# Flexible Textile Antenna for IoT Applications at 2.4 GHz Analyzed with Characteristic Modes

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**Abstract.** In this paper, the design of a flexible textile antenna operating at a frequency of 2.4 GHz is presented. The structure has been inspired by the e vowel and has dimensions close to a $\lambda/4$ resonator. The structure has been then analysed using the Characteristic Mode Theory (CMT) to understand the structure's operation in the absence of the feed point. The characteristic angles, radiation patterns, and modal current distributions are represented. The S-parameter results of the proposed antenna using different types of conductive materials such as copper tape, silver ink, and buddy paint are presented below. Finally, the process used to manufacture the antennas and how the materials impact the antenna's performance are described.

**Keywords:** Characteristic modes theory · conductive materials · flexible antenna · IoT systems

## 1 Introduction

The accelerated development of wearable electronics and the Internet of Things (IoT) highlights a revolution in real-time human performance monitoring and analysis [8]. With the advancement of the fourth and fifth generation of wireless mobile communications, antennas have taken on a central role in the evolution of wearable technology, favoring the development of more compact antennas [17]. This technological synergy, particularly relevant in the field of high-performance sports, has generated an exponential demand for flexible and efficient antennas. The ability to collect and transmit

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critical biomedical data, such as heart rate, body temperature, and oxygen saturation, during physical activity opens up a range of possibilities to optimize training, prevent injuries, and improve the health of athletes.

Within this context, the 2.4 GHz of the Industrial, Scientific, and Medical (ISM) frequency bands has established itself as the preferred spectrum for wearable applications, thanks to its widespread adoption in ubiquitous wireless technologies such as Wireless Fidelity (Wi-Fi) and Bluetooth [4,6]. This standardization facilitates interoperability and global connectivity, crucial elements for real-time data transmission. However, integrating antennas into textiles poses significant engineering challenges that require innovative solutions [7].

The dynamic nature of physical activity requires antennas to maintain stable electromagnetic performance under bending, torsion, and stretching conditions [3,11]. Furthermore, the proximity of the antenna to the human body introduces absorption and tuning effects that must be taken into account. The need to ensure device comfort and durability without compromising radiation efficiency imposes additional constraints on design and material selection.

Although textile antennas are highly appreciated for their physical appearance, the design and manufacturing process, as well as limitations in conductive materials that adhere to the textile correctly, make the evolution of this class of antennas slow. The appropriate antenna design for integration into wearable technology operating in the ISM band is the patch antenna, either rectangular or circular, with different types of slots, which allows the control of surface waves and improves impedance matching [5,10]. Textile antennas use different woven fibers as substrates; therefore, it is necessary to know their electromagnetic properties ($\epsilon_r$, $\tan(\delta)$) for efficient antenna design. However, each textile has its own dielectric values and these must be measured through a methodical material characterization process [16]. The most commonly used textile substrates for textile antennas are: silk, felt, nylon, polyester, among others [9,18].

Therefore, the main objective of this scientific article is to optimally design and implement a textile antenna using commercial conductive inks. Characteristic Mode Theory has been used to understand its operation. To achieve this objective, the antenna design, behavioral analysis, and manufacturing process are described; the results measured and obtained through simulation are discussed in detail below. Finally, the final section describes the conclusions of this research work.

## 2 Flexible Textile Antenna Design

The design of the proposed antenna is inspired by a geometry shaped like the letter "e" as shown in Fig. 1. The structure has been optimized to dimensions of length $\lambda/4$ to resonate at the 2.4 GHz frequency, a crucial ISM band for interoperability with Wi-Fi and Bluetooth devices. The geometric configuration of the antenna is the result of a parametric simulation process, achieving an antenna with dimensions of $0.2088\ \lambda_0 \times 0.156\lambda_0$ at the resonance frequency, which can be easily integrated into any work environment. This shape is chosen because the electrical length can be increased without increasing the physical area; the "e" shape allows reducing the size of the antenna while maintaining a low resonant frequency compared to a patch type.

