Chapter 11

Bio-Inspired Wearable Antennas

Paulo Fernandes da Silva Júnior,
Alexandre Jean René Serres,
Raimundo Carlos Silvério Freire,
Georgina Karla de Freitas Serres,
Edmar Candeia Gurjão,
Joabson Nogueira de Carvalho and
Ewaldo Eder Carvalho Santana

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.75912

Abstract

Due to the recent miniaturization of wireless devices, the use of wearable antennas is steadily increasing. A wearable antenna is intended to be a part of the clothing used for communication purposes. In this way, a lower visual cost may be achieved. Recently, biologically inspired design, a kind of design by cross-domain analogy is a promising paradigm for innovation as well as low visual cost. The shapes of the plants are structures optimized by nature with the primary goal of light energy capture, transforming it into chemical energy. In this case, they have similar behavior to that of parabolic reflectors; this enables microwave engineers design innovative antennas using bio-inspired concepts. One of the advantages of using bio-inspired plant shapes is the design of antennas with great perimeters in compact structures. Thus, we have small antennas operating in low frequencies. This chapter presents the recent development in bio-inspired wearable antennas, easily integrated to the clothes and accessories used by the body, built in denim, low-cost flexible dielectric, and polyamide flexible dielectric, that is flexible with high resistance to twists and temperatures, for wireless body area network (WBAN) applications, operating in cellular mobile (2G, 3G, and 4G) and wireless local area network (2.4 and 5 GHz) protocols.

Keywords: wearable flexible antenna, bio-inspired plant shape, wireless body area network

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1. Introduction

Wireless body area network (WBAN) are sensor networks with elements located in the human body whose mobility and chemical composition impose challenges to wireless communication in such networks. Antennas are crucial elements for such communication and beyond the requirements of gain, directivity and others, for WBAN network wearable antennas as they are named have other important design requirements such as minimum destructive coupling between antenna and body, low visual impact, low-cost, flexible, and compact structure, ease of integration to the clothes and accessories used next to the body [1]. Its applications can be extended for continuous health and sports monitoring, safety, and security of people [2]. Research into development of wearable antennas has used several materials and shapes operating in different resonance frequencies [1–7].

Evolution has permitted animals and natural structures to adjust their behavior and formats to obtain optimum performance in various aspects. Engineering has observed and applied such aspects to solve problems. Examples are genetic algorithms and ant colony optimization. Natural plant leaves present similar characteristics to fractals, as, for example, reduction of dimensions with perimeter increase and also that they have complex and efficient light harvesting-reaction center, that is, an array of antennas capable of operating in the visible light range (400–700 nm) with characteristics analogous to satellite dishes.

The leaves characteristics are well suited to antenna design, including the ones for wearable antennas and this bio-inspiration (leaf-shaped antennas) open a vast research field for more compact and efficient antennas. In this chapter, we use a polar expression developed to represent the geometry of plants and other living beings known as Gielis formula [8] to design wearable antennas operating in cellular mobile systems and WBAN. Antennas were developed for various plant shapes and different substrates, and their superior performance compared to classical antennas developed to the same application is clear.

Projects of the bio-inspired wearable antennas were realized with patch and monopole antennas, built in denim and polyamide, with shapes generated by Gielis formula, for WBAN application operating in WLAN (2.4–2.4835 and 5.4–5.85 GHz), 2G (1.8–2.1 GHz), 3G (1.885–2.17 GHz), and 4G (2.5–2.69 GHz) bands.

2. Bio-inspired antenna design

2.1. Gielis formula

In plants, the process of photosynthesis uses visible light (electromagnetic waves) to produce chemical energy. The leaves have two sections for processing the light, the complex capture centers and the reaction centers. The complex capture centers are formed by an arrangement to perform the highest light energy capture [9]. Thus the leaves act as receiving electromagnetic wave antennas with similar structure to parabolic reflectors, formats of the leaves evolved to give the optimum performance in terms of energy capture; thus for antennas design plants shapes represent a great potential research field. Based on this characteristic, leaf shapes have been used as inspiration in the geometry of antennas via formulation projected to automatically reproduce such shapes as fractal geometry [10], the Fibonacci series, the Gold number [10], and the Gielis formula [8].

The formulation proposed by Johan Gielis in 2003 allows mathematically describing a wide variety of natural and abstract forms, such as leaf and flower shapes. Based on the concept of superellipses given by.

$$\left|\frac{x}{a}\right|^{n} + \left|\frac{x}{b}\right|^{n} = 1 \tag{1}$$

and modifying Eq. (1) considering idea that many natural forms can be interpreted as modified circles, Gielis obtained what is called a superformula (Eq. (2)) by using polar coordinates, replacing $x = r.cos(\theta)$ and $y = r.sin(\theta)$ in addition to inserting the argument $m/4$ to create specific rotational symmetry in some structures, and the possibility of using different values of exponent n for each term (n_1, n_2, n_3).

$$f = f(\theta)\frac{1}{\sqrt[n_1]{\left(\left|\frac{1}{a}\cos\left(\theta\frac{m}{4}\right)\right|\right)^{n_2}\left(\left|\frac{1}{b}\sin\left(\theta\frac{m}{4}\right)\right|\right)^{n_3}}} \tag{2}$$

From this expression, it is possible to generate and modify several shapes by the manipulation of the six parameters (a, b, m, n_1, n_2, n_3).

This expression can also be combined with other functions, (θ), generating other forms. In order to illustrate the possibilities of the Gielis formula some example of shapes can be seen with the respective parameters in **Figure 1**.

In [11] the Gielis formula is used to generate various metamaterial unit cells with resonant frequencies in range of 6–8 GHz. In [5], a wearable textile printed monopole antenna is bio-inspired in *Gingko biloba* leaf shape, generated by Gielis formula with bandwidth of 2.7 GHz, operating in 2G, 3G, and 4G bands.

