb electromagnetic waves of specific wavelengths proportional to the size of the antenna. Introduced by Robert L. Bailey in 1972, nano-antennas operate in the solar spectrum with wavelengths

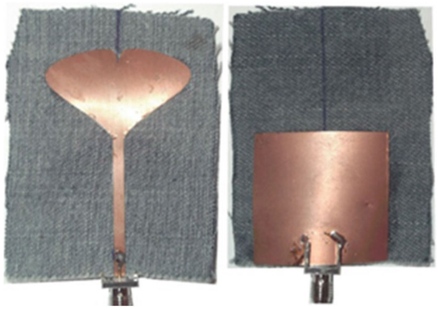

FIGURE 16. Prototype of the bio-inspired ginkgo biloba wearable antenna of [78].

ranging from 0.3 to 2.0μm. Operating on the rectification principle, incoming light strikes the antenna, causing electrons to vibrate at the same frequency, generating strong localized energy in the form of an electrical signal.

Researchers have also explored the use of bio-inspired nano-antennas, which are structures inspired by specific biological shapes. These nano-antennas have shown great potential in enhancing communication capabilities. An optical nano antenna with a maple-leaf-shaped geometry has been presented in [17] for nano photonic applications. The antenna was capable of covering the optical communication wavelength range from 666 to 6000 nm, and utilized a hybrid plasmonic waveguide-based feeding mechanism for energy transfer.

In [18], authors proposed a tree-shaped compact MIMO antenna on a polyimide substrate, renowned for micro-scaling applications due to its chemical resistance, thermal stability, and mechanical toughness. Utilizing graphene and gold as conducting materials, the antenna achieves impressive performance parameters: an impedance bandwidth of 0.435 THz (0.276–0.711 THz, fractional BW $=$ 88.14%) and excellent isolation characteristics (less than -20 dB across the entire working band). The MIMO structure, with a compact size of $600 \times 300 \times 45$ μm^3, demonstrates robust diversity performance (MEG ≤ -3.0 dB, TARC ≤ -10.0 dB, DG $\approx$ 10 dB, CCL $<$ 0.5 bps/Hz/s, and ECC $<$ 0.01), addressing challenges in short-distance communication like signal fading, multipath propagation, and increased interference.

The antenna is useful for high-speed short-range communication in indoor environments, video-rate imaging, biomedical imaging, sensing, and security scanning in the terahertz frequency band. Overall, it offers superior performance and compactness compared to existing THz antenna designs, making it an attractive choice for a variety of applications.

To achieve reconfigurable characteristics in dipole nano-antennas and absorbers, graphene is utilized at THz and optical frequencies due to its ability to enhance the transmittance and absorption characteristics of nano antennas and particles [81]. Additionally, fractal geometries are being developed through mathematical abstraction of similar or