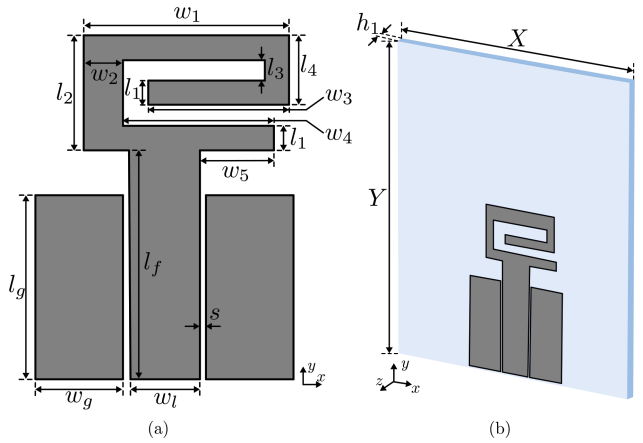


**Fig. 1.** Proposed flexible textile antenna. a) Frontal view and, b) 3D view.

**Table 1.** Optimized parameters of proposed flexible textile Antenna

| Variable | Value $[mm]$ | Variable | Value $[mm]$ |
|---|---|---|---|
| $X$ | 50.00 | $Y$ | 50.00 |
| $s$ | 0.25 | $l_g$ | 14.30 |
| $l_f$ | 17.60 | $l_1$ | 1.50 |
| $l_2$ | 8.50 | $l_3$ | 2.00 |
| $l_4$ | 5.70 | $w_g$ | 6.80 |
| $w_l$ | 5.70 | $w_1$ | 14.50 |
| $w_2$ | 1.50 | $w_3$ | 10.50 |
| $w_4$ | 13.50 | $w_5$ | 5.75 |

Table 1 provides a detailed summary of the values for each of the variables that make up the proposed structure.

The antenna is fed through a coplanar waveguide (CPW) line, a strategic choice that addresses the need for stable impedance matching and easy integration on flexible substrates [2,15]. The CPW structure, characterized by a conductive center line flanked by two parallel ground planes, offers several intrinsic advantages. First, it simplifies the manufacturing process by eliminating the need for metallic layers on the back of the substrate. Second, it provides greater stability in the frequency response against mechanical deformations, a crucial factor in wearable electronics applications where the antenna is subject to bending and twisting. However, although this type of antenna may present certain disadvantages in specific environments—particularly in the presence of the human body—such as increased energy absorption (high Specific Absorption Rate SAR values), a reduction in radiation efficiency due to coupling with lossy biological tissues, and possible detuning caused by the body's dielectric charge, these effects do not represent a significant limitation when the textile antenna is used for off-body

communication applications. This is the case of the proposed antenna, whose potential application contemplates its integration into hospital textile elements, such as gowns, sheets or pillows, in which an omnidirectional radiation diagram is required that allows the efficient location of patients within the hospital environment, without the antenna necessarily being in direct contact or in immediate proximity to the human body.

Furthermore, the selection of the Lycra textile substrate is based on its exceptional mechanical and dielectric properties. Lycra, with its high flexibility and mechanical strength, is perfectly suited to the demands of wearable electronics. Its dielectric properties, characterized by a relative permittivity $\varepsilon_r = 1.50$ and a loss tangent $\tan\delta = 0.0093$ and a height $h$ = 0.65 $mm$, allow an optimal balance between material flexibility and electromagnetic performance. The low loss tangent minimizes energy dissipation in the substrate, improving the antenna radiation efficiency. Furthermore, the low relative permittivity facilitates impedance matching, contributing to a better overall device performance [1].

To understand the structure's operation and corroborate the location of an excitation point to achieve the desired resonance, the CMT is used.

## 3 Characteristics Modes Analysis

In recent years, Characteristic Mode Theory (CMT) has grown considerably, becoming a very powerful tool for antenna design. This is because it provides important information about an arbitrary structure in the absence of excitation [13].

