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Research Article

Computational Modeling of the Bent Antenna in an On-Body Mode Using the Cylindrical TLM Approach

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This paper presents the suitability and computational features of the cylindrical TLM approach, when it is used as an accurate and efficient alternative for the analysis of the bending effect on performances of the antenna operating in an on-body mode. A design goal was to create the model of the rectangular patch antenna wrapped around the part of a cylinder, which can be used to represent a human body (torso, leg, or arm) and simultaneously to model dielectric properties of muscle tissue. Moreover, the paper illustrates problems in terms of accuracy and limitations when the antenna deformation is modelled by using numerical methods based on the cubic mesh. The advantages of the cylindrical TLM method over the rectangular TLM approach have been emphasized through an analysis of how the bending affects the resonant frequency of the antenna.

1. Introduction

Biomedical engineering (BME) has been a hot research topic in the past few decades. A number of problem-solving techniques of engineering have already found useful applications in biology and medicine, leading to many advanced BME devices [1, 2]. These devices can contribute to better quality of human health and care when used in diagnostics, treatment, or studies of treatment and recovery. Currently, there is a wide range of BME products of various complexities and applications, and they can be in general classified as either diagnostic or treatment devices.

One of the key components in many BME devices is an antenna, which can be placed near to, inside, or on a human body [3]. For devices employed for diagnosis or treatment, one or more antennas are usually placed near to and around the human body, e.g., for microwave resonant imaging (MRI) and microwave imaging (MI) diagnosis [2, 4] or for hyperthermia treatment [5]. The antenna can also be implanted into the human body either directly or through a capsule travelling through the body [6] or it can be positioned on the human body, e.g., placed on a garment or mounted directly over the torso [3] in order to form a bio-wireless sensing and communication system for on-body or off-body transmission links [7]. The design of majority of these antennas faces with physical constraints such as size, power, and safety limitations, which can overall affect the efficiency of the BME device itself.

Focusing on antennas deployed on the different parts on the human body (so-called on-body and wearable antennas), either embedded into human skin or clothing (e.g., textile antennas), other challenges in their design exist, such as the close proximity of the human body leading to antenna detuning, disturbing the antenna impedance and reducing the antenna gain and efficiency [8, 9]. Also, variations of human body posture and motions in everyday activities are causing a number of deformations such as stretching, twisting, bending, and crumpling or more often a combination of two or more of these deformations. As a result of deformed antenna geometry, many antenna parameters change like shifting resonant frequency, changing gain, radiation pattern, and polarization [9].

In literature, the impact of cylindrical bending on mostly printed textile antenna performances has been dominantly considered, both numerically and experimentally [10]. It should be also pointed out that the human body is a nonplanar structure and that antenna with different shapes is required to operate on different body parts. To address these challenges, different types of anatomical models of human body or its parts are usually used in experimental measurements in order to account for body tissues presence. They can be of different geometrical complexity including single and multilayer canonical structures, such as three-layer phantom model (skin, fat, and muscle) made by using gels and/or liquids.

Still, in order to provide a fully conformal BME device that can be seamlessly and unobtrusively integrated onto the human body characterized by curvilinear surfaces and dynamically changing motions, electromagnetic (EM) computer simulation tools play a vital role in the overall design of BME antenna. These tools, usually based on some of available differential or integral full-wave numerical techniques such as FDTD [11], MoM [12], FEM [13], and TLM [14], should be able to accurately account for dispersive, lossy, and, in some cases, anisotropic human body tissues. Also, they should be capable to accurately generate geometrical models of antennas, which are either deformed due to garment-on-body posture and movement, or simply they are conformal to some curvilinear parts of human body such as arms and legs. Most of these tools are based on constructive solid geometry (e.g., using Boolean geometry operations) and cubic grid/mesh space discretization, which means that they are either able to capture simpler deformations such as bending and/or to use a very fine staircase approximation to mesh such deformed antenna geometry or antenna geometry that follows curvilinear shape of the body part. In a case of differential time-domain numerical techniques (e.g., the FDTD), this approach could lead to a very small-time step and excessive runtime and also in some cases may produce so-called dirty interfaces (when interfaces on the antenna do not perfectly align), which are detrimental for EM simulations. Computer graphic methods (e.g., green coordinates [15]) are recently proposed to overcome the limitations of classical Boolean geometry-based commercial EM tools [16, 17]. These advanced geometry generators can allow for manipulations of antennas shape under arbitrary deformation and in combination with suitable numerical method and tetrahedral mesh to minimize the discretization errors and present a powerful tool for conformal BME device design.

