# Modelling of Conformal Antennas using Time-Domain TLM Method

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***Abstract*—As textile antennas are seeing a major growth in recent years, there is a demand for understanding how they behave when exposed to a realistic environment. Typically, that is done by analyzing the effect of bending on antenna performance. To achieve that, an appropriate, accurate and reliable modeling approach is required. This paper uses two computational methods that employ different discretisation approaches to analyse the effect of bending on antenna performance, namely antenna reflection coefficient. The paper further aims to investigate how the discretisation approach influences the nature and the accuracy of results.**

***Index Terms*—Bending effect, textile antennas, patch antennas, TLM method.**

## I. Introduction

WEARABLE applications have experienced an enormous rise in a recent decade fueled by rapid development of 5G technology and continued demand for better health and wellbeing. One of the current challenges in designing wearable antennas is to account for realistic environment which may include the effect of the human tissue but also the impact of arbitrary deformations of textile antenna caused by human movement in everyday activities. Some initial results on the impact of human tissue have been reported in [1-3], showing that the level of performance degradation is dependent on the antenna design.

For the case of arbitrary antenna deformation, a focus has been placed on the special case of cylindrical bending which is also the simplest way of deformation. An analytical model of the cylindrical bending using the cavity mode theory has been presented in [4] with the conclusion that conformally mounted patch antenna that has substrate thickness less than one tenth of the bending radius experiences less than 5% change in resonant frequency and can be therefore treated as a planar antenna [4]. A number of papers used either experimental or simulation approaches to evaluate impact of bending on antenna performance [5-10] and show that bending of antenna can affect the resonant frequency of the antenna. Antenna can be bent along the length of the patch (E-plane) or along the width of the patch (H-plane). Results have shown that E-plane bending has a more significant impact on antenna performance as it directly affects the length of antenna which in turn determines the resonant frequency [7-8]. More recently it has been shown that the thickness of the substrate also plays an important role on how antenna will experience the bending deformation [10].

Whilst experimental measurements are necessary for full deployment, the electromagnetic (EM) computer analysis and simulation plays a vital role in the overall design process. It is important to note that the case of cylindrical bending is the one that can be described using Boolean geometry and as such can be analyzed using commercial time domain EM software that typically uses cubic grid for discretization of the problem space. However, the geometry of the cylindrically bent antenna does not conform to cubic mesh and in order to develop an accurate numerical model the antenna geometry needs to be sampled using a very fine mesh which in turn can demand large computation resources. For example, for time domain computational methods, very fine cubic mesh results in a very small timestep and long runtime. On the other hand, discretization mesh such as cylindrical or tetrahedral mesh that conforms to the structure is preferred as it eliminates the discretization errors and results in much faster and more accurate simulations.

In this paper, the well-established, time domain numerical TLM method has been used to analyze the impact of the bending on textile patch antenna on the $S_{11}$ parameter. The paper considers only the case of E-plane bending as it has a more severe impact on antenna performance. The paper compares the antenna results for several bending angles obtained using TLM method based on the rectangular mesh (recTLM) [11], and the TLM method based on purely cylindrical mesh (cylTLM) [11]. Computational requirements needed for converged results are also compared between these two methods. The paper also seeks to understand whether the type of the mesh used would influence the nature of results. In the following sections a brief description of the TLM method is given, followed by the results and conclusion section.

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## II. THE TLM METHODOLOGY

The TLM method is a time-domain numerical modeling technique based on equivalences between Maxwell's equations and equations for voltage and current pulses propagation along transmission lines to determine electromagnetic field components [11]. It uses a network of interconnected nodes filling out the propagation space while appropriately representing electromagnetic properties of the homogeneous or inhomogeneous media. A basic TLM cell is the symmetrical condensed node (SCN), but usually HSN (hybrid SCN) node is used to enable modelling of a non-uniform mesh [11]. Depending on the modeling problem, nodes can be generated as cubes or cuboids for Cartesian mesh, "slice of cake" type node for a cylindrical mesh [11] or tetrahedral nodes for an unstructured mesh [12]. Different types of nodes, a cuboid in a Cartesian grid, a part of a slice of cake in a cylindrical grid, and a tetrahedral one, are illustrated in Fig.1.