The mathematical formulation that describes the characteristic modes or characteristic currents $\boldsymbol{J_n}$ involve the impedance matrix of the structure, these modal currents are obtained as the eigenfunctions of the weighted eigenvalue equation which is shown below:

$$X(\boldsymbol{J_n}) = \lambda_n R(\boldsymbol{J_n}) \tag{1}$$

where $R$ and $X$ are the real and imaginary parts of the impedance operator, while $\lambda_n$ are the eigenvalues and $\boldsymbol{J_n}$ are the eigenfunctions or eigencurrents [12].

The characteristic modes form a complete set of orthogonal modes, which allow to decompose any induced current and the far fields generated by an external source. In this way, the induced currents on a Perfect Electrical Conductor (PEC) surface can be described as a linear combination of characteristic currents [14]:

$$\mathbf{J} = \sum_n a_n \mathbf{J}_n \tag{2}$$

The physical interpretation of characteristic modes can be done in various ways, but for this study, it will be done through characteristic angles. Therefore, a structure is in resonance when the characteristic angle value is equal to 180°.

In Fig. 2, the characteristic angle of the proposed structure can be seen for the frequency range of 1.5 to 3.5 GHz obtained by the Altair FEKO electromagnetic computational solver can be seen. It is evident that there is a resonant mode at a frequency very close to 2.4 GHz. The representation of the modal current distribution and its characteristic angle have been inserted within Fig. 2. From the shape of the radiation pattern

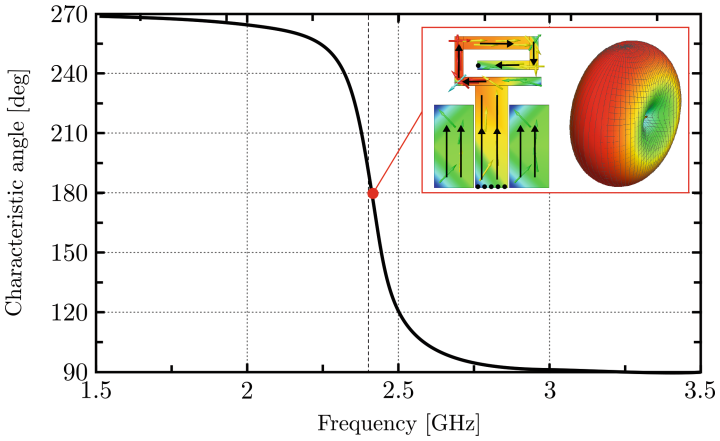


**Fig. 2.** Characteristic Angle of proposed antenna without feeding point.

and the direction in which the currents flow on the surface of the structure and the pair of current nulls generated at the bottom and inner end of the "e" shape, it is clear that the excited mode is the fundamental mode $J_1$. Furthermore, with the generation of the current null at the bottom of the structure, it is confirmed that it is the optimal position to locate the power port, this is because the excitation of a structure can be forced at a point where the current is maximum through an inductive power supply, or at a point of zero current using a capacitive power supply [12].

## 4 Results and Discussion

To generate the results presented in this section, a full-wave analysis was performed using the commercial electromagnetic simulator CST Studio Suite. The conductive material used for the modelling and simulation processes is the copper tape conductive material with the following conductive properties $\sim 5.8 \times 10^7$ S/m (seems the pure copper). The results of the reflection coefficient $S_{11}$ obtained through the simulation are shown in Fig. 3, which represents a well-marked resonance at 2.4 GHz, with an impedance coupling of less than $<-10$ dB of 10.28 %.