Patch antennas using the Gielis formula were presented in [12], operating in cellular mobile and WLAN band, built in denim and fiber-glass (FR4). A parametrical analysis of bio-inspired leaf shape of jasmine flower, developed by Gielis formula, in printed monopole antennas with application in ultra-wide band, and X-band frequencies was presented in [13]. A transparent

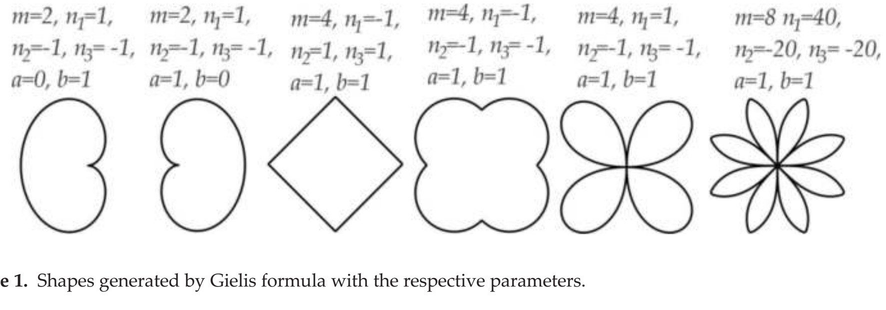

Figure 1. Shapes generated by Gielis formula with the respective parameters.

patch antenna operating in WLAN 5G, with bio-inspired plant shape of *Inga edulis mart* was performed in [14].

2.2. Procedure to design antenna via Gielis formula

Parameters of an antenna, such as resonance frequency, bandwidth, gain and radiation pattern are directly affected by the shape and materials used for its construction. Beyond such characteristics, wearable antennas should preferably have flexible structures for conductive material and dielectric substrate and must be as flat as possible [15]. In addition, characteristics of permittivity and thickness of dielectric substrate are crucial to determine the bandwidth and the antenna efficiency.

The design methodology of bio-inspired antennas in plants generated by the expression of Gielis was adapted from [16] for the design of wearable antennas, and consists of the following 11 steps:

1. Definition of the application;
2. Identification of operating frequencies;
3. Choice of antenna characteristics suitable for the application, broadband or narrowband, type of polarization, among others;
4. Selection of the conductor and dielectric material;
5. Characterization of the properties of the materials, using the technical data informed by the manufacturers or using some available characterization method;
6. Design of an antenna with Euclidean geometry (square, rectangular, or circular) in order to obtain total perimeter of the structure;
7. Selection of the bio-inspired shape between elliptic leaves that have total perimeter closest to the antenna with Euclidean geometry;
8. Generation of the image by the Gielis expression with the use of computer aided (CAD) techniques in a format exportable to the full-wave simulation software;
9. Simulation and optimization of the antenna characteristics, with adjustments to obtain the desired resonance frequency;
10. Construction of the bio-inspired antenna;
11. Validation using measurement and comparison with simulated results.

In order to choose the shapes of the elliptical sheets, in step 7, it may observed that for the patch antenna design, the width of the sheet will follow the same principle of the design of microstrip transmission lines [16, 17]. Thus, the use of substrate with lower thickness (h) and higher relative electrical permittivity (ε_r) will imply the design of smaller width sheets.

For the design of planar monopole leaves having width greater than the length allows the development of antennas with greater bandwidth. The bio-inspired antennas presented in this chapter use symmetrical sheets structures, with the purpose of providing diagrams of broadside radiation, that is, with maximum gain in the axial direction to the axis of the antenna. Depending on the application, non-symmetrical structures can be used.

In the choice of structure with composite sheets we must consider the perimeter identified in the design of the antenna with Euclidean geometry. The objective is to obtain a bio-inspired structure with total perimeter closest to the antenna with Euclidean geometry.

Microstrip patch antennas and monopole antennas are a well-known concept. In the following sections the formulation of bio-inspired shapes using the Gielis formula and the electrical characterization of wearable materials employed to design the antennas are presented.

2.3. Electrical characterization of wearable substrate

Researches in wearable antennas cover medical and non-medical applications, operating in several frequency ranges, and built on various substrates [2, 18–21]. For the development of wearable antennas and other electromagnetic wearable devices, it is crucial to know the electrical characteristics of the flexible substrate used. The objective is to identify the relative permittivity and the loss tangent of the materials. According to [22], the main methods employed to characterize dielectric materials are: coaxial probe, transmission line, free space, resonant cavity, and parallel plates.

The measurement of the flexible materials performed with coaxial probe method is the more popular technique to measure complex dielectric permittivity of many materials. This method is non-destructive, broadband and measurements at high-temperature can be performed with a commercial instrumentation easily available.

In this chapter, design of wearable bio-inspired antennas used two flexible substrates, namely the denim and the polyamide.

Research presented antennas and other devices in textile substrate with applications in different frequency bands. In [23], the performance of textile antenna under two-dimensional crumpling conditions for 2.45 and 5.8 GHz is shown. In [6], a shielded stripline made in textile materials is designed as wearable flexible transmission line for broadband operation until 8 GHz. Denim is porous material with planar structure whose properties are determined by its fiber arrangement, density, volume, and size. Jeans is a fabric of denim that is very thin with a planar dielectric structure.

Polyamide laminate is flexible material with thermal and mechanical resistance characteristics, which has possibility of used in development of the devices for monitoring in situations of high-temperature risks such as monitoring the level of blood oxygenation and cardiac beats in firefighters and workers of metal machining centers. A wearable rectangular patch antenna for medical body area network (MBAN) (2.36–2.4 GHz) built in polyamide was presented in [24].

