TLM MODELLING OF THIN WIRE STRUCTURES

Bratislav D. Milovanović[1], Nebojša S. Dončov[1], Vladica M. Trenkić[2]
[1]Faculty of Electronic Engineering, University of Niš,
P.O.Box 73, Beogradska 14, 18000 Niš, Yugoslavia
[2]Kimberley Communications Consultants Ltd.,
P.O.Box 5037, Nottingham, NG16 3BF, United Kingdom

Abstract-**In this paper, coupling between electromagnetic field of dipole antenna and thin wire structures is modelled by using the transmission-line modelling (TLM) method. Two basic integrated 3-D TLM solutions of wire modelling are presented and compared by the appropriate example. Two models, for describing resistive load at the ends of wire structures and its connection to another structures are proposed and verified. Calculated numerical results for induced wire current are presented in the frequency domain and compared with those obtained by running miniNEC and NEC2 simulators.**

INTRODUCTION

In many problems in applied electromagnetics it is necessary to simulate coupling between electromagnetic field and thin wire structures. Examples are in electromagnetic compatibility (EMC), in antennas and in microwave design. Focusing in particular on the electromagnetic compatibility problems, the main difficulty as far as numerical modelling is concerned is that it is normally inefficient to describe in detail the geometrical features of wires in a mesh which is normally configured to model propagation in a large space, e.g. free-space, room, or equipment cabinet. The problem is particularly acute when differential numerical methods, such as transmission-line modelling (TLM) method [1] and finite-difference time-domain (FD-TD) method [2], are used in modelling.

Two basic approaches for treating wires in TLM have evolved: the so-called separated and integrated solutions. In the separated solutions, the wires are treated separately from the rest of the problem, allowing for field coupling to the wire by introducing equivalent sources derived from knowledge of the incident fields in the vicinity of the wire. Separated solutions for TLM are simple and can deal easily with both single and multi-wire problems [3]. However, they have obvious limitation that any electromagnetic interaction of the wires with the rest of the modelled structures must be negligible small. So, it is only one-way coupling from the electromagnetic field to the wires that is effectively modelled by separated solutions which is, clearly, inadequate for EMC problems.

The simplest integrated solutions in TLM are those where wires are modelled by using short-circuit nodes or shorted link-lines adjacent to the wire surface [1,4]. In that way wires are explicitly included in the model, hence the model is consistent and two-way coupling is simulated. However, computational resource limitations and geometrical disparity between whole modelled space and core of the EMC problem, means that the wire is usually modelled by no more than a single node cross-section on a rectangular Cartesian mesh. This results in a rather crude rectangular shape model of the wire.

More sophisticated integrated solution (so-called TLM wire node), which can allow for accurate modelling of wires with a considerably smaller diameter then the node size, uses special wire networks embedded between [5] or within nodes [6,7] to model signal propagation along the wire, while allowing for interaction with the electromagnetic field. In order to accomplish this task, the wire network is formed by using additional link and stub lines. The ability to model very fine wires without excessive computational costs [8] makes the wire node increasingly popular in TLM simulations.

In this paper, for the example of resonant frequency calculation of dipole antenna in free space, advantage of TLM wire node in relation to first integrated wire solutions is shown. After that, wire conductor above perfectly conducting ground (Fig. 1) and two-wire line in free space (Fig. 2), as the characteristic forms of EMC problems, are modelled by using TLM wire node. Both structures are excited by dipole antenna as the real excitation for the most cases of EMC problems. In order to verify the obtained TLM results for the cases of unloaded wire conductor ($R_1 = R_2 \rightarrow \infty$) and shorted two-wire line ($R_1 = R_2 = 0$), the same structures are analysed by using miniNEC and NEC2, a simulators based on the method of moments.