The radiation pattern and total currents of the proposed antenna at the resonant frequency are presented in Fig. 4. The shape of the current flow over the surface of the structure is similar to that of the $J_1$ fundamental mode shown in the previous section, therefore, the radiation pattern will be omnidirectional with a directivity of about 1.778 dBi and 1.50 dB in gain in the direction of maximum radiation, which represents a radiation efficiency close to 94%

Subsequently, to contrast the results and verify the correct operation of the proposal, the antenna was manufactured using a commercial copper adhesive tape placed over the dielectric material (lycra). The $S_{11}$ reflection coefficient is shown in Fig. 3. As can be seen, the simulated and measured dispersion parameters are very similar. Within the frequency range analyzed, there is a minimal shift toward a higher frequency of around

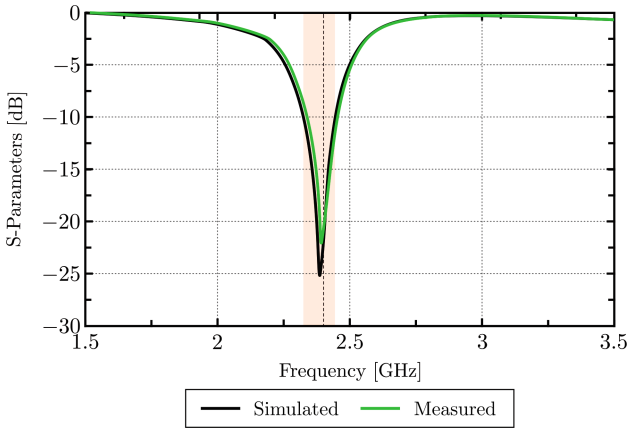


**Fig. 3.** Comparative plot of reflection coefficient between simulated and measured results of the proposed antenna.

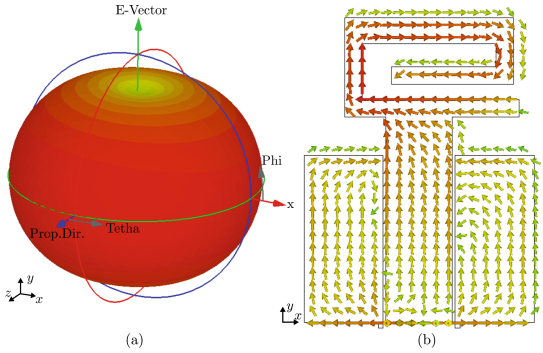


**Fig. 4.** 3D view of radiation pattern and total current distribution at 2,4 GHz of the proposed antenna.

20 MHz and an increase in return loss of approximately -3dB relative to the minimum value generated in the simulation. This variation is linked to the manufacturing quality and process used. However, the material used for manufacturing is not the most appropriate, as it is very fragile and will easily come off over time, causing the properties obtained through simulation and optimization to be lost.

## 5 Experimental Manufacture

Despite having successfully designed an antenna integrated into a textile and operating at a 2.4 GHz frequency, it is essential to seek alternatives that improve versatility and user comfort, especially considering its exposure to liquids and fluids. Therefore, experiments have been conducted with different conductive materials to improve the antenna's characteristics, such as silver ink, Buddy Paint, and bare conductive ink.

Working with liquid conductive materials and to prevent these materials from running through the textile material, a thin layer of textile vinyl was deposited on the Lycra fabric. This vinyl has plastic properties that prevent the conductive ink from seeping through the substrate without compromising the system's flexibility.

To impregnate the conductive materials (silver ink, Buddy Paint) onto the textile substrate, a technique based on transparent vinyl molds was used. First, the antenna design is replicated on the vinyl, and then the excess material is removed before applying the conductive ink. This process requires precise and uniform application, as any unevenness in distribution affects the antenna's performance.

In all cases, after depositing the inks on the material, they must undergo a drying process at room temperature. This ensures that their physical and electrical properties are not affected and that they do not impact the antenna's performance. Figure 5 shows the front views of the antennas manufactured with various materials. The first one used as a reference is the one made with copper tape, followed by the one made with silver ink, and finally, the one made with Buddy Paint.