The alternative to this highly advanced solution, but still costly, regarding the memory and runtime, may be an implementation of chosen numerical technique in the coordinate system that conforms to the considered antenna-deformed geometry. In case of the antenna bending, the cylindrical discretization mesh is perfectly suited to accurately describe this deformation and to eliminate the discretization errors leading to much faster and more efficient simulation compared to either rectangular of tetrahedral meshes. In addition to that, any change in bending angle will be simple-handled in the cylindrical mesh allowing to exclude the influence of different mesh sizes (and therefore slightly differently placed source and output points due to mesh adjustment) when performing an analysis of different antenna bending angles impact on its performances.

In this paper, the cylindrical TLM approach is applied to modeling of bending deformation of an antenna placed on the human body. The advantages of this approach, which simultaneously provides an accurate modeling of the antenna geometry and dielectric properties and efficient analysis of the effect of bending at different angles, are illustrated and compared to the case when the rectangular TLM method is used instead. Achieving the accuracy of the physical model of the antenna has enabled the analysis of the effect of bending on the performance of the antenna in the presence of the muscle tissue.

Section 2 of this paper explains the TLM method with the compact wire model in the cylindrical coordinate system through defining the TLM wire node along a radial direction, which is needed to model a coaxial feed, and modifications of boundaries in radial and angular directions providing better efficiency of the solver in this particular case. Main issues to realize the TLM model of the antenna are related to the description of EM properties of the medium together with an extension of the computational area, providing a possibility to define external boundaries in angular and radial direction. Simulated results obtained by the TLM models of antenna bending in the body presence and numerical analyses for different angles of the bent antenna are presented in Section 3, which is followed by the conclusion in Section 4.

2. TLM Methodology Based on the Cylindrical Mesh

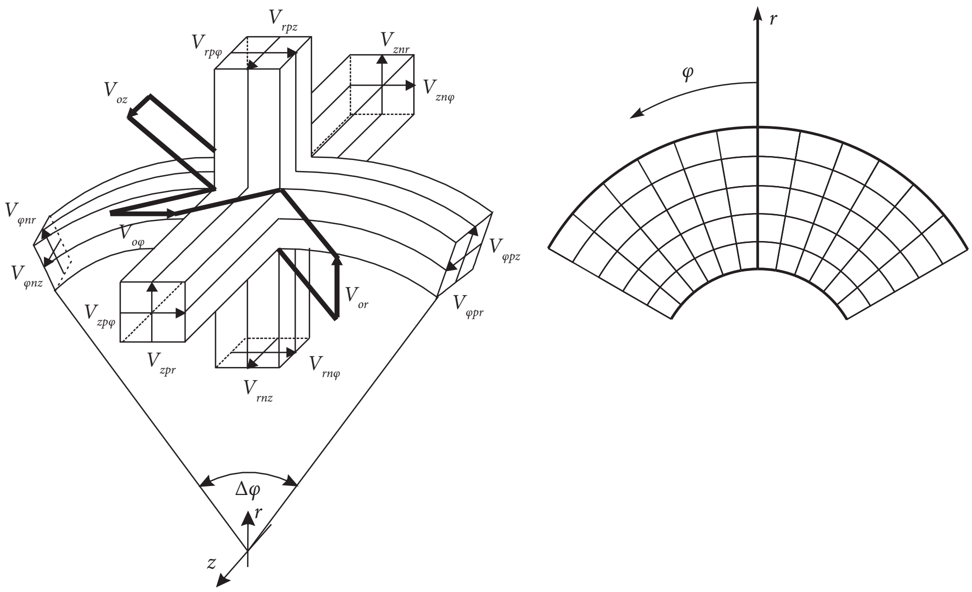
The TLM method is a numerical method belonging to the group of differential methods suitable for solving EM problems in the time-domain [14]. It is based on the equivalences between Maxwell's equations and propagation of voltages and currents along transmission lines. By using a network of interconnected nodes, it is used to model the EM wave propagation considering discontinuities and interaction with different material properties. Traditionally, the TLM method is developed in a Cartesian coordinate system, but for structures containing only circular/cylindrical surfaces, the TLM method based on the cylindrical mesh is found to be more convenient and efficient. However, when EM problems involve in much more complex geometries, then the usage of a tetrahedral mesh might emerge as the most optimal solution.

