Modelling of Textile Patch Antenna Deformations by the Cylindrical TLM Method

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Abstract — **This paper explores the potential of the cylindrical Transmission Line Matrix (TLM) method for modeling textile-integrated antennas in wearable applications. It emphasizes the method's capability to independently address geometric and structural variations under bending and stretching conditions. Various scenarios involving conductive patch and textile substrate characterization are analyzed to demonstrate the suitability of the cylindrical TLM approach as a benchmark tool in the design and optimization of wearable antennas subjected to typical deformation.**

Keywords — **Wearable applications, Textile antenna, Transmission Line-Matrix method.**

I. INTRODUCTION

In recent years, with an increased interest in enhance quality of life by improving sensing, detection, and monitoring capabilities, a wide range of applications has been proposed, ranging from the ability to monitor signals and parameters in medicine and health status, through the capacity to interact with the environment, to help in emergency situations such as firefighting operations [1-3]. To meet the requirements of these applications the body-centric sensor and communication systems are designed to provide continuous stream of information, where key elements are wearable antennas that must be flexible and capable of integrating into clothing or uniforms. Besides aesthetic standards, these antennas must simultaneously meet technical requirements and the demands of wearable applications, along with safety regulations.

The textile material is fundamental to the antenna's functionality, enabling integration into wearable electronics while maintaining flexibility, lightweight properties, and even washability [3-5]. The current textile technologies are based on materials where 3D knitted fabrics serve as substrates, with properties such as low dielectric constant and thickness variations, while conductive surfaces are screen-printed or made from conductive yarns. These features make the textile-integrated antenna suitable for wearable electronics and body-centric communication systems, allowing optimal integration and comfort. However, flexible patch antenna may be subjected to deforming and conforming its shape to the surface on which it is placed. As a result, elongation of resonant patch length and variation of the dielectric permittivity caused by substrate stretching can occur. Consequently, the frequency response varies significantly among the different antennas due to manufacturing methods and materials whose characteristics are depend on antenna deformation or interaction with body. The variations in body posture and motion highlight the challenges of achieving precise frequency responses in textile-integrated antennas, especially in bending conditions along with stretching of textile materials. Different geometrical and structural changes in textile materials caused by interaction with body significantly impact antenna performance, particularly in terms of frequency response, efficiency, gain, and polarization [6]. Consequently, the characterization of textile material under deformations plays a crucial role in the performance of textile-integrated antennas due to its unique properties and influence on design and functionality.

Modeling of textile antennas under deformation requires specialized techniques to account for the flexible and often irregular shapes that these antennas can take on during wear. Several approaches are used, including space deformation techniques, advanced geometry generators, and the consideration of textile material properties [7-9]. Various numerical methods that generate geometric models of deformed antennas, while accounting for the properties of textile materials, enable parametric studies that support the design and evaluation of wearable antenna systems. They often utilize fine cubic grid or tetrahedral meshes to minimize discretization errors during simulation. However, inaccuracies in modeling the conductive patch and textile substrate under deformation conditions lead to frequency shifts and bandwidth variations, introducing systematic errors that cannot be isolated from the outcomes of parametric analyses. In numerical methods employing a rectangular grid, such as the rectangular grid-based TLM method [10], the choice of the mesh density significantly influences the accuracy of antenna performance predictions, presenting a trade-off between computational efficiency and solution precision [10]. On the other hand, the cylindrical TLM mesh offers superior results for bent antenna modeling, consistent in terms of accuracy when the bending angle is changed as shown in [11,12]. The flexibility of modelling of conductive patch and textile

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substrate integrated into wearable applications is based on the possibility of building of conformal mesh for bent structures. Simultaneously, the computational costs are dramatically reduced with a possibility of creating computational box as part of the cylinder.