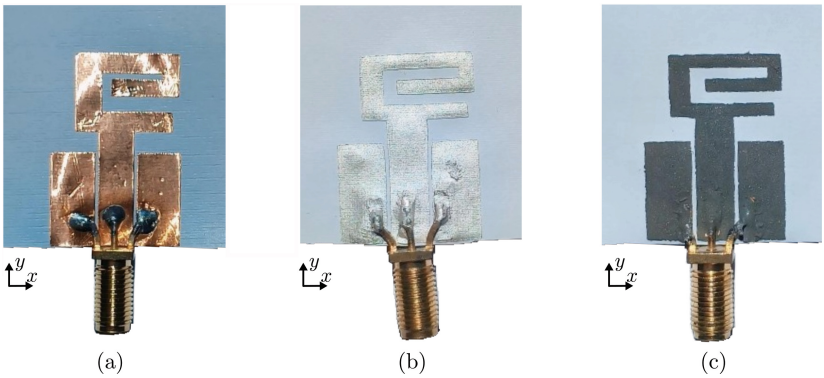


**Fig. 5.** Front view of the proposed manufactured antenna made from different materials. a) Copper tape, b) silver ink and c) buddy paint.

A comparative graph of the S-Parameters obtained through the RIGOL RSA5065N Vector Network Analyzer (VNA) using the SOLT (Short-Open-Load-Through) calibration method for each of the fabricated antennas is shown in Fig. 6. As can be seen, in all cases the operating frequency remains at 2.4 GHz; however, a significant improvement in bandwidth is evident when using Buddy Paint. This increase in bandwidth appears to be related to the conductivity of the materials used. In the case of silver ink and Buddy Paint, conductivity is not constant, as it depends on factors such as the thickness of the applied layer, the type and amount of binder, and the curing process. These variations can affect radiation efficiency and, therefore, influence the frequency behaviour of antennas made with these materials.

However, despite this performance optimization, the next challenge lies in ensuring the antenna's flexibility and fluid resistance without compromising its performance or

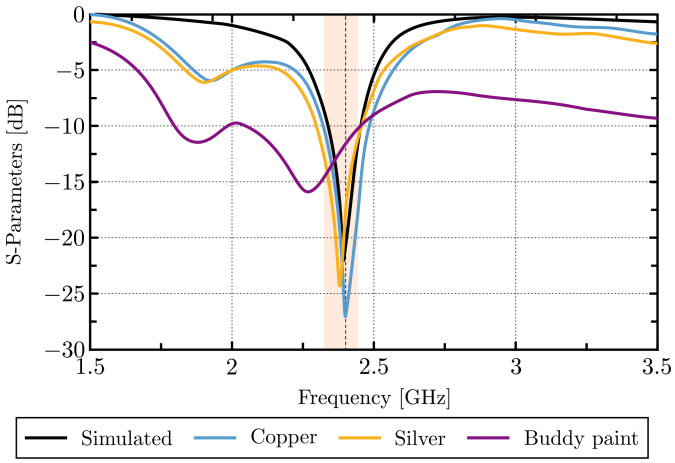


**Fig. 6.** A comparative plot of the reflection coefficient of the proposed manufactured antenna with different materials.

its electrical and mechanical characteristics. To address this challenge, several empirical experiments were conducted, as shown in Fig. 7. In this experiment, a flexibility test was performed; each of the antennas, with its different conductive materials, was subjected to a variation in shape. To this end, the structures were mounted on a cylindrical substrate with $\varepsilon_r = 1.0$ and a variable radius $R$, which is linked to the following equation:

$$R = \frac{L \times 360^0}{2\pi \times \phi} \tag{3}$$

where $L$ represents the physical length of the antenna and $\phi$ describes the angle generated between both ends of the structure. As the radius decreases, the antenna will deform into a cylindrical shape. However, when the cylinder is extraordinarily large, the antenna deforms minimally, i.e., the antenna will have a flat shape.

The results revealed that, among all the inks used, silver ink is the only one that shows no significant changes in its properties after exposure to adverse conditions (see Fig. 8). The S-parameters measured before and after testing indicate that the antenna fabricated with silver ink maintains stable behaviour, without any degradation in performance. This is due to its rapid drying and the ability of its components to repel liquids, thus preventing moisture absorption and preserving its structure and operational efficiency. These findings represent an important advance in design optimisation, enabling the development of more robust textile antennas suitable for applications in demanding environments.