The hybrid symmetrical condensed node (HSCN) representing a cell in orthogonal polar network is presented in Figure 1(a).

Such network of cells is used to describe EM properties of the medium, where characteristic impedances and admittances of link lines are obtained as follows:

$$Y_{ij} = Y_{ji} = Y_0 \frac{2c\Delta t \Delta k}{\mu_{rk} \Delta i \Delta j}. \tag{1}$$

However, characteristic admittances of open stubs are as follows:



(a) (b)

Figure 1: Cylindrical mesh: (a) cylindrical HSCN; (b) space discretization in φ-r plane within a section of the cylinder.

$$Y_{ok} = Y_0\left[\frac{2\varepsilon_{rk}\Delta i\Delta j}{c\Delta r\Delta k} - \frac{4c\Delta t}{\Delta k}\left(\frac{\Delta i}{\mu_{ri}\Delta j} + \frac{\Delta j}{\mu_{rj}\Delta i}\right)\right], \quad (2)$$

where $(\Delta i, \Delta j, \Delta k) = (r\Delta\varphi, \Delta r, \Delta z)$. Δt is the time step, c is the speed of light, and Y_0 is the characteristic admittance of free space [18].

When voltage pulses are introduced into the system, calculated link and stub lines admittances are used to determine equivalent voltages and currents on the link and stub lines. The iterative procedure of the TLM algorithm consists of two main procedures known as the scattering and the connection [14]. They are adjusted to the orthogonal polar mesh and are additionally modified to account for excitation, boundaries, and inhomogeneous medium and losses [18, 19].

An adaptation and implementation of the compact wire model to the cylindrical grid [18] has enabled representation of the wires placed along the radial direction. The connection procedure has had to be appropriately adjusted to describe a straight wire segment located along the radial direction as described in [18, 19]. Impedances of link lines and a stub, which are embedded into the existing network of cells to account for the wire, are different for adjacent nodes k and $k+1$:

$$Z_{wr}^{k} = \frac{\Delta t}{\Delta r}\frac{\ln\left(k_{Cr}\Delta r_c^k/r_w\right)}{2\pi\varepsilon}, Z_{wsr}^{k} = \frac{\mu}{2\pi}\ln\left(\frac{k_{Lr}\Delta r_c^k}{r_w}\right)\frac{\Delta r}{\Delta t} - Z_{wr}^{k}, \quad (3)$$

where r_w is the wire radius and k_{Cr} and k_{Lr} are factors empirically obtained by using known characteristics of the TLM network [20]. Therefore, an additional connecting procedure for wire segments running along a radial direction [18] and along z-direction [21] has been developed and implemented into the existing TLM-based software in the cylindrical grid.

Besides relevant representation of the geometry and EM properties of inhomogeneous medium, in case of the so-called open problems such as the patch antenna, it is necessary to add an appropriate extension around the structure forming a computational box, in order to include the antenna surroundings, e.g., the so-called fringing fields associated with the patch edges.

However, all the previous work has assumed that the surrounding area of a considered structure, making a computational box with defined external boundaries, is of a completely cylindrical shape. Hence, simulations demanded definition of a padding all around the structure placed in the center of the cylinder, without any boundary condition defined along the angular direction. Instead, only the first and the last nodes in the angular direction are needed to exchange pulses. In the example presented here, the patch antenna is located away from the center of the cylindrical coordinate system, and the usage of the whole cylinder as the computational box is found to be memory consuming. For this reason, the TLM algorithm is adjusted to allow for setting up boundary conditions along the angular directions. An orthogonal polar network in the φ-r plane is illustrated in Figure 1(b) showing a space discretization represented within the section of a cylinder. Additional improvements are achieved by enabling a possibility to define a boundary condition on the inner surface of the computational cylinder box along the radial direction, instead of defining the central node.

Generally, the TLM method allows three types of boundaries to be described: an electric wall, a magnetic wall, and an absorbing wall. In case of the patch antenna modeling, the electric wall is used for the ground plane and the radiated patch, while the outer boundaries of the extended region are described as absorbing the reflection coefficient of the relevant link line calculated as follows (ρ_{w} is the reflection coefficient of the wall, and $\widehat{Z}_{ij}$ is the normalized link line impedance) [22]:

$$\rho_{ij} = \frac{(1+\rho_w) - \widehat{Z}_{ij}(1-\rho_w)}{(1+\rho_w) + \widehat{Z}_{ij}(1-\rho_w)}. \quad (4)$$