In EMC problems, beside geometrical features of the wire, it is necessary to model exactly resistive load terminations of the wire structures [9,10,11]. In this paper, for the example of loaded wire conductor and loaded two-wire line (Figs. 1 and 2, respectively) in the field of dipole antenna and by using TLM wire node, two

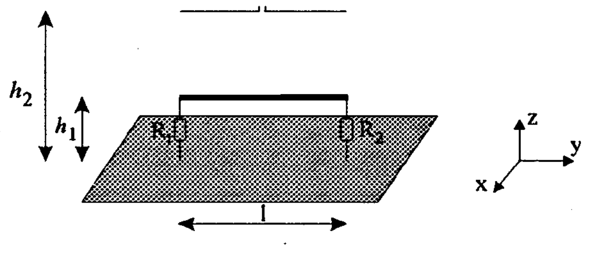


Fig. 1. A loaded wire conductor above perfectly conducting ground

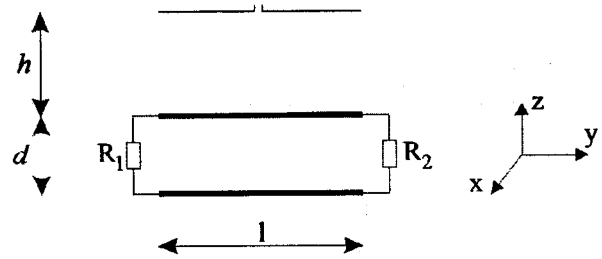


Fig. 2. A loaded two-wire line in free space

possible models of resistive load realisation at the ends of wire structures and its connection to another structures are considered. Calculated results for the current induced at the one end of wire conductor are shown in the frequency domain and compared with those obtained by running miniNEC and NEC2 simulators.

THEORETICAL ANALYSIS

The simplest integrated TLM solutions describe wire by using short-circuit nodes (Fig. 3a) or shorted link-lines adjacent to the wire surface (Fig. 3b) [1]. In the first case, wire presence in the mesh is included by modifying the scattering matrix for the short-circuit node in the following way:

$$ {}_nV^r = -{}_nV^i \tag{1} $$

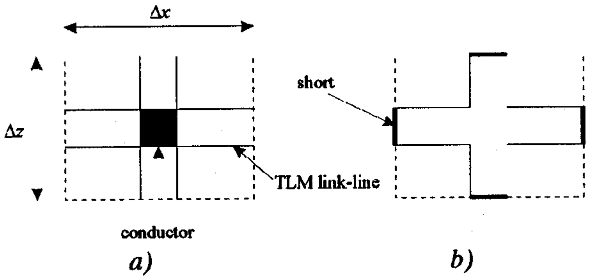
where ${}_nV^i$ and ${}_nV^r$ are vectors of incident and reflected voltages, respectively, on the appropriate TLM link-lines at time- step n. The scattering matrix for the short-circuit node is diagonal with elements equal to -1.

In the second case, the connection matrix is modified in the following way:

$$ {}_{n+1}V^i = -{}_nV^r . \tag{2} $$

In both cases, the wire is usually modelled by no more than a single cross- section, which causes shift of the resonance by 5-10 % to lower frequencies, a problem that is referred to as "resonance error" [7].

In TLM wire node, wire structures are considered as new elements that increase the capacitance and inductance of the medium in which they are placed. Thus, an appropriate wire network needs to be interposed over the existing TLM network to model the required deficit of electromagnetic parameters of the medium. In order to achieve consistency with the rest of the TLM model, it is most suitable to form wire networks by using TLM link and stub lines (Fig. 4) with characteristic impedances, denoted as Z_{wy} and Z_{wsy}, respectively.



a) b)

Fig. 3. Cross-section of the wire running in y direction, modelled by: a) short- circuit TLM node, b) shorted TLM link-lines