The dielectric substrates were characterized in the Laboratory of Measurements of the Federal Institute of Paraíba (IFPB), Campus of João Pessoa using a Vector Network Analyzer (VNA) of Agilent model S5071C (300 kHz–20 GHz) and the Dielectric Probe Kit 85070 of Agilent. **Figure 2** shows the electrical characterization measurement setup of the flexible dielectrics used to design wearable antennas, polyamide and denim.

Figure 3 shows dielectric characterization, permittivity and loss tangent, of polyamide and denim substrates. The denim substrate was characterized with $\varepsilon_r = 2.03$, loss tangent of 0.2, and

Figure 2. Electrical characterization measurement setup: (a) polyamide; and (b) denim.

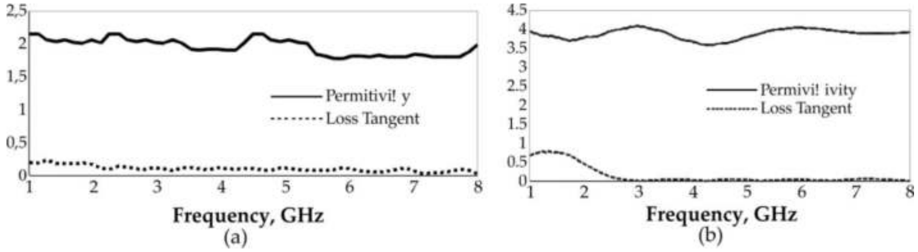

Figure 3. Electrical characterization: (a) denim; and (b) polyamide.

thickness of 1 mm and the polyamide substrate was characterized with $\varepsilon_r = 4$, loss tangent of 0.04, and thickness of 0.05 mm.

3. Bio-inspired wearable antennas

This section presents wearable bio-inspired antennas built in denim and polyamide operating in cellular mobile communication (2G, 3G, and 4G), and WLAN in 2.4 and 5 GHz applications.

3.1. Wearable bio-inspired antennas built in denim

3.1.1. Wearable monopole antenna bio-inspired in jasmine flower shape

The jasmine flower presented in **Figure 4(a)** was the bio-inspiration for antennas operating in mobile cellular system (2G, 3G, and 4G). **Figure 4(b)** presents the simulated antenna and **Figure 4(c)** the simulated ground plane. **Figure 4(d)**, **(e)** presents the implemented antenna front and back respectively. The shape of the jasmine flower was generated by the Gielis formula with value: $m = 8$, $n_1 = -40$, n_2 and $n_3 = 20$, a and $b = 1$.

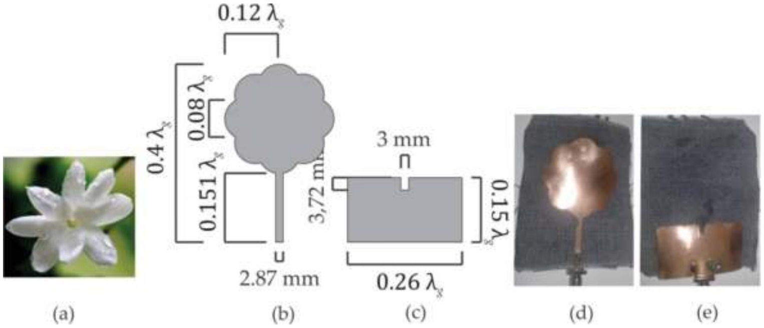

Figure 4. Developed wearable textile monopole antenna bio-inspired in jasmine flower shape: (a) jasmine flower [25]; (b) simulated patch element; (c) simulate ground plane; prototype, front vision (d); prototype, back vision (e).

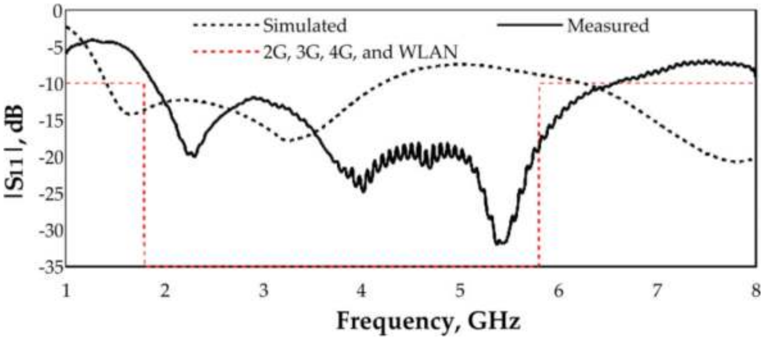

Figure 5. |S11| curves for the simulated and measured (prototype) jasmine flower wearable monopole bio-inspired antenna.

Figure 5 presents curves for the simulated and measured values of $|S_{11}|$ for the jasmine flower bio-inspired antenna parameters of wearable monopole antenna bio-inspired presented in **Figure 4**. In **Figure 5**, the frequency mask for 2G, 3G, 4G, and WLAN 2.4 and 5 GHz band are indicated. The mismatch between the simulated and measured results can be explained by the manufacture process of the antenna. However, a wider band at −10 dB can be observed with the built antenna covering all of frequency bands.

Considering that the projected antenna have to be wearable, it was necessary to perform measurements near the body, as also considering that in certain situations the antenna can be bent. **Figure 6** presents some of the positions for the near body situations, namely on the hand, in the pocket, and on the chest of the prototype proposed. **Figure 7** presents the $|S_{11}|$ curves in each configuration. For comparison, in **Figure 7**, the curve measured was obtained with the antenna in the free space, that is, with the minimum reflections in its neighborhood. It can be noticed when the antenna is close to the body its first resonance frequency modifies, and the highest variation compared to the Measured value (1.9 GHz) occurs with the antenna on the hand

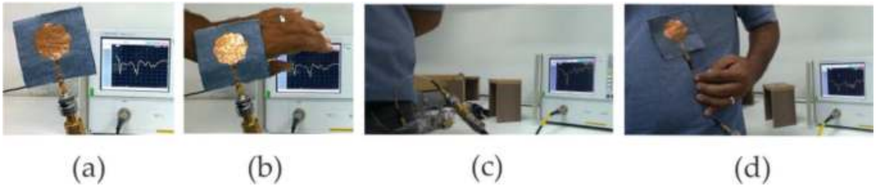

Figure 6. Positions of measurement for the jasmine flower antenna: (a) free space(measured), (b) on the hand, (c) in the pocket, and (d) on the chest.