As a result of defining a modeling space as a part of a cylinder together with boundary conditions, the computational area is significantly reduced, demanding much smaller number of TLM cells and leading to higher efficiency on both time and memory savings. Advantages of this approach would be particularly noticeable in cases when the curvature such as the bending is small, when the large radius of the cylindrical area is requested, consequently a significantly larger number of cells, if the computational area is represented by the whole cylinder instead of the section. Furthermore, in this way, with sufficiently large values of the radius of the cylinder, it is possible to model rectangular structures in the cylindrical network. By changing a cylindrical radius only, it is possible to create models with different bending angles, using the same mesh in terms of resolution, and analyze the bending influence on antenna performances, independently from other model parameters that change due to approximation, such as the surface of radiated patch, substrate, and coaxial feed position.

3. TLM Modeling of Antenna Bending in the Body Presence

The in-house TLM solver has been used to analyze the impact of bending on the patch antenna performances when placed on a human body. In the considered case, a part of a muscle tissue is placed beneath the antenna. The patch antenna with dimensions $w \times l = (50 \times 39.5)\ \text{mm}^2$, placed on the substrate and ground plane of dimensions $W \times L = (100 \times 100)\ \text{mm}^2$ and bent over a part of cylinder representing muscle tissue is schematically shown in Figure 2. The antenna is realized on the substrate of the relative permittivity 2.1 and the thickness $h = 2$ mm, while the permittivity of the muscle tissue is 52.67-j13 [23], and the muscle thickness is $d = 35$ mm. In the TLM model, the radiated patch and the ground plane are represented as the perfect electric conductor (PEC), and the antenna is fed through a coaxial feed connecting the ground plane and the patch, which is described via the compact wire model. Its position is optimized to achieve an impedance matching between the feed and the antenna, and it is located at 11.5 mm from the patch edge. The operating frequency of the antenna is 2.45 GHz.

Describing a problem with an appropriate mesh, in terms of a cell size and a conformity, is very important in order to ensure convergence of results. Opposite to a staircase approximation, which must be used in a rectangular TLM mesh to describe curved boundaries, accurate modeling of circular boundaries is straightforward in the cylindrical TLM mesh, with dimensions of cells limited only by a maximum frequency of interest [14]. As a result, curved boundaries can be precisely modelled using the cylindrical mesh irrespective of the mesh resolution, whereas the rectangular mesh must be fine enough to achieve better accuracy. To prove this, the considered antenna model is created also by using the

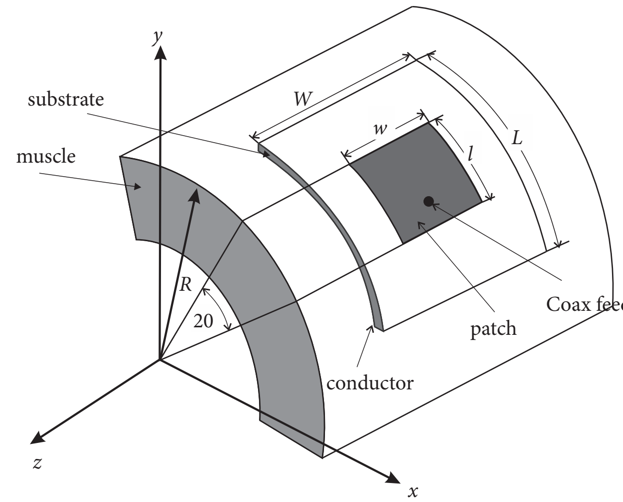


Figure 2: A rectangular patch antenna with a bending 2θ in an E-plane.

rectangular TLM solver. Simulations are performed for the flat antenna, but also for the bent antenna, to investigate an impact of the bending on the antenna resonant frequency. Two bending angles are considered, $2\theta = 25$ and 50°. Simulated results, representing the reflection coefficient, are presented in Figures 3 and 4 obtained by the cylindrical TLM and the rectangular TLM, respectively, when the 1.0 mm cell size is applied for antenna modeling.

According to the results of the flat antenna modeling, it is possible to notice the agreement of the results obtained by applying the cylindrical mesh with the corresponding results of applying the rectangular network, both with 1 mm resolution (black line at Figures 3 and 4). Practically, in the case of antenna model in the cylindrical grid, the flat antenna has been designed by applying a very small bending angle, $2\theta = 0.1^\circ$, which is equivalent to the radius of the cylinder satisfying the condition, $R >> l$ (about 500 times); hence, it can be considered as the flat one. The applicability of the cylindrical mesh to model structures with almost no curvatures is confirmed with the obtained value of the resonant frequency −2.444 MHz, with respect to the one based on the rectangular mesh −2.473 MHz.