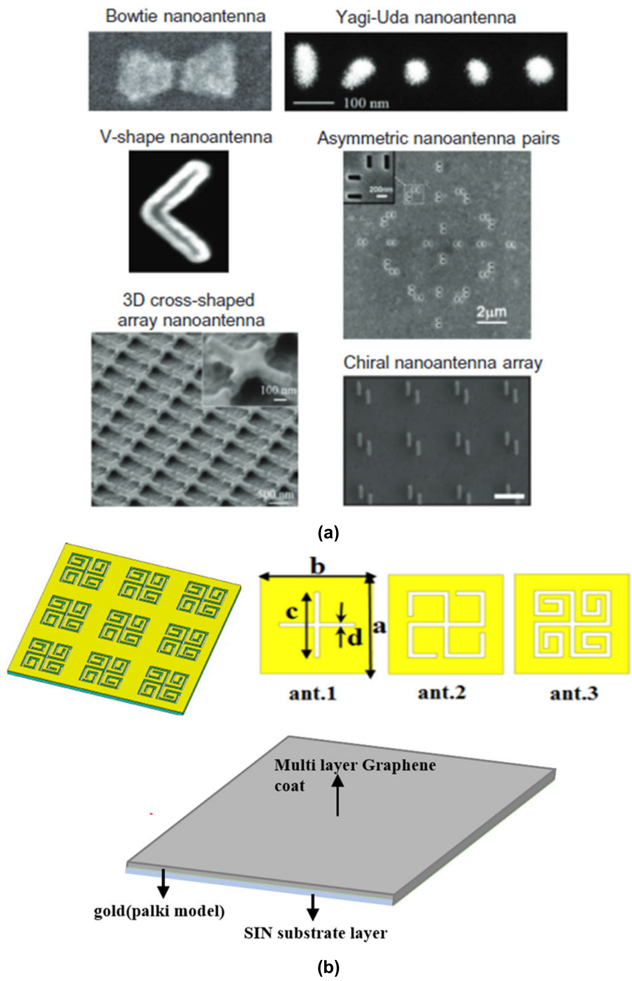

FIGURE 17. (a) Various types of nano antennas, (b) three prototypes of nano antennas designed with the dimensions of a = b = 2400 nm, c = 600 nm, d = 100 nm, as well as the prototype antenna with multilayer graphene [82].

dissimilar designs to improve the radiation quality in nano antennas and particles.

In [82], a novel fractal-shaped nano-antenna with a single-layer graphene coat, depicted in Fig. 17(b), was presented. The prototype proved useful as a highly sensitive sensor, showcasing a dual-band feature in the mid-infrared range at 46 and 86 THz. The graphene layer implementation resulted in enhanced E-field, controllability of the figure of merit (FOM) factor, and polarization invariance. With increased electrical field in both X and Y directions due to the fractal formation, the structure exhibited orthogonal polarization. The antenna's dual-band characteristic at 46 and 86 THz suggests diverse applications, especially in mid-infrared biomedical sensing.

The research presented in [83] introduced a new design for 3D interfacial sensing of small molecules and cellular activities using an insect-inspired heterostructure with antenna-like TiO_2 nanowire arms and nanoporous Prussian blue (PB) nanocube heads. This design draws inspiration from the dual functionality of insect tentacles: signal detection at the tip and

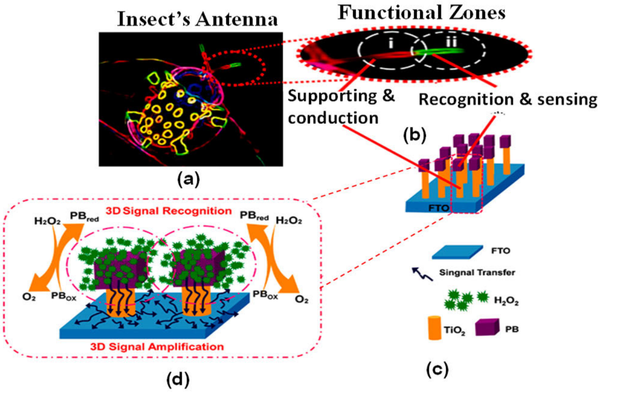

FIGURE 18. Schematic illustration of three-dimensional (3D) signal recognition and amplification based on porous bio-mimetic antenna nanowire arrays: (a) a typical structure of an insect's antennas, (b) enlarged drawing of an antenna illustrating their different functional zones, (c) designed nanoporous bio-mimetic antenna arrays growth on a conducting substrate, and (d) 3D signal recognition and amplification [83].