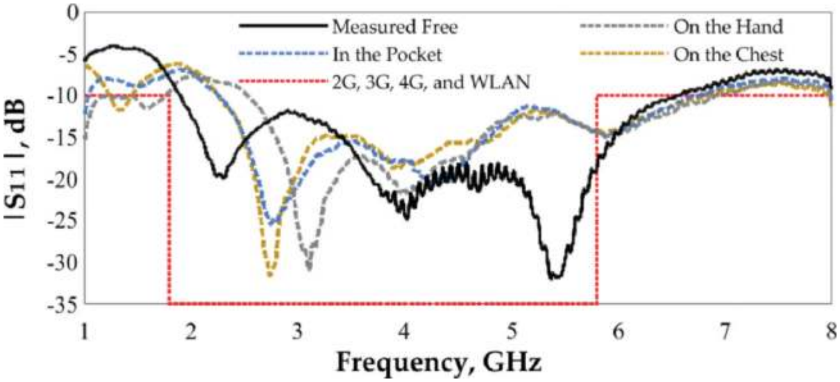

Figure 7. |S11| curves for the simulated and measured (prototype) of the wearable antenna with body interference.

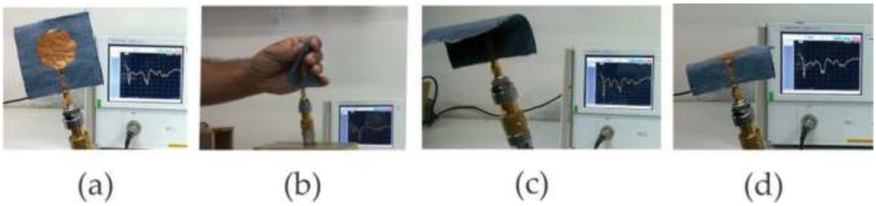

Figure 8. Position of measurement for bending the antenna: (a) free space, (b) creased, (c) forward bended, and (d) backward bended for the jasmine flower wearable antenna.

(2.52 GHz). The permittivity of the various parts of the body can be different according to the percent water and mainly modifying the resonance frequencies in the UHF band.

Another set of measurement considers that the antenna can be bent or even creased as occurs in clothes. **Figure 8(a)** presents the free space, **Figure 8(b)** creased, **Figure 8c)** forward bending, and **Figure 8(d)** backward bending positions. **Figure 9** presents the measured $|S_{11}|$ values for each configuration. Again, the free space (Measured curve) is the reference and it can be noticed that the greatest difference in the first resonance frequency occurs in the forward

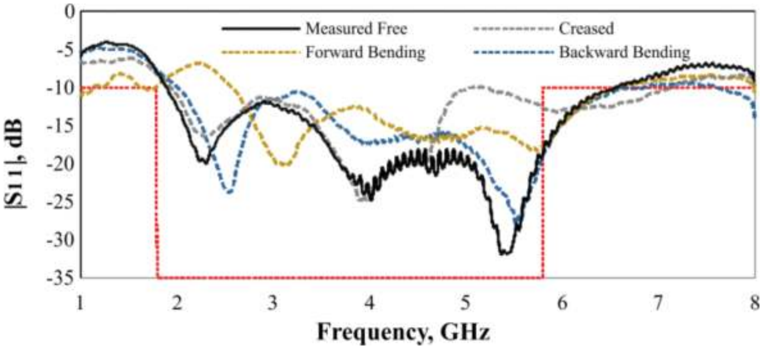

Figure 9. |S11| curves for bending positions of the jasmine flower wearable antenna.

bending configuration and a greater bandwidth (5.21 GHz) is observed in the creased configuration.

The different bending of the antenna generates a discontinuity of the current density on the radiating element, thus modifying its impedance. In spite of that, all the frequency bands are covered except for the forward bending in low frequencies.

In **Table 1** are presented values for the first resonance frequency (f_1), last resonance frequency (f_2) in −10 dB, and bandwidth for the proposed wearable antenna for each configuration presented above.

Observing values in **Table 1** we can notice that the Jasmine wearable antenna simulated, measured free and forward bending presents difference in first resonance frequency (f_1), resonance of 35.26%, and smaller bandwidth of 14.77%. The most significant points are the five similar results, with bandwidth ranging from 4.4 to 4.87 GHz. Only two results are outside these limits, with a bandwidth below of 4 GHz and greater than 5 GHz. It can be observed a difference about 1 GHz between the backward and forward bending that is important information for this kind of wearable antenna.

Antenna	f_1 (GHz)	f_2 (GHz)	Bandwidth (GHz)
Simulated	1.42	4.20	2.78
Measured	1.90	6.57	4.67
On the hand	2.52	6.92	4.40
In the pocket	2.25	6.75	4.50
On the chest	2.25	6.85	4.60
Creased	1.94	7.15	5.21
Forward bending	2.57	6.55	3.98
Backward bending	2.01	6.88	4.87

Table 1. Measured and simulated values of resonant frequencies and bandwidth of the wearable bio-inspired antenna.

The 2D and 3D radiation patterns, gain, half power beamwidth (HPBW), and current density simulated at 3 and 1.6 GHz can be observed in **Figure 10(a)**, **(b)**. The results are according to the Federal Communications Commission (FCC) for a UWB antenna with a gain of 4.2 dBi at 3 GHz, omnidirectional pattern, and a HPBW greater than 75°.