On the other hand, results obtained by the cylindrical TLM and the rectangular TLM, with 1.0 mm cell size applied for antenna modeling, show difference in the frequency shift due to the bending of antenna placed on the muscle tissue. In fact, with the cylindrical approach, it can be observed that a larger bending angle gives a larger resonant frequency deviation, whilst, at the same time, results of modeling by the rectangular grid with 1.0 mm resolution show decreasing of the frequency compared to the flat case together with nonconsistency regarding dependence of the frequency shifting versus the bending angle. This can be explained by the fact that the rectangular model, in case of the bent antenna, introduces an approximation of the curved radiated patch affecting its resonant frequency. Consequently, it is necessary to use a finer mesh that would reduce the staircase approximation error and ensure accurate results. In order to illustrate the impact of the mesh resolution when

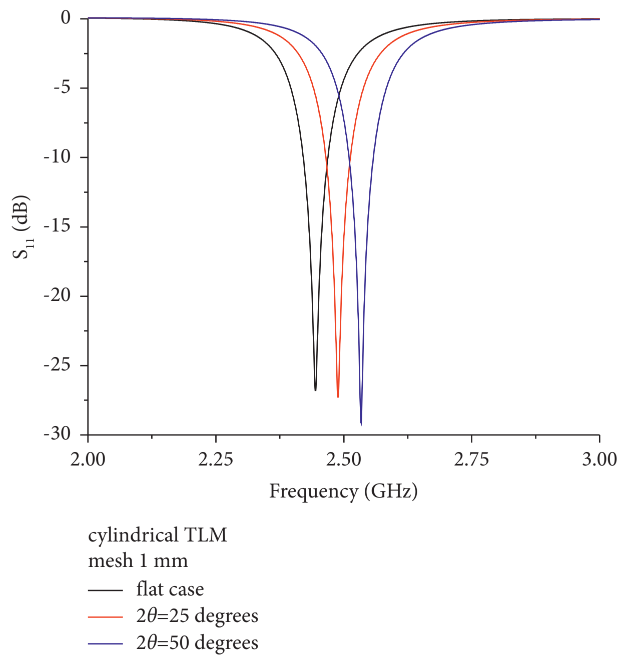


FIGURE 3: S_{11} parameter of the flat antenna and the bent antenna on the muscle tissue obtained using the cylindrical TLM method (1.0 mm cell size).

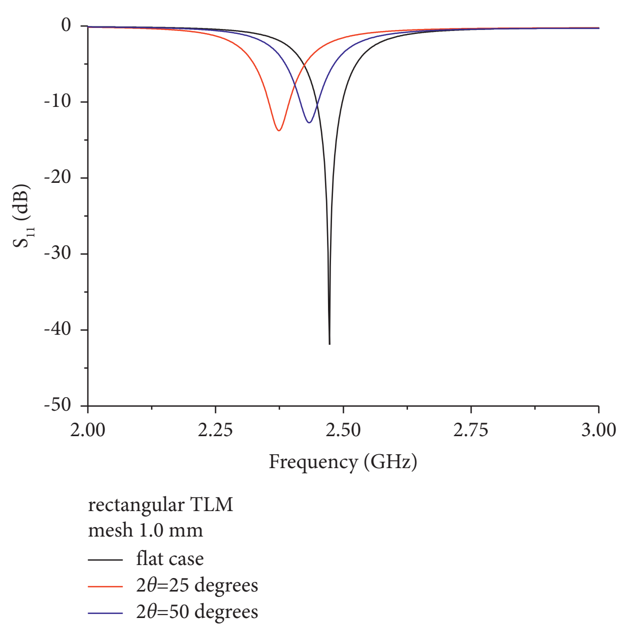


FIGURE 4: S_{11} parameter of the flat antenna and bent antenna on the muscle tissue obtained using the rectangular TLM method (1.0 mm cell size).

the rectangular TLM is used, the antenna model is described by the rectangular mesh of 0.1 mm cell size. The simulated resonant frequency obtained by this rectangular mesh, presented in Figure 5, shows that the resonant frequency is rising with increasing the bending angle, similar as it is the case when the cylindrical TLM mesh is used.