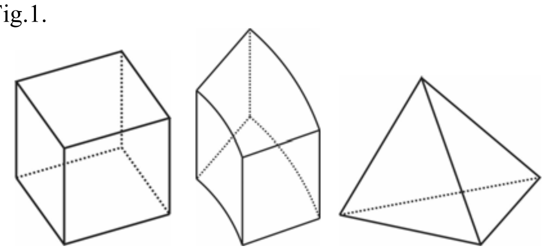


Fig. 1. TLM cell: a) rectangular, b) cylindrical, c) tetrahedral.

In the conventional TLM algorithm, in both rectangular and cylindrical grid, a problem geometry and initial conditions are firstly defined, followed by the calculation of equivalent voltages and currents for each cell, which may be further used to calculate the desired electromagnetic field component. The main algorithm consists of two basic processes that are iteratively repeated for all the nodes within the computational area, and these are, scattering, where reflected voltages at each node are calculated from the incident voltages, and connection where reflected pulses become incident pulses to the neighboring nodes for the next time step. The simulation starts by defining excitation voltages which then propagate through series of reflections and scattering between adjacent nodes while different propagation conditions pertaining to pulse velocity and boundaries are considered. Hence, a dielectric presence is characterized by its relative permittivity and loss tangent. As an output of the simulation, a voltage or a current induced in the wire can be obtained which is further manipulated to determine the reflection coefficient [13].

## III. RESULTS AND DISCUSSION

The textile patch antenna bent over a cylinder is schematically shown in Fig.2. The patch has the length $l$ and the width $w$ and is bent over the cylinder of radius $R$ over angle $2\theta$. A coaxial feed is modelled as a wire which is used as an excitation. For the patch antenna considered in this paper, both the patch and the ground plane are described as PEC layers, while the wire is modelled using the compact wire model adapted to the cylindrical mesh [14]. The length and the width of the patch are $l = 50$ mm and $w = 39.5$ mm, respectively, while the length and the width of the substrate and ground plane are $W = L = 100$ mm. It is realized on the substrate of the relative permittivity 2.1 and the thickness $h = 2$ mm. A coaxial feed is placed at 11.5 mm from the patch edge. The flat antenna is designed to resonate at 2.45 GHz.

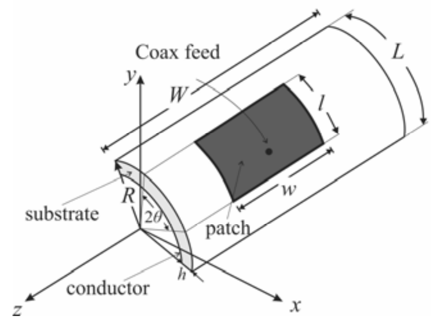



Fig.2. A rectangular patch antenna with a bending 2θ in an E-plane.

To investigate an influence of a curvature on the antenna performances several models of the antenna are considered, and each model is generated for a specific bending angle whilst preserving patch dimensions. All models are meshed with the rectangular and cylindrical TLM mesh. A convergence analysis has been conducted for both recTLM and cylTLM to determine the most adequate mesh. The convergence analysis of the recTLM method is done for the bent antenna with $2\theta = 25$ degrees and for cylindrical case the convergence analysis is done for the case of flat antenna. In both cases the methods consider the structures that do not conform to a particular mesh type. In the case of cylTLM, the flat antenna has been designed by applying very small bending angle, i.e., $2\theta = 0.1$ degrees (corresponding to the radius of $R = 22.63$ m in a cylindrical grid), i.e. $R >> l$, hence it can be considered as the flat one. Fig.3 shows the convergence of the resonant frequency for different mesh size $\Delta l$, where $\Delta l$ represents the cell size within an area around the structure with a refined mesh applied. In the cylTLM method, this area is simply the substrate area.