3.1.2. Wearable antenna bio-inspired in Bidens pilosa *plant shape*

In **Figure 11(a)** is presented the *Bidens pilosa* plant that consists of a shape with three elliptical leaves, this format was used as the bio-inspiration for a narrowband wearable antenna that covers the WLAN range at 2.40 GHz (2.40–2.4835 GHz). **Figure 11(b)**, **(c)** present the single leaf and the simulated antenna respectively, and **Figure 11(d)** the prototype antenna.

In the simulation and the prototype the under leaf was inclined at 20°, and the down leaves were inclined at 40° in relation to the geometry of *Bidens pilosa*, in order to provide fine-tuning of the resonance frequency. From the Gielis formula, the leaves were generated with the parameters, $n_1 = 2$, $m = 400$, n_2 and $n_3 = 1200$, a and $b = 1$. The final structure obtained total perimeter of 143.3 mm.

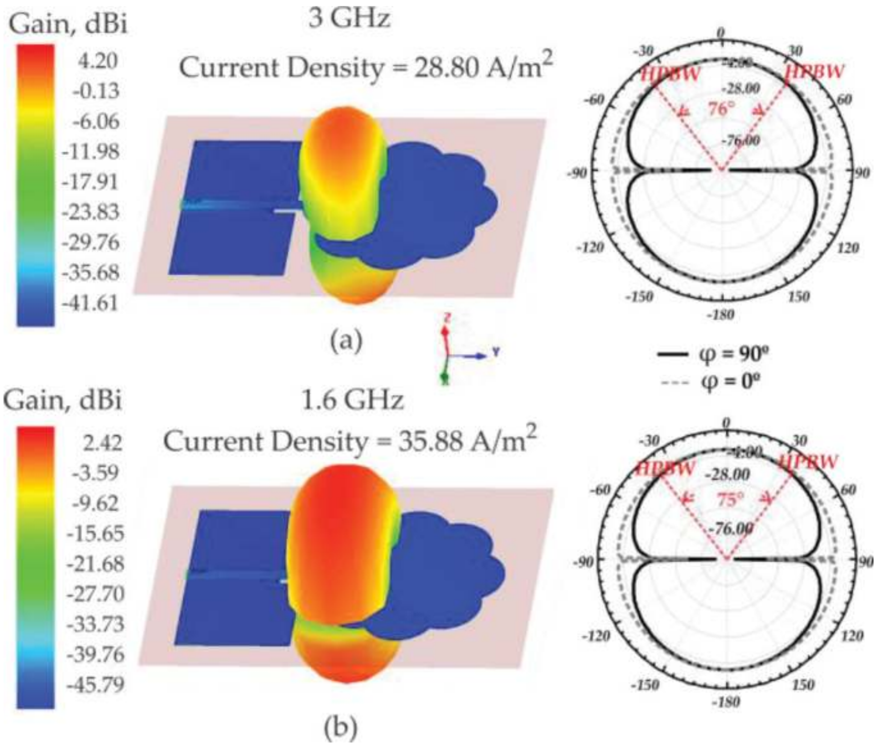

Figure 10. 3D and 2D radiation pattern of wearable textile monopole antenna bio-inspired in jasmine flower shape: (a) 3 GHz; and (b) 1.6 GHz.

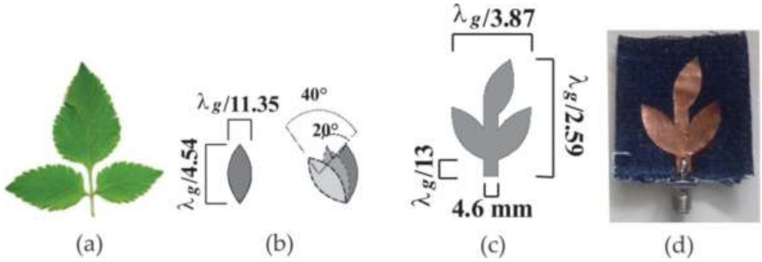

Figure 11. Project of wearable antenna bio-inspired in *Bidens pilosa* plant shape: (a) *Bidens pilosa* leaf [26]; (b) single leaf with inclination; (c) simulated antenna; (d) prototype.

Figure 12. Measurement of prototype of the wearable textile antenna bio-inspired in *Bidens pilosa* plant shape: (a) free space; (b) creased; (c) bended; (d) on the hand.

Figure 12 illustrates the measurements positions of the wearable antenna bio-inspired in *Bidens pilosa* plant shape in anechoic chamber.

Simulated and Measured $|S_{11}|$ curves for the wearable antenna proposed are presented in **Figure 13(a)**. As it can be observed, the simulated and measured values present similar behavior. However the results present a difference of resonance frequency and bandwidth of 1.23% and 74.07%, respectively. The mismatch between the simulated and measured results can be explained by the manufacture process of the antenna and the dielectric permittivity variation of denim. Denim is a product used in the manufacture of clothing, that is, was not prepared by the factory to be used as a dielectric substrate in the construction of antennas. Difference in tenths of the dielectric permittivity may contribute to variations in MHz in the resonant frequency.

Figure 13(b) presents the measured $|S_{11}|$ curves to each configuration illustrated in **Figure 12**. The greatest difference for resonance frequency and bandwidth (14.28%) appears with the wearable antenna on the hand, but still fully covering the WLAN band. The different bending of the antenna generates a discontinuity of the current density on the radiating element thus modifying its impedance and return loss. The greater difference is observed with the antenna close to the hand with the modification of the ground plane characteristic.