Figure 6 summarizes a resonant frequency deviation, caused by the bending of patch antenna placed on muscle

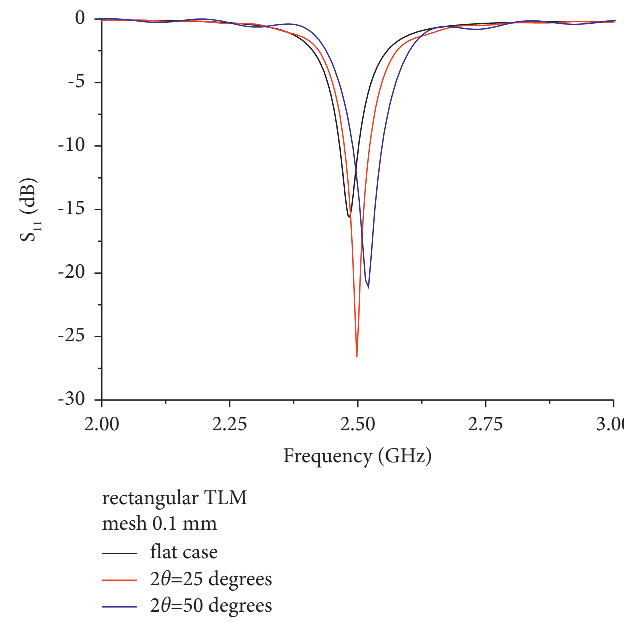


FIGURE 5: S_{11} parameter of the flat antenna and bent antenna on the muscle tissue obtained using the rectangular TLM method (0.1 mm cell size).

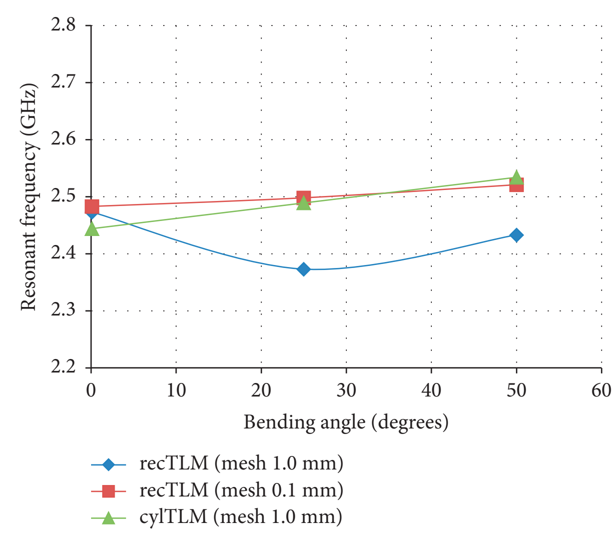


FIGURE 6: The resonant frequency vs. the bending angle (2θ) of the rectangular patch antenna on the muscle tissue obtained by the cylindrical TLM method (1.0 mm cell size) and rectangular TLM method (1.0 mm and 0.1 cell size).

tissue, obtained by the cylindrical mesh of 1.0 mm cell size and by the rectangular TLM mesh with 1.0 mm and 0.1 mm cell sizes. As can be seen, when the same cell size is used in the rectangular and cylindrical method (1.0 mm), the behavior of the resonant frequency is different. Therefore, a much finer rectangular mesh (0.1 mm) ensures consistency of results in terms of frequency shift, similar as the ones provided by cylindrical coarser mesh (1.0 mm).

The computational mesh parameters such as the cell size and the number of cells, in case of the flat antenna, are presented in Table 1 for the cylindrical TLM approach and in

Table 1: Computational mesh parameters (cell size and number of cells) in the cylindrical TLM used for the modeling of the flat patch antenna and bent antenna on the muscle tissue.

Axis	Medium	Cylindrical TLM (1.0 mm)	
		Cell size (mm)	Number of cells
r-axis (substrate height)	Muscle	~0.2	175
	Substrate	1	2
	Air	1.449	28
φ-axis (length)	Padding	1.449	28
	Substrate	~1	99
	Padding	1.449	28
z-axis (width)	Padding	1.449	28
	Substrate	~1	99
	Padding	1.449	28
Total number of cells			*4.9 M*

Table 2: Computational mesh parameters (cell size and number of cells) in the rectangular TLM used for the modeling of the flat patch antenna placed on the muscle tissue.