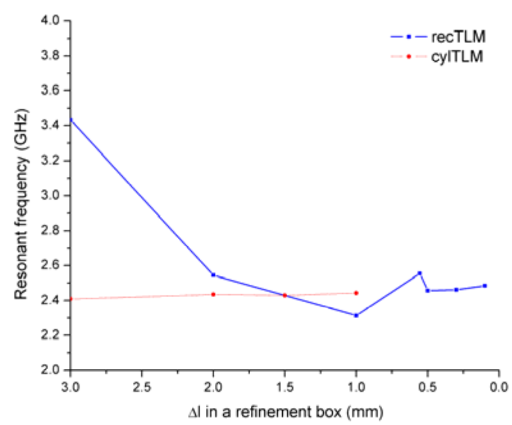



Fig.3. Illustration of the resonant frequency convergence with the mesh refinement when the recTLM method (blue line) is used for the bent antenna, and cylTLM method (red line) is used for the flat antenna (Δl represents the observed cell size).

As can be seen, the resonant frequency of the antenna converges to a different value in the recTLM and cylTLM method. This is as expected since the bending affects the resonant frequency. Furthermore, the recTLM achieves convergence for much smaller values of $\Delta l$ confirming that discretization error around the curved surfaces can affect the convergence analysis. The cylTLM on the other hand has much smoother and faster convergence since the mesh is ideally suited to the structure even though the considered antenna is almost flat resulting in 10 times smaller mesh for the converged result compared to recTLM.

The comparison of a number of cells and their dimensions required for different mesh types is shown in Table 1. It shows that rectangular TLM requires much larger computational resources than cylindrical TLM, resulting in about 6 times larger mesh when 0.5 mm rectangular cell size is used, and about 360 times larger mesh for 0.1 mm cell size. This is a significant advantage of cylindrical TLM method for this particular application.

Table 1. The comparison of computational mesh size between recTLM and cylTLM approach

| Method | Cell size (general mesh/ refined area) | Number of nodes | Wire radius |
|---|---|---|---|
| recTLM | 1 mm/0.5 mm | 80×280×260 ~6M | 0.1mm |
| recTLM | 1 mm/0.1 mm | 240×1240×1140 339M | 0.025mm |
| cylTLM | 1.449 mm/1 mm | 151×42×149 944k | 0.1mm |

For the case of flat antenna, the cylTLM method with 1 mm mesh gives resonant frequency at 2.443 GHz and the recTLM gives resonant frequency at 2.454 GHz if 0.5 mm mesh is used and 2.492 GHz if 0.1 mm mesh is used. Further investigation has included modeling of antennas cases with a different bending angle, i.e., $2\theta$=25, 50 and 60 degrees, while patch dimensions are kept the same. The $S_{11}$ results obtained using cylTLM, and recTLM methods are shown in Figs. 4 and 5, respectively. The $S_{11}$ of the flat antenna is also included in figures for reference. All results show that resonant frequency values are influenced by the curvature. According to the Fig.4, when the cylTLM approach is used, results show that the resonant frequency is increased with rising the bending angle in an almost linear fashion, while the matching condition is affected as well. However, in the case of recTLM method, as presented in Fig.5a, the trend is different for coarser mesh (0.5 mm), showing reduction in resonant frequency for various bending angles compared to Fig.4. When a finer mesh is used (0.1mm), as shown in Fig.5b the trend is more similar to the cylTLM results. A difference between the resonant frequency values by two approaches might be attributed to introducing the wire for excitation of much smaller wire radius in the recTLM than in the cylTLM approach, due to a much smaller cell size. Also, a better matching is possible to achieve when a finer rectangular mesh is used.