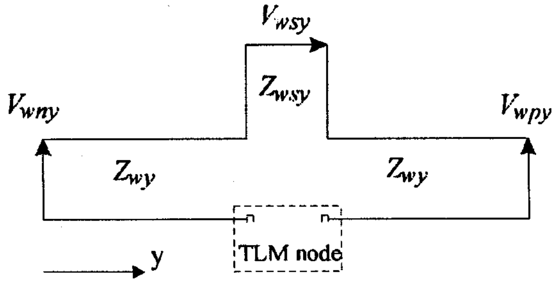


Fig. 4. Wire network

An interface between the wire network and the rest of TLM network must be devised to simulate coupling between the electromagnetic field and the wire. In order to model wire junction and bends, wire network segments pass through the centre of the TLM node (Fig. 5). In that case, coupling between the field and wire coincides with the scattering event in the node which makes the scattering matrix calculation, for the nodes containing a segment of wire network, more complex. Because of that, a simple and elegant approach is developed [8], which solves interfacing between arbitrary complex wire network and arbitrary complex TLM nodes without a modification of the scattering procedure.

RESISTIVE LOAD TERMINATION

In TLM method, resistive load at the end of the wire can be treated in two ways [9]. In the first case, resistive termination is shifted to the centre of the last wire segment, causing changes in scattering procedure of the wire node. Also, resistive load can be defined exactly at the wire end, and in that case, a Thevenin equivalent circuit is used to determine the required reflection coefficient (Fig. 6). A resistor R has been used to connect the end of wire to a nearby ground or metal. The required reflection coefficient r for this wire termination is given by:

$$ \rho = \frac{R - Z_{wy}}{R + Z_{wy}} \tag{3} $$

Depending of its location, resistive load connects wire to basis of fictitious cylinder in points a and b (Fig. 7). Fictitious cylinder represents capacitance and inductance of wire per unit length and approximately is modelled by the single column of TLM cells through which is passes. Its diameter is the effective diameter of a column of metal filled TLM cells, which is unfortunately, different for capacitance and inductance and it is obtained empirically [9]. Connection between fictitious

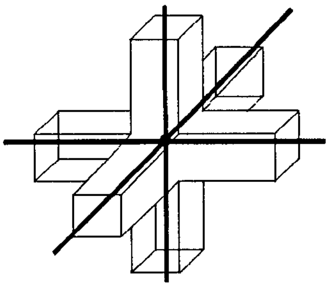


Fig. 5. Wire network segments embedded within the TLM node

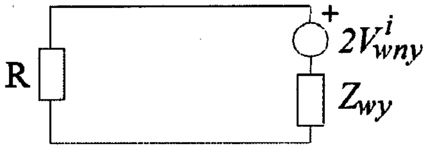


Fig.6. Resistive load for minimum end of wire (y = 0)

cylinder and wire is realised only if they are on equal potential, i.e. if appropriate TLM ports are shorted.

For resistive load realization at the wire ends and its connection to another structures, e.g. nearby ground or wire conductor, two possible models are presented in this paper [10,11]. The first model is based on using short lines on the appropriate face of the last TLM wire nodes (Fig. 8a and 9a), while the second model beside straight wire segments, uses bent-wire segments, defined in [9], at the ends of the wire (Figs. 8b and 9b). In both models, resistive load should be located at the end of the last wire segment (R is included by calculating the reflection coefficient from Eq. (3)) or shifted to the centre of the last wire segment (R is included in the scattering matrix calculation).

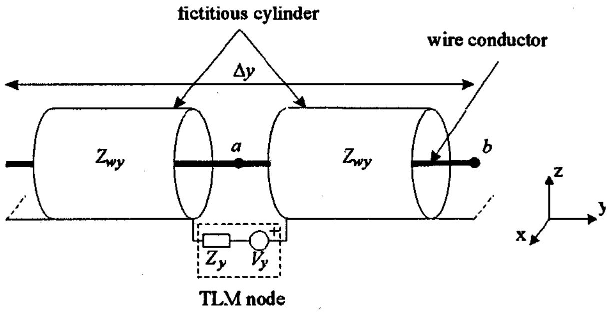


Fig.7. Fictitious cylinder

NUMERICAL RESULTS

Advantage of TLM wire node in relation to first integrated wire solutions is shown for the example of resonant frequencies calculation of dipole antenna, length l=1 m, in free space. At first, dipole antenna is modelled by using shorted link-lines adjacent to the wire surface with a single node cross-section on a rectangular Cartesian mesh. Dipole antenna is excited by impulse magnetic field along a closed path c surrounding the wire, based on Ampere's law:

$$\int_C \vec{H}\,d\vec{l} = I. \tag{4}$$

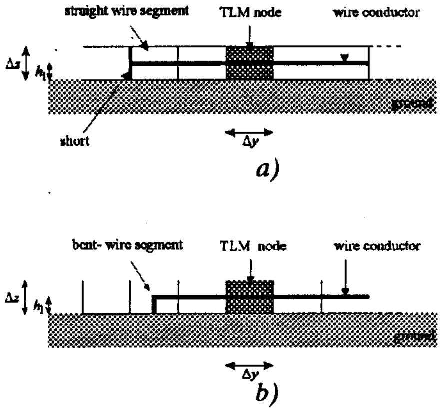


Fig. 8. Models of describing resistive load at the wire ends and its connection to perfectly conducting ground

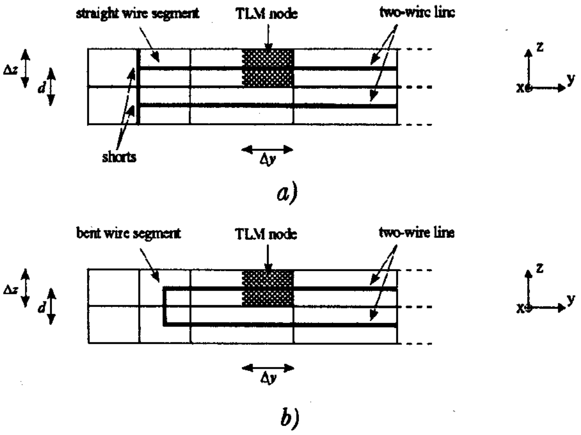


Fig. 9. Models of describing resistive load at the ends of two-wire line and its connection to other wire structure

Axial component of electromagnetic field of dipole antenna, for the case of uniform TLM mesh ($\Delta x = \Delta y = \Delta z$ = 4.76 cm), is shown in Fig. 10. Two resonances, which can be noticed, are far away from two theoretical resonant frequencies for thin dipole antenna: 150 MHz and 450 MHz. This great deviation between calculated and theoretical results can be explained with a rather crude rectangular shape model of the wire.

At the same time, dipole antenna is modelled by using TLM wire node implemented in the developed software [12]. For the TLM simulation, a uniform TLM mesh, with 35x35x50 nodes and dimensions of node $\Delta x = \Delta y = \Delta z$ = 4.76 cm, is used. Radius of dipole antenna is r=5 mm. At the centre of dipole antenna, voltage source V_{source}=1 V, with 50-Ohm impedance to reduce the sharpness of the resonances, is applied as an excitation. Fig. 11 shows the current magnitude at the centre of dipole antenna. As it can be seen from Fig. 11, calculated TLM results are much closer to theoretical resonant frequencies, even the same TLM node dimensions are used as in the previous case.

After that, unloaded wire conductor (Fig.1, $R_1 = R_2 \to \infty$), length l=1 m and radius r=2.5 mm, above perfectly

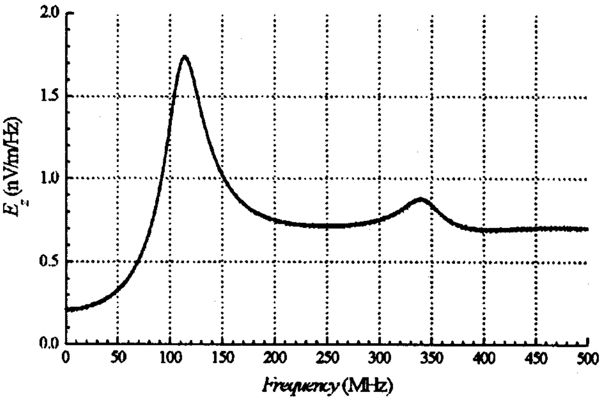


Fig. 10. Resonant frequencies of dipole antenna in free space, modelled by using shorted TLM link-lines