Axis	Medium	Rectangular TLM (1.0 mm)		Rectangular TLM (0.1 mm)	
		Cell size (mm)	Number of cells	Cell size (mm)	Number of cells
x-axis (substrate height)	Muscle	~0.2	175	~0.02	1750
	Substrate	1	2	0.1	20
	Air	1.449	28	0.1449	280
y-axis (length)	Padding	1.449	28	0.1449	280
	Substrate	~1	99	~0.1	990
	Padding	1.449	28	0.1449	280
z-axis (width)	Padding	1.449	28	0.1449	280
	Substrate	~1	99	~0.1	990
	Padding	1.449	28	0.1449	280
Total number of cells			4.9 M		4900 M

Table 2 for the rectangular TLM. Note that the mesh resolution is set to accomplish time synchronization demands [14]. Details of cell sizes and number of cells are divided by the axis relevant to a corresponding coordinate system (r, φ, and z in the cylindrical grid and x, y, and z in the rectangular grid). It can be observed that, in case of the same cell size (1.0 mm), the total number of cells is equal in both cylindrical and rectangular mesh.

Presented results based on 1 mm mesh confirmed that the cylindrical model can be used in the bending impact analysis, while the rectangular mesh is not adequate and a finer resolution is required. Moreover, there is an increment of more than 1000 times in the number of cells when 0.1 mm rectangular mesh is used, proving the strong advantages of the cylindrical mesh in this particular case.

4. Conclusion

In this paper, the TLM method adapted to the orthogonal polar mesh has been used to design and analyze bending deformation of a patch antenna placed on a human body. Since the effect of deformation on antenna parameters should be made independent of numerical errors, creating a relevant TLM antenna model requires setting up model dimensions, network resolution, appropriate modeling region expansion, and the coaxial feed position optimization. The approach has been modified to allow for using boundary conditions along a radial and angular direction leading to a significant reduction of a computational area and hence for the memory and time reductions as well. Presented results show the advantages of the model created in the cylindrical TLM mesh, which simultaneously provides accurate modeling of the antenna geometry and dielectric properties of the substrate and tissue. The method's accuracy and possibilities are compared with the rectangular TLM method.

In overall, presented numerical results have shown that the TLM method based on cylindrical mesh is more convenient and more accurate for the modeling of the antenna under bending. Major advantages of the cylindrical TLM method compared to the rectangular TLM are the conformal modeling of cylindrical boundaries, with an accuracy achieved with smaller number of cells, and additionally a flexibility to model realistic bending for different angles. This work is based on a model of a narrow band rectangular antenna, in order to illustrate the capabilities of the solver in the analysis of flexible antenna systems. However, the proposed method is generally suitable for analyses of bending effect and can also be successfully applied to the parametric analysis of complex geometry antennas designed for the dual band mode of operation or wideband applications [24, 25]. The possibilities of defining different dielectric layers in the radial direction also provide an accurate modeling of antenna wrapped around a cylinder in order to mimic the human tissue presented as the standard multilayer model consisting of skin, fat, muscle, and bone, used in the simulations. For these reasons, the solver can be efficiently used to carry out a parametric study to characterize bending antenna in an on-body mode related to a resonant frequency shifting, bandwidth, and return loss changing.

Data Availability

All data sources and references are listed in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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References

[1] J. Enderle and J. Bronzino, *Introduction to Biomedical Engineering*, Academic Press, Netherland, Europe, 2011.

[2] L. Wang, *Electromagnetic Waves and Antennas for Biomedical Applications*, IET, London, UK, 2021.

[3] G. Kaur, A. Kaur, G. K. Toor, B. S. Dhaliwal, and S. S. Pattnaik, "Antennas for biomedical applications," *Biomedical Engineering Letters*, vol. 5, no. 3, pp. 203–212, 2015.

[4] G. Solomakha, J. T. Svejda, C. Van Leeuwen et al., "A self-matched leaky-wave antenna for ultrahigh-field magnetic resonance imaging with low specific absorption rate," *Nature Communications*, vol. 12, no. 1, p. 455, 2021.

[5] W. C. Choi, S. Lim, and Y. J. Yoon, "Evaluation of transmit-array lens antenna for deep-seated hyperthermia tumor treatment," *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 5, pp. 866–870, 2020.

[6] A. Kiourti and K. S. Nikita, "A review of implantable patch antennas for biomedical telemetry: challenges and solutions [wireless corner]," *IEEE Antennas and Propagation Magazine*, vol. 54, no. 3, pp. 210–228, 2012.

[7] H. Yang and X. Liu, "Wearable dual-band and dual-polarized textile antenna for on- and off-body communications," *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 12, pp. 2324–2328, 2020.