The research presented here illustrates the potential of the cylindrical TLM method [11,12] to model textile-integrated patch antennas for wearable applications, separately characterizing geometrical and technological aspects under deformations. The subject of accurately and computationally non-expensive modeling, without fine-grained meshes, has been geometric variations due to human movement along with their impact to textile structure. The effect of antenna bending followed by stretching that results in patch elongation and substrate permittivity variation have been analyzed using relevant descriptors of geometry and dielectric properties. The paper discusses the cylindrical TLM model development and characterization of bent rectangular antennas integrated into knitted fabrics for the 2.4 GHz band, focusing on the impact of textile structural changes to antenna parameters.

II. Antenna Model and Simulation Results

This section presents results obtained using the TLM method applied on the wearable textile antenna placed on a human tissue. The model is based on rectangular patch antenna, with length l = 39.5 mm and width w = 50 mm of radiation patch, as shown in Fig.1 [10,11]. The length and the width of the ground plane are $L = W$ = 100 mm, while the substrate thickness is h = 2 mm. The patch and the ground plane are modelled as the perfect conductors, and the coaxial feed is used to feed the antenna. A coaxial feed with an inner conductor radius of 0.1 mm, connecting the ground plane to the patch, is positioned 11.5 mm from the patch edge to provide impedance matching with the antenna [11,12]. The relative permittivity of substrate in the models of antenna is $\varepsilon_r = 2.1 - j\,0.001$ (loss tangent σ = 0.00048), and it is bent over a part of a cylinder. The antenna is placed on the human tissue, a muscle of the relative permittivity 52.67 - j13, and the thickness of d = 35 mm [11].

The in-house TLM solver based on the cylindrical mesh, with 1.0 mm cell size [11], has been used to model the antenna to analyze effects of deformation. An orthogonal polar conformal mesh used for modelling of a patch antenna under bending is presented in Fig.2, showing a space discretization within the section of a cylinder in r-φ plane. The presented cross-section of the patch antenna model illustrates the conformity of the mesh along the angular and radial direction regarding description of bending and stretching effects. Considering the radiated patch as a solid, metallic, non-stretchable structure, when the antenna is bent the cell dimensions are defined satisfying the condition that dimensions of the radiated patch (specifically l, in the case of E-plane bending) are kept constant for different bending angles. Therefore, in case of bending without stretching effects, $\Delta\theta_{patch}$ is defined by the bending angle 2θ in respect to the length of the patch l as

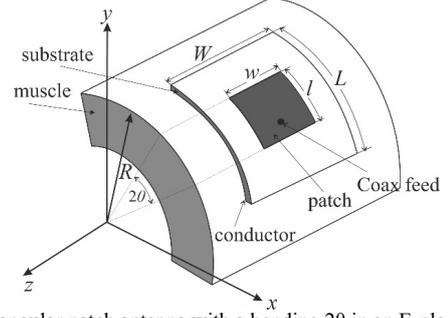$$2\theta = l / (R + h) = \Delta\theta_{patch} \times N_{cells}(patch), \tag{1}$$

Fig.1. A rectangular patch antenna with a bending 2θ in an E-plane [11].
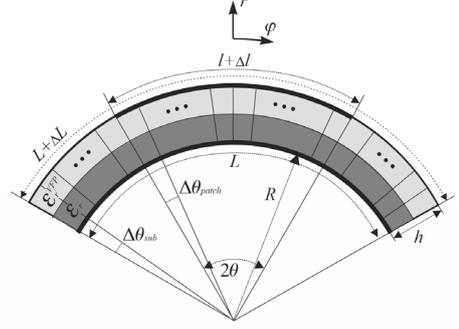

Fig.2 Space discretization in r-φ plane in the TLM antenna model without a muscle layer.

where $N_{cells}(patch)$ is a number of cells corresponding to the length of radiated patch.

When the patch elongation caused by the bending is included in the model, $\Delta\theta_{patch}$ should be slightly modified and determined by the bending angle 2θ in respect to the elongated length of the patch $l + \Delta l$ as

$$2\theta = (l + \Delta l) / (R + h) = l / R = \Delta\theta_{patch} \times N_{cells}(patch). \tag{2}$$

In both models, $\Delta\theta_{sub}$ is determined according to the condition that the ground length L is kept constant under bending

$$L = R (2\theta + \Delta\theta_{sub} \times (N_{cells}(ground) - N_{cells}(patch)), \tag{3}$$

where $N_{cells}(ground)$ represents a total number of cells corresponding to the length of the ground plane.