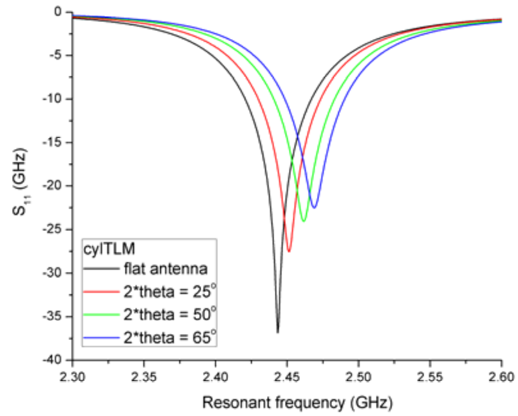
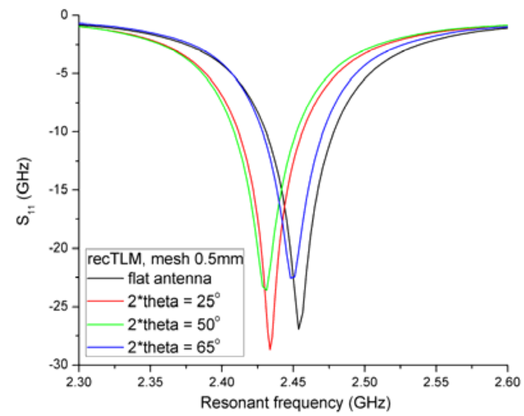
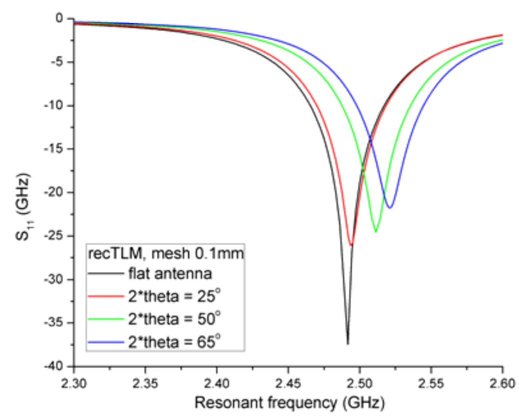



Fig.4. Comparison of S11 parameter of the flat antenna and antenna bent over a cylinder of angle 2θ =25, 50 and 60 degrees. Results are obtained using cylTLM method (1.0 mm cell size).




a)




b)

Fig.5. Comparison of S11 parameter of the flat antenna and antenna bent over a cylinder of angle 2θ =25, 50 and 60 degrees. Results are obtained using recTLM method with a) courser mesh (0.5 mm cell size), b) finer mesh (0.1 mm cell size).

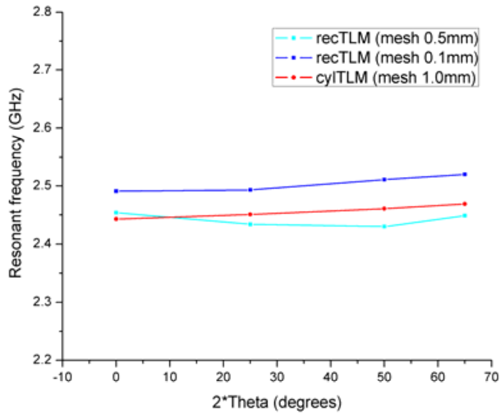



Fig.6. The resonant frequency vs the bending angle (2*theta) of the flat and bent rectangular patch antenna obtained by recTLM, and cylTLM approaches.

Fig. 6. presents the comparison of the resonant frequency reached via these two methods for various bending angles. Fig.7. reveals that the maximum frequency shift when the cylTLM approach is applied is 26 MHz, while the recTLM approach with the courser mesh gives 13 MHz, and 29 MHz for the finer mesh.

According to the presented results and the ease of convergence of the cylTLM method it can be concluded that results obtained using cylTLM method agree much better with the reported literature stating that E-plane bending causes the resonant frequency to shift to higher frequencies. The results obtained using the recTLM method are heavily affected by the discretization error which is confirmed by comparing results obtained using 0.5 mm and 0.1 mm mesh. It can be concluded that only a very fine mesh is needed so that the discretization error is not affecting the main EM phenomena.

## IV. Conclusion

In this paper, the well-established TLM method is applied to investigate the influence of the curvature on the rectangular patch antenna resonant frequency. Two different types of the TLM mesh, based on different cell geometries are used, namely the rectangular, and the cylindrical TLM method. Results show that when using rectangular TLM method a very fine mesh must be used to minimize the discretization error and observe correct behavior. This is not the case for the cylTLM method as the mesh is perfectly aligned with the structure resulting in a tenfold increase in the mesh size and significant reduction in computation time and memory. The converged results of both methods show that when antenna is bent in the E-plane the resonant frequency of antenna shifts to higher frequencies.

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