Values of bandwidth (BW), resonance frequency (f_0), first (f_1) and last (f_2) resonance at −10 dB are presented in **Table 2**. The mismatch between the measured and simulated results can be explained by the rudimentary manufacture process. However, all measured results are coherent and demonstrate a certain immunity of the antenna when creased, bent, or close to the

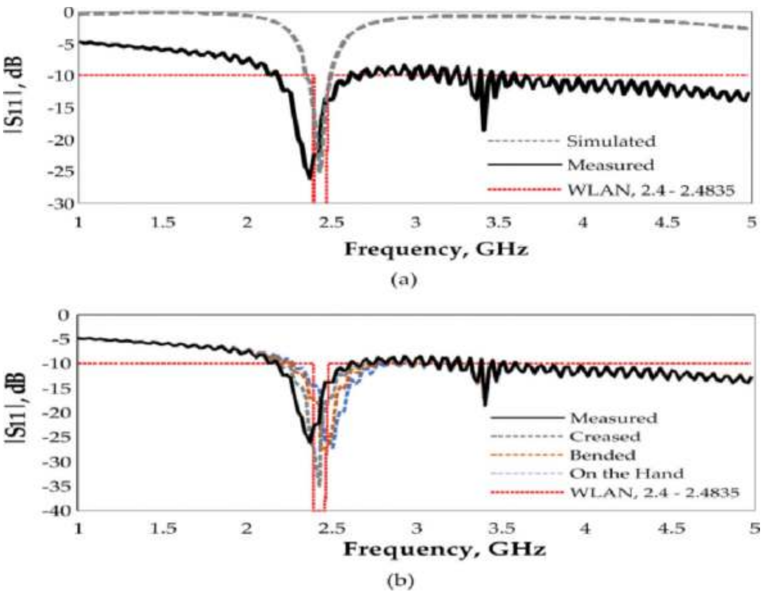

Figure 13. Comparison of |S11| parameters of wearable textile antenna bio-inspired in *Bidens pilosa* plant shape: (a) simulated and measured; (b) creased, bended and on the hand.

Antenna	f_0 (GHz)	f_1 (GHz)	f_2 (GHz)	*BW* (GHz)
Simulated	2.43	2.35	2.49	0.14
Measured	2.40	2.19	2.73	0.54
Measured creased	2.43	2.22	2.82	0.60
Measured bended	2.44	2.28	2.82	0.54
Measured on the hand	2.50	2.28	2.91	0.63

Table 2. Values for resonance frequency and bandwidth for the wearable textile antenna bio-inspired in *Bidens pilosa* plant shape.

body with 60, 0, and 90 MHz of difference compared to the free space measurement, respectively.

Figure 14 shows the 2D and 3D radiation patterns of the wearable antenna bio-inspired proposed. The maximum current density observed was 48.06 A/m^2 at 2.42 GHz, with gain of 6.73 dBi, HPBW of 92°, and relative front-to-back (F/B) of 25 dB. It can be noted than the radiation pattern measured and simulated presented similar behavior indicating good relationship between results. A higher concentration of current density in a smaller physical area is a characteristic of the bio-inspired antenna.

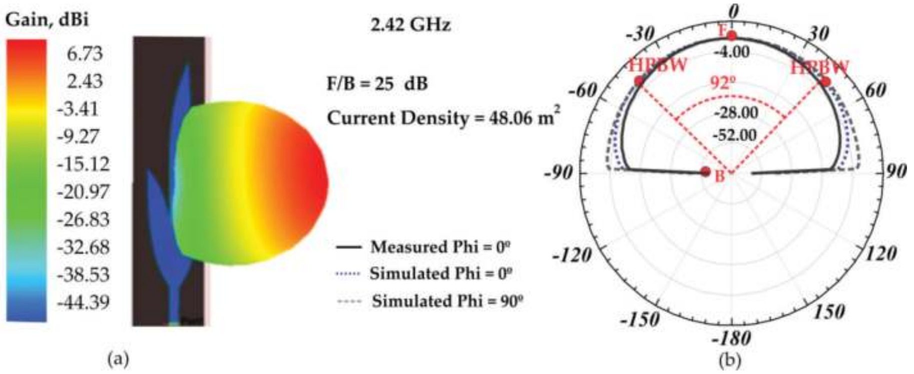

Figure 14. Radiation pattern of wearable textile antenna bio-inspired in *Bidens pilosa* plant shape [27]: (a) 3D; (b) 2D.

3.2. Wearable bio-inspired antennas built in polyamide

In this section, Gielis formula is used in the design of a wearable flexible antenna array bio-inspired in *Inga maritimus* plant shape, and it is designed both one leaf for 5.4 and 5.8 GHz, and two patch antenna arrays with two and four leaves covering the WLAN 5 GHz band.

3.2.1. Wearable antenna arrays bio-inspired in Inga maritimus *plant shape*

Figure 15 shows the leaves of *Inga maritimus*, the single elliptical leaf for 5.4 and 5.8 GHz, the dimensions of the antenna arrays with two and four leaves and the prototypes built in polyamide. The single leaf was generated by Gielis formula, with parameters: m = 2, n_1 = 20; n_2 and n_3 = 12, a and b = 1. To prevent mutual coupling between the radiating elements, a distance of one effective wavelength between the leaves was used. Position of leaves in the patch antenna array with four elements has been inverted, thus the radiation pattern stays in the center of the structure.

Figure 16 shows the curves for simulated and measured $|S_{11}|$ curves for wearable antenna bio-inspired in *Inga maritimus* plant shape with one leaf, with the indication in dashed lines of wireless local area network (WLAN) band in 5 GHz (5.15–5.85 GHz). As observed, the single leaf shape antennas cover part of the WLAN band. The greater difference in resonance frequency (3.85%) was observed for the single leaf antenna at 5.4 GHz, and bandwidth 57.8% was observed for the single leaf antenna at 5.8 GHz.

Figure 17(a) shows the simulated and measured $|S_{11}|$ curves of the wearable bio-inspired antenna arrays with two elements and four elements in **Figure 17(b)**. The greater difference in bandwidth (52.39%) was observed for the wearable antenna with two elements, with difference in first resonance less than 1.01%, **Table 3**.