Finally, the model is extended with the descriptor of the permittivity variation due to stretching, representing the substrate as a multilayered structure in a radial direction. The permittivity of each layer considered as air-solid mixture structure can be determined according to formulas based on volume fraction permittivity (VFP) that depends on substrate structural changes caused by the stretching [13]. Therefore, starting from the permittivity of the bottom layer of the substrate placed on the ground plane, ε_r, the permittivity of the upper layer of the substrate in the antenna model is calculated from [13] as

$$\varepsilon_r^{VFP} = \varepsilon_r / (f + (1 - f) \times \varepsilon_r) \tag{4}$$

where f represents the volume fraction permittivity of the air-solid mixture structures based on the textile strain

$$f = 1 / (1 + \Delta L/L) = 1 / (1 + \Delta l/l). \tag{5}$$

Starting from the flat case configuration ($2\theta=0.1°$, $R>>l$), the antenna is bent over a cylinder of radius R to achieve the bending angles of $2\theta = 25°$ and $2\theta = 50°$, in order to investigate the influence of the E-plane bending on resonant frequency values. Beyond geometric variations, strain-induced effects on the conductive patch and textile-based substrate, resulting from bending, also influence the performance of bent antennas. This research focuses on patch elongation and substrate permittivity variation induced by bending, with the ground plane assumed to remain rigid and non-stretchable. The parameters used for description and modeling of the considered effects are presented in Table I.

TABLE I
MODELLING PARAMETERS OF THE ANTENNA WITH EFFECTS OF DEFORMATIONS

Angle 2θ	Bending, R	Patch Elongation, $\Delta l/l$ %	Substrate Permittivity, ε_r^{VFP}
0.1	$R>>l$, (22.63 m)	0	2.1
25	90.53 mm	2.21% (Δl= 0.87mm)	2.05
50	45.26 mm	4.42% (Δl= 1.75mm)	2.01

Fig. 3. presents the comparison of simulated results obtained by the cylindrical TLM method, representing the reflection coefficient for different scenarios in terms of various bending angle, patch elongation and substrate permittivity variation due to stretching. Reflection coefficient results in Fig. 3. highlight the strong dependence of the resonant frequency behavior on bending and stretching conditions. Starting from the flat configuration, the cylindrical TLM solver successfully reproduces shifts in the resonant frequency with increasing bending angles ($2\theta = 25°$, 50°) and generates corresponding results based on added patch elongation Δl and substrate permittivity descriptor, ε_r^{VFP}. While bending itself introduces the detuning effect with frequency shifts increasing at larger angles, elongation lowers the resonant frequency caused by extending the electrical length of the patch. Finally, stretching reflecting the dielectric redistribution within the textile substrate and modifying the effective permittivity, leads to increasing the frequency.

Fig. 4. summarizes and quantifies the influence of antenna deformations to resonant frequency values by separating effects of bending, and patch elongation and substrate permittivity variation as secondary effects of the bending. As expected, larger bending angles cause a greater additional frequency shift toward lower values due to the effective elongation of the current path along the patch, as well as toward higher frequencies due to permittivity changes due to substrate stretching. The particular and cumulative effects of the considered effects can be illustrate with approximate frequency shifts in percent based on the reference frequency of about 2.444 GHz of the flat case antenna. For example, bending of 50° generates a rise in frequency of +3.68%, while the patch elongation added in model produces shifts of –4.10% downward in respect to bending case, generating cumulative small negative shifts with respect to the
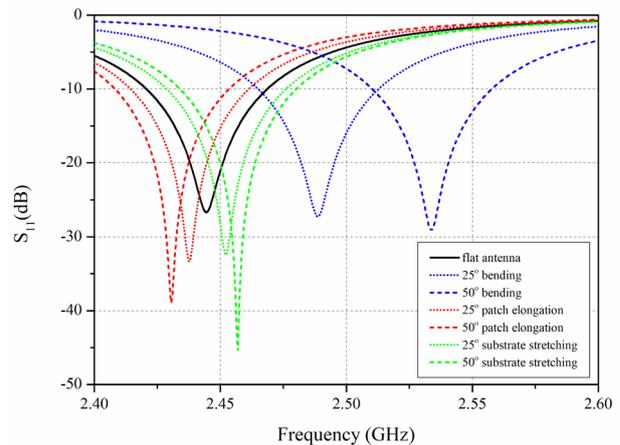