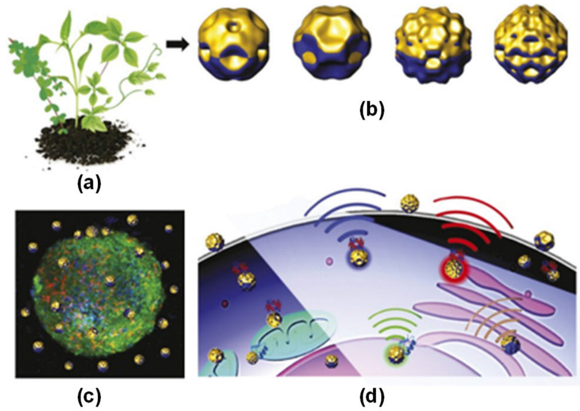

FIGURE 19. Schematic illustrations of the use of gold viruses for molecular imaging: (a) using various plant hosts, (b) generation of gold viruses through gold conjugation. Gold viruses can be envisioned as optical nanosatellites in (c) a biological galaxy such as cellular tissues intracellular spaces, and (d) exhibiting various biomolecular imaging capabilities [19].

transfer via the trunk segment to the neuron networks. To create this heterostructure, the researchers hydrothermally grew TiO_2 nanowires on conducting substrates and then etched PB nanocubes onto the top of the nanowire arrays. The PB nanocubes exhibit high selectivity and sensitivity for hydrogen peroxide (H_2O_2), while the exceptional electron mobility of the TiO_2 nanowires enables fast and efficient charge flow from the PB redox center to the underlying electrode surface. Compared to PB-functionalized planar electrochemical interfaces, the PB-TiO_2 antenna offers several advantages, including a wide detection range from 10^{-8} to 10^{-5} m, a low detection limit of approximately 20 nm, a short response time of 5 seconds, and long-term bio-catalytic activity of up to 6 months. This antenna also exhibits selectivity and bio-affinity toward living cells, making it useful for cell culture adhesion conditions. Figure 18 shows the antenna architecture.

In an attempt to capture and emit light, researchers developed a nano-antenna utilizing short DNA strands, two gold nanoparticles, and a small fluorescent molecule [84]. The inspiration behind this project was to apply the principle used to amplify radio and television signals with antennas to the realm of light. The design included grafting synthetic DNA strands, each 10 to 15 nm in length, with 36 nm-diameter gold particles and a fluorescent organic colorant to create a miniaturized structure. The fluorescent molecule functions as a quantum source, providing photons to the antenna, while the gold nanoparticles amplify the interaction between the emitter and the light.

In a study presented in [19], a novel approach to the development of bio-inspired nanoscale optical antennas was proposed. The research team leveraged the distinctive topologies of plant viruses to craft antennas tailored for molecular absorption and vibration imaging applications. The integration of optical antennas with viruses aimed to extract valuable information by deploying these nanosatellites into living cells. To create the bio-inspired antennas, a thin layer of gold (with a thickness ranging from 2-10 nm) was deposited onto the capsid, which is the protein shell of a virus enclosing its genetic material. Through simulations across different virus types and variations in gold layer thickness and capsid structures, which included both protrusions and smooth surfaces, the team sought to identify optimal antenna designs. Their findings revealed that the careful selection of virus type and metal thickness allowed the fabrication of antennas with a broad spectrum of optical resonances, suitable for diverse sensing applications. Furthermore, the team observed that capsids with protrusions and valleys created more hot spots near the tips of the gold structures, resulting in heightened electromagnetic energy compared to smooth-surfaced nanospheres.

Bio-inspired nano-antennas offer several compelling advantages over conventional designs. Their compact size and biomimetic shapes enable efficient interaction with light and electromagnetic waves at nanoscale wavelengths. These miniature structures boast impressive performance characteristics, including wide bandwidths, high sensitivity, and tunable functionalities. However, challenges remain in the precise fabrication and manipulation of nano-antennas, requiring advanced synthesis techniques and control over material properties. Addressing these challenges through innovative material advancements, computational modeling, and integration with nanotechnology platforms will be crucial in unlocking the full potential of bio-inspired nano-antennas.

Table 4 presents an overview of various bio-inspired nano and wearable antennas, providing details on their feeding mechanism, frequency range, dimensions, gain, and radiation characteristics.