[8] N. H. Abd Rahman, Y. Yamada, and M. S. Amin Nordin, "Analysis on the effects of the human body on the performance of electro-textile antennas for wearable monitoring and tracking application," *Materials*, vol. 12, no. 10, p. 1636, 2019.

[9] N. F. M. Aun, P. J. Soh, A. A. Al-Hadi, M. F. Jamlos, G. A. Vandenbosch, and D. Schreurs, "Revolutionizing wearables for 5G: 5G technologies: recent developments and future perspectives for wearable devices and antennas," *IEEE Microwave Magazine*, vol. 18, no. 3, pp. 108–124, 2017.

[10] L. Song and Y. Rahmat-Samii, "A systematic investigation of rectangular patch antenna bending effects for wearable applications," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 5, pp. 2219–2228, 2018.

[11] K. S. Kunz and R. J. Luebbers, *The Finite Difference Time Domain Method for Electromagnetics*, CRC Press, Boca Raton, FL, 1993.

[12] W. C. Gibson, *The Method of Moments in Electromagnetics*, Chapman and Hall/CRC, Boca Raton, Florida, 2021.

[13] T. J. R. Hughes, *The Finite Element Method: Linear Static and Dynamic Finite Element Analysis*, Prentice-Hall, New Jersey, NY, USA, 1987.

[14] C. Christopoulos, *The Transmission-Line Modelling Method: TLM*, Institute of Electrical and Electronics Engineers, New York, NY, USA, 1995.

[15] Y. Lipman, D. Levin, and D. Cohen-Or, "Green coordinates," *ACM Transactions on Graphics*, vol. 27, no. 3, pp. 1–10, 2008.

[16] P. Sewell, T. M. Benson, C. Christopoulos, D. W. P. Thomas, A. Vukovic, and J. G. Wykes, "Transmission-line modeling (TLM) based upon unstructured tetrahedral meshes," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 6, pp. 1919–1928, 2005.

[17] E. Altinozen, I. Harrison, A. Vukovic, and P. D. Sewel, "Green Coordinates for Generation of Conformal Antenna Geometries," in *Proceedings of the 14th European Conference on Antennas and Propagation – EuCAP*, IEEE, Copenhagen, Denmark, March 2020.

[18] T. Dimitrijević, J. Joković, B. Milovanović, and N. Doncov, "TLM modeling of a probe-coupled cylindrical cavity based on compact wire model in the cylindrical mesh," *International Journal of RF and Microwave Computer-Aided Engineering*, vol. 22, no. 2, pp. 184–192, 2012.

[19] J. Jokovic, T. Dimitrijevic, N. Doncov, and B Milovanovic, "Efficient integral cylindrical transmission line matrix modelling of a coaxially loaded probe coupled cavity," *IET Microwaves, Antennas & Propagation*, vol. 9, no. 8, pp. 788–794, 2015.

[20] V. Trenkic, A. J. Wlodarzcyk, and R. A. Scaramuzza, "Modelling of coupling between transient electromagnetic field and complex wire structures," *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 12, no. 4, pp. 257–273, 1999.

[21] J. J. Joković, T. Z. Dimitrijević, and N. S. Dončov, "Computational analysis and validation of the cylindrical TLM approach on IMCP antennas," *Wireless Personal Communications*, vol. 106, no. 3, pp. 1573–1589, 2019.

[22] T. Z. Dimitrijevic, J. J. Jokovic, and N. S. Doncov, "Efficient modeling of a circular patch-ring antenna using the cylindrical TLM approach," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2070–2073, 2017.

[23] C. X. Mao, D. Vital, D. H. Werner, Y. Wu, and S. Bhardwaj, "Dual-polarized embroidered textile armband Antenna array with omnidirectional radiation for on-/off-body wearable applications," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 4, pp. 2575–2584, 2020.

[24] M. M. Khan, K. Islam, Md. N. A. Shovon, M. Masud, M. Baz, and M. A. AlZain, "Various textiles-based comparative analysis of a millimeter wave miniaturized novel antenna design for body-centric communications," *Int. Jour. Ant. Prop*, vol. 2021, Article ID 2360440, 14 pages, 2021.

[25] H. Singh, B. K. Kanaujia, S. Kumar, and K. Srivastava, "A compact wideband flexible antenna for wireless medical telemetry services," *Wireless Personal Communications*, vol. 123, pp. 2393–2411, 2022.