The differences between the measured and simulated results of antennas and antenna arrays in polyamide can be the result of the variation in the dielectric properties of the material, and of the manufacture process. As the transmission lines are very thin, and the bio-inspired antennas

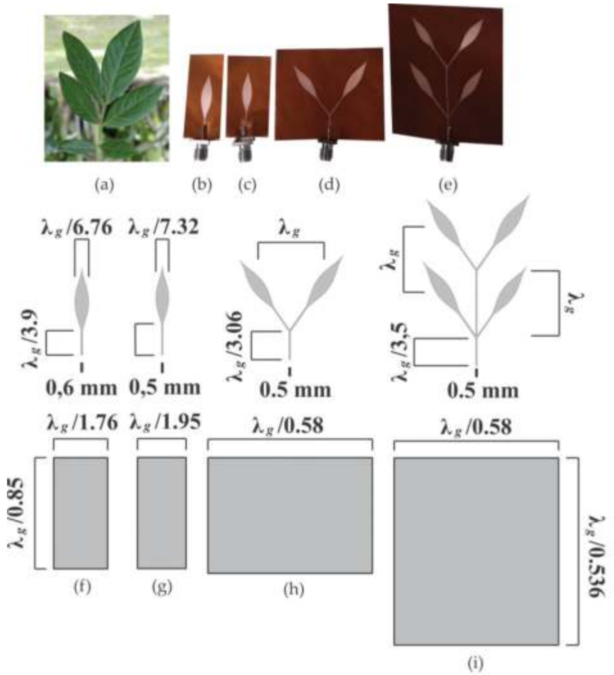

Figure 15. Project of wearable antenna arrays bio-inspired in Inga maritimus plant shape: (a) *Inga maritimus* leaves [28]; (b) prototype for 5.4 GHz; (c) prototype for 5.8 GHz; (d) prototype antenna array with two leaves; (e) prototype antenna array with four leaves.

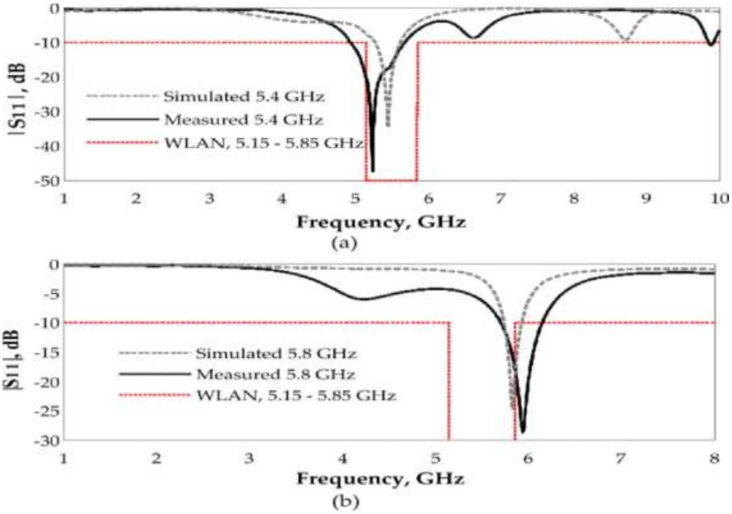

Figure 16. Simulated and measured |S11| parameter of wearable antenna bio-inspired in *Inga maritimus* plant shape: (a) 5.4 GHz; (b) 5.8 GHz.

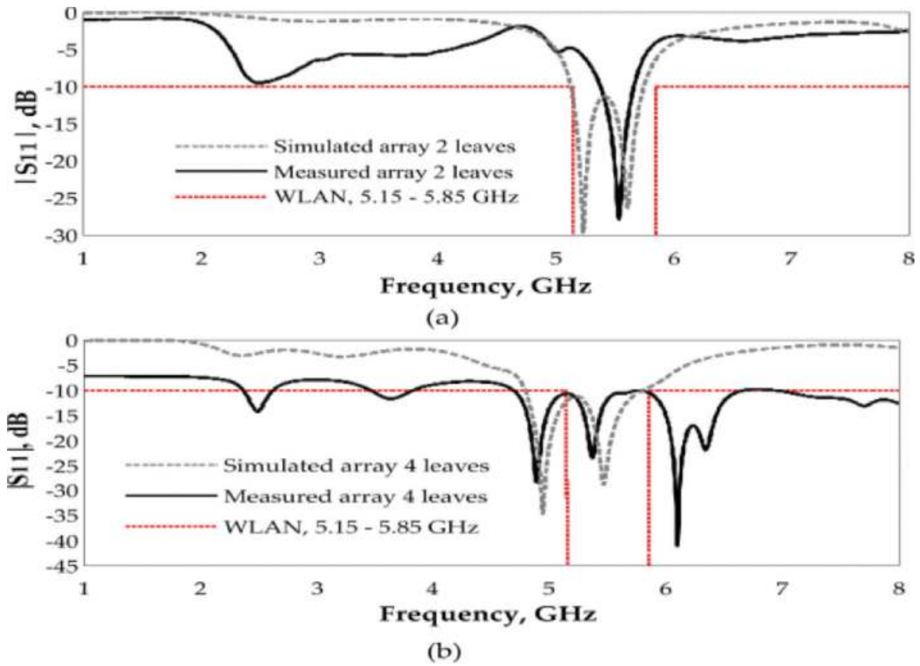

Figure 17. Comparison of simulated and measured |S11| parameters of wearable antenna arrays bio-inspired in *Inga maritimus* plant shape: (a) antenna array with two leaves; (b) antenna array with four leaves.