VI. TECHNICAL ANALYSIS OF BIO-INSPIRED ANTENNAS: EXPLORING THEIR ADVANTAGES AND FUTURE PERSPECTIVES

Antennas play a crucial role in modern communication systems, and the demand for smaller, more efficient, and wider

TABLE 4. Summary of nano and wearable bio inspired antennas with their respective parameters and adopted techniques.

Ref.	Design Approach	Antenna Type	Feeding mechanism	Operating Frequency (GHz/ THz)	Fractal BW (%)	Dimensions (mm), (nm)	Gain (dBi)	Radiation Characteristics
[17]	Maple leaf shape	Optical nano-antenna	Hybrid plasmonic waveguide based feed	50–450 THz	160	1600×1600 (nm)	11.4	N/A
[77]	Simi-Vitis vinifera leaf shaped	Electromagnetic bandgap integrated wearable antenna	Asymmetric feedline	2.45,5.7 GHz	4, 15.7	22×12×0.7 (mm)	5.9 at 2.45GHz & 10.7 at 5.7 GHz	Directional
[78]	Ginkgo biloba leaf	Printed monopole antenna		1.80–3.2 GHz	56	N/A	3.10	Omni-directional

bandwidth antennas is rapidly growing. Traditional antennas often face challenges in meeting the requirements of emerging technologies concerning bandwidth, gain, radiation pattern, and size. To tackle these engineering complexities, bio-inspired designs that mimic diverse shapes found in nature emerge as a potential solution, capable of revolutionizing antenna design and delivering superior performance. Bio-inspired shapes, with larger electrical perimeters and operation at lower frequencies, facilitate antenna size reduction, making them a compelling choice for achieving greater miniaturization.

In antenna design, a well-established principle is that the operating frequency of a microstrip antenna is inversely proportional to the dimensions of the radiating element. Therefore, techniques employed for antenna miniaturization aim to identify optimized geometries that maximize the dimension-to-area ratio of the radiating aperture. Bio-inspired shapes derived from plant and animal life forms offer a rich source of inspiration for designing highly optimized and compact structures that deliver exceptional performance.

The golden ratio, widely recognized in natural systems and various contemporary applications, serves as the foundation for the development of bio-inspired antennas. By leveraging this design pattern and order, which resembles the Fibonacci number series, it is possible to improve the radiation efficiency. Fractal antennas mimicking shapes found in nature provide another way to design structures that can achieve optimum performance in pursuit of developing diminutive and multiband antennas. The superiority of fractal geometries in terms of compactness, low profile, and wideband operation is due to their space-filling property and self-similarity property. Devices utilizing these geometries facilitate miniaturization and wider impedance bandwidth, making them highly attractive options for optimizing antenna design.

The demand for high data rates has led to the evolution of wireless communication and exploration of millimeter and terahertz spectrum. One of the options to further enhance communication capabilities is the employment of nano-antennas, including bio-inspired ones.

The efficient light capturing ability of sunflowers and trees has been used to design antennas as well. A sunflower-inspired antenna design [85] was implemented based on the Fibonacci pattern found in a sunflower, while a tree-inspired design [86] was proposed using the distribution of leaves in oak trees. The lotus flower-shaped antenna [87] was designed using inherent inductive and capacitive components to resonate at 30 GHz. Bio-inspired designs have also been used to design ultra-high frequency (UHF) RFID tag antennas for IoT and wearable applications. Mimicking the shapes and structures of birds, butterflies, and leaves has led to reduced antenna size, and improved read ranges over the global UHF RFID frequency band.

The irregular shapes of bio-inspired antennas introduce additional degrees of freedom that contribute to their performance enhancement. These edges create irregularities and discontinuities, which can contribute to a wider frequency response [32]. Additionally, they provide additional surface area for radiation, enhancing the antenna's directivity [17]. Moreover, the irregular edges can create additional current paths, enabling multi-band response [88]. Notably, some bio-inspired antennas, particularly those with fractal geometries, exhibit a balanced dual-beam property due to their symmetrical design and mirrored current distribution [15].