Fig.3. The reflection coefficient of rectangular patch antenna with bending, patch elongation and substrate permittivity caused by the stretching.
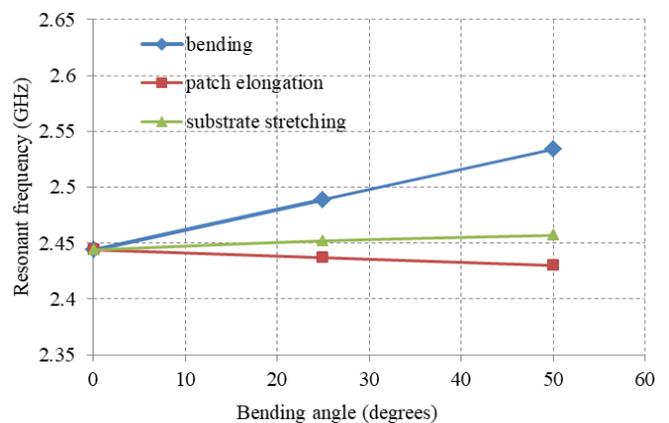

Fig.4. The resonant frequency changing with bending, patch elongation and substrate stretching effect.

flat case, of about –0.57%. Finally, dielectric permittivity change due to stretching as result of 50° bending leads to shifts of about +1.11%, generating total cumulative modest positive shifts in respect to the flat case resonant frequency of +0.53%. Generally, these trends are consistent with previous analytical, numerical and experimental studies on textile antennas [5-9, 11-12], where bending elongates the antenna effective length while stretching alters both geometry and the substrate dielectric distribution.

III. DISCUSSION AND CONCLUSIONS

This study demonstrates that the cylindrical TLM solver provides a reliable and computationally efficient tool for modelling the electromagnetic response of textile-based wearable antennas under realistic deformation conditions. The analysis of textile antenna bending along with effects of patch elongation and dielectric permittivity change due to stretching, confirms that deformations significantly affect antenna resonances, within tolerances that can be engineered for practical applications.

The cylindrical TLM solver demonstrates capability and robustness in maintaining geometry consistency during textile antenna deformation, which is a key advantage over fine-mesh rectangular grid approaches. Presented results quantify the influence of antenna deformations by separating bending itself

in geometrical sense, patch elongation and substrate permittivity variation due to stretching effects of textile structure. Importantly, these three mechanisms contribute differently: bending causes frequency increasing, elongation dominates creating cumulative detuning to lower frequencies, and stretching based on material-dependent dispersion induces smaller but measurable variations to higher frequencies. This decomposition validates the modelling approach, as it captures both geometric and material responses under real wearable conditions.

The combined results emphasize that frequency stability is highly sensitive to both geometrical and structural changes and provide valuable insights into the influence of deformations on the resonant characteristics of the textile antennas. Therefore, accurate characterization of textile antennas cannot rely solely on flat-case considerations but must account for body-induced deformations. The cylindrical TLM method provides a computationally efficient framework to predict these effects without resorting to fine meshes, reducing cost while improving physical insight based on parametric description on effects of deformation separately. In addition, the cylindrical TLM approach provides a strong foundation for further exploration of reliable, flexible, and high-performance textile antennas in body-centric communication systems.

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