Antenna	f_0 (GHz)	f_1 (GHz)	f_2 (GHz)	BW (GHz)	RL (dB)
Simulated 5.4 GHz	5.45	5.27	5.62	0.35	34.63
Measured 5.4 GHz	5.24	4.93	5.68	0.75	47.25
Simulated 5.8 GHz	5.83	5.74	5.93	0.19	24.62
Measured 5.8 GHz	5.94	5.7	6.15	0.45	28.54
Simulated Array 2	5.24/5.61	5.12	5.75	0.63	26.39
Measured Array 2	5.54	5.37	5.67	0.3	27.94
Simulated Array 4	4.94/5.48	4.78	5.82	1.04	34.6/28.8
Measured Array 4	4.89/5.38	4.53	6.52	1.99	23.51/41.91

Table 3. Frequency responses of wearable antenna arrays bio-inspired in *Inga maritimus* plant shape.

in the Inga *maratimus* plant shape are compact and have sharp cuts, small variations in the built structure can cause significant variations in resonant frequencies and bandwidth, which can be numerically observed in **Table 3**. Even with the differences observed, the results indicate that the antennas presented antenna array characteristics, with increased gain (by increasing metal), and bandwidth, covering the frequency band indicated for WLAN technology at 5 GHz, indicating than there are possibility of using this type of antennas and substrate

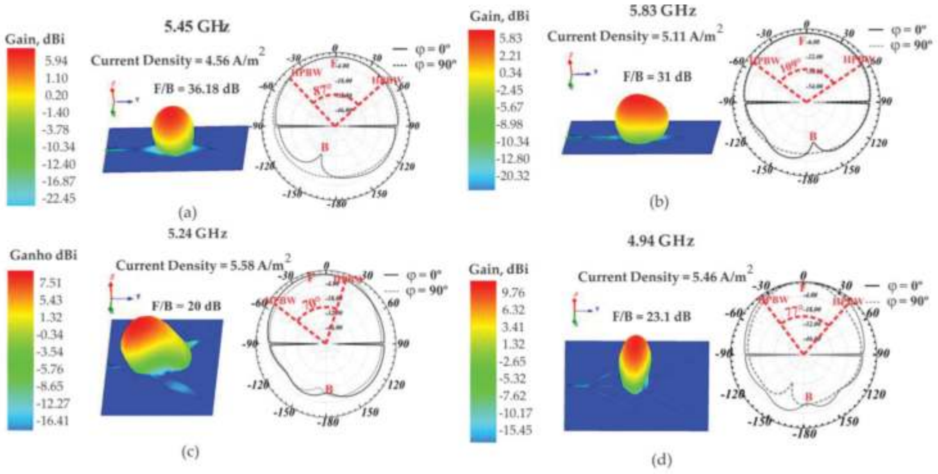

Figure 18. 3D and 2D radiation pattern of wearable antenna arrays bio-inspired in *Inga maritimus* plant shape: (a) 5.4 GHz; (b) 5.8 GHz; (c) antenna array with two leaves; (d) antenna array with four leaves.

in an environment that requires components resistant to the high temperature. In **Table 3**, the measured and simulated values, resonant frequencies at −10 dB, bandwidth (BW), return loss (RL), can be observed of each structure presented.

Figure 18 shows the 2D and 3D radiation patterns at respective resonance frequencies, with indication of gain, front-to-back (F/B) relation, half power beamwidth (HPBW), and current density of simulated wearable antennas bio-inspired in *Inga maritimus* plant shape. As observed, the use of bio-inspired leaf shape on the antenna array permits an increase in both bandwidth and gain. In comparison with wearable bio-inspired antenna with single leaf shape, wearable antenna arrays bio-inspired in *Inga maritimus* plant shape with four leaves presented gain 2.25 dBi greater than antenna array with two leaves, and 3.96 dBi greater than antenna with single leaf shape. From the radiation patterns of the bio-inspired antenna array with four elements, a lower HPBW (77°) can be observed, which indicates a higher concentration of radiated energy, added to the highest gain (9.76 dBi), and a higher front-to-back ratio (23 dB), this indicates that the arrangement can be used for communication of greater distances or with less signal intensity.

4. Conclusion

Wearable wireless systems impose new challenges to antenna design since the utilization in clothes, the proximity of the human body, and the possibility of format variations as bending implies in parameters like good esthetical appearance, low cost, integration to the clothes and accessories used next to the body, among others related to the wear like use of the antenna. In this chapter, we presented some trends for design innovative wearable bio-inspired antennas using plant leaves as inspiration parameterized by the Gielis formula to design antennas, and also we characterize different wearable flexible and low-cost dielectric materials (denim and polyamide). Designed antennas were analyzed by simulation and by measurement in implemented prototypes. The proposed bio-inspiration results in more compact antennas by the reduction of the antennas radiating element. However, compared to Euclidean shapes, two side effects were observed a reduction of the gain and an increase of the current density. On the other hand, the bio-inspired antennas present a higher concentration of the surface current and the decrease of gain can be prevented using leaf arrays with esthetic appeal. The gain can be improved by using thicker substrates and the current density can be regulated using plant shapes with flat geometries or the least sharp possible. These characteristics open a large research field for wearable embedded antennas.

Author details

Paulo Fernandes da Silva Júnior[1]*, Alexandre Jean René Serres[1],
Raimundo Carlos Silvério Freire[1], Georgina Karla de Freitas Serres[1], Edmar Candeia Gurjão[1],
Joabson Nogueira de Carvalho[2] and Ewaldo Eder Carvalho Santana[3]

*Address all correspondence to: paulo.junior@ee.ufcg.edu.br

1 Electrical Engineering – COPELE, Federal University of Campina Grande – UFCG, Campina Grande, Brazil

2 Electrical Engineering – PPGEE, Federal Institute of Paraiba – IFPB, João Pessoa, Brazil

3 State University of Maranhão, São Luis, Brazil

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