Additionally, the current distribution in these antennas tends to concentrate more around the edges, leading to a longer current path and consequently, a lower resonant frequency. This phenomenon is further explained in reference [88]. The increased current density observed in bio-inspired designs (e.g., in [6] 40.06 A/m^2 compared to 5.86 A/m^2 for a conventional circular patch) further supports this point..

Miniaturized bio-inspired antennas [2], [40], [41] are particularly valuable in space-constrained applications where weight reduction is crucial. This makes them ideal for

TABLE 5. Parametric camparison of conventional microstrip antennas (MSA) with several bio-inspired antennas.

Ref.	Design Approach	Operating Frequency (GHz)	Fractal Bandwidth (%)	Dimensions (mm)	Gain (dBi)
[1]	Butterfly-shaped	100-10,000	196	N/A	16.95
[2]	Crops leaf	2.3–2.5 4.03–4.3	8.33, 6.59	57×47	15.8
[10]	Fibonacci sequence based golden spiral microstrip antenna	1–35	188.9	40×40	1.9–5.2
[28]	Tree shape MSA	2.2–19.5	158	28.3×35.3	7.5
[42]	Semi-Vine-leaf shape Asymmetric microstrip fed antenna	2.37, 3.06, 3.52, 4.28, 4.88, 6.0	11.97, 4.61, 12.43, 6.77, 2.46, 11.55 respectively	30×12	3.21
[89]	Conventional MSA	3.7–4.2	12.9	70×70	N/A
[90]	Conventional MSA	5.7–6.0	5.17	100×100	5.37

implantable medical devices, Internet of Things (IoT) sensors, and compact unmanned aerial vehicles (UAVs). Furthermore, their inherent broadband characteristics make them well-suited for applications requiring extensive coverage, such as radar systems, wireless communication systems, and frequency-hopping spread spectrum applications [10], [78]. Due to their non-standard shapes and intricate designs, bio-inspired antennas can also achieve low radar cross-sections, significantly reducing their visibility. This makes them ideal for applications where minimizing antenna detectability is paramount, such as military aircraft. Additionally, these antennas can demonstrate superior performance with highly directional radiation, making them well-suited for inter- and intra-chip optical communications and sensing applications [17]. In some cases, bio-inspired antennas exhibit higher gain compared to their conventional counterparts [87] while others offer simple structures, making them versatile for a range of applications, including millimeter-wave and satellite communication [85].

Table 5 presents a concise comparison of performance parameters between bio-inspired antennas and conventional MSAs. The results demonstrate that bio-inspired structures outperform conventional patch antennas in terms of bandwidth, size, and gain, while also addressing the limitations of conventional MSAs such as narrow bandwidth, low gain, large size, polarization issues, and surface wave losses.

VII. CONCLUSION

This review comprehensively surveyed the state-of-the-art in bio-inspired antenna design, focusing on plant-inspired geometries optimized for size and multiband functionality, and fractal-based structures leveraging self-similarity and space-filling properties to achieve miniaturization and enhanced radiation characteristics. The growing popularity of these approaches underscores their potential to address the increasingly stringent performance requirements of emerging wireless technologies. As conventional antenna designs approach theoretical limits, bio-inspired solutions may offer a path towards previously unattainable performance characteristics, for instance exceeding bandwidth limitations or achieving unique radiation patterns. This burgeoning field presents a plethora of research avenues for both seasoned and early-career researchers, including the exploration of novel bio-inspired geometries, advanced material integrations, and efficient computational optimization techniques. Further investigation into these areas holds immense promise for revolutionizing antenna design and unlocking the full potential of bio-inspired solutions for next-generation wireless communication systems.

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