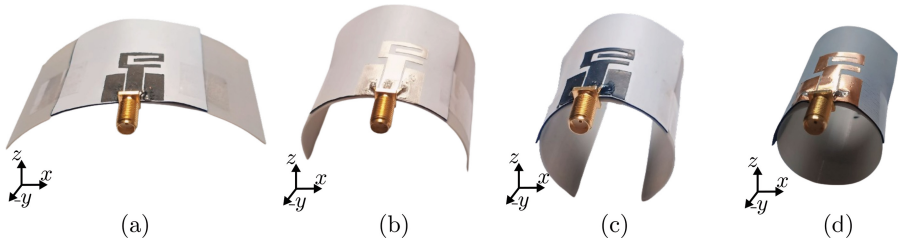


**Fig. 7.** Progressive flexibility test of the implemented textile antennas over a cylindrical shape. (a) at 100° setup, (b) at 200° setup, (c) at 300° setup and (d) at 360° setup.

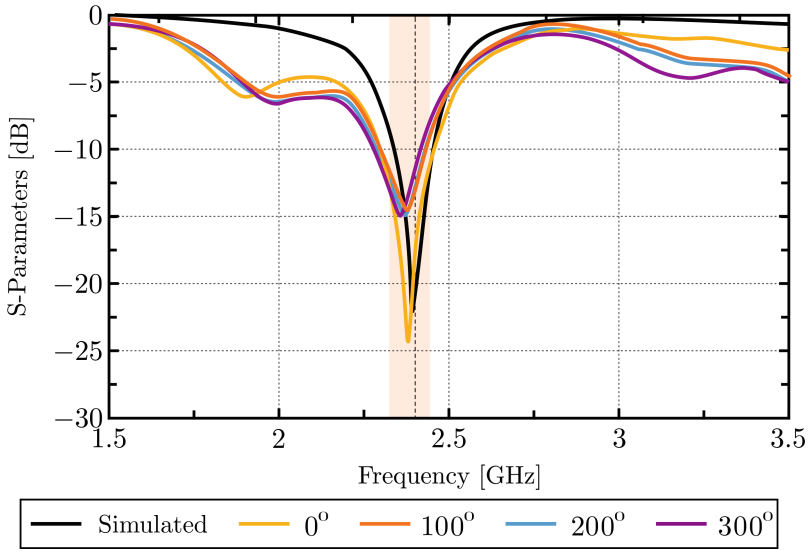


**Fig. 8.** Antenna manufacturer's reflection coefficient with silver ink at different angle variations.

## 6 Conclusions

The paper shows the design of a flexible textile-integrated antenna for IoT applications. Its dimensions are linked to a resonator with a length of $\lambda_0/4$ at a frequency of 2.4 GHz and a characteristic impedance of 50 Ω.

An "e"-shaped geometry is used because it allows the antenna's physical dimensions to be reduced without altering its operating frequency. This configuration is complemented by a CPW (coplanar waveguide) feed, which facilitates impedance matching.

To understand the operation of the proposed structure, an analysis using the characteristic modes theory was used, where the fundamental mode $J_1$ was represented, forcing the generation of an omnidirectional radiation pattern, where the resonance directly depends on the physical dimensions of the antenna.

The results of the S-parameters, both simulated and measured, were presented for various antennas made from different conductive materials. While all resonated at the

desired operating frequency, the antenna made with buddy paint showed the best performance in terms of bandwidth. However, its usefulness is limited when in contact with fluids due to its solubility.

The silver ink demonstrated greater stability, as its electrical properties did not undergo significant changes either when exposed to mechanical deformation conditions.

The results of the simulated and measured S-parameters of several types of antennas manufactured with different conductive materials were shown. Each of them resonates at the working frequency, but the one with the best characteristics in relation to bandwidth is the buddy paint material. However, the material that has not changed its properties when exposed to fluids and deformation is that which has been manufactured with silver ink.

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