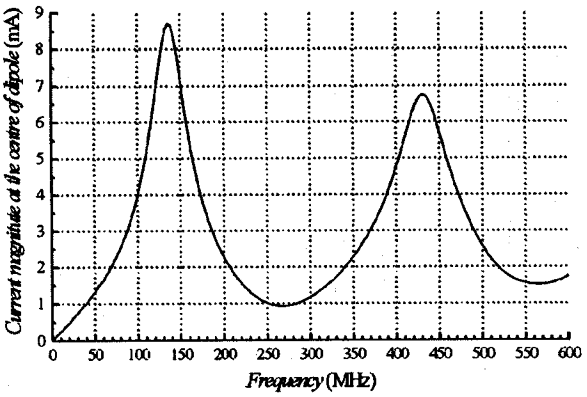


Fig. 11. Resonant frequencies of dipole antenna in free space, modelled by using TLM wire node

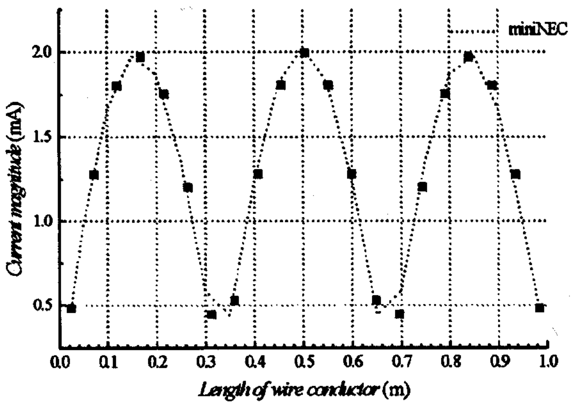


Fig.13. Current distribution along unloaded wire conductor at f=440 MHz, obtained by using: TLM wire node (♦) and

conducting ground (h_1=2.4 cm), in the field of dipole antenna (h_2=52.4 cm), is modelled by using TLM wire node. For the TLM simulation, non-uniform mesh with 35x75x50 nodes is used. Resolution of the TLM mesh is increased in the space between wire conductor and dipole antenna in order to simulate better coupling between electromagnetic filed of dipole antenna and wire conductor. Magnitude of induced current at the centre of wire conductor, and current distribution along wire conductor at resonant frequency f=440 MHz, obtained by using TLM wire node (solid line) and miniNEC simulator (dotted line) are shown in Figs.12 and 13, respectively. To reduce the sharpness of the resonances, 50-Ohm impedance is placed at the centre of wire conductor. It can be noticed excellent agreement between TLM results and results obtained by running miniNEC simulator, which indicates good TLM modelling of coupling between EM field of dipole antenna and wire conductor above perfectly conducting ground.

Also, two-wire line (Fig. 2), excited by dipole antenna (h=20 cm), as the characteristic form of EMC problems, is modelled by using TLM wire node. Two-wire line is formed with two parallel conductors of same cross-section, radius r=1 mm and length l=1 m with the mutual distance d=1 cm. For the TLM simulation of shorted two-wire line (Fig. 2, R_1 = R_2 = 0), it is used non-uniform mesh with 41x61x62 nodes. Resolution of the TLM mesh is increased in the space between two-wire line and dipole antenna for the same reason as in the previous example. Ends of the wires are treated by using bent-wire segments. Current magnitude in the centre of lower conductor, loaded with 50-Ohm impedance to reduce the sharpness of the resonances, is shown in Fig. 14. It can be noticed excellent agreement between TLM results and results obtained by running NEC2 simulator, which indicates good TLM modelling of coupling between electromagnetic field of dipole antenna and two-wire line in free space.

For the example of wire conductor (Fig. 1) with same dimensions, terminated at both ends with R_1 = R_2 =50 Ohm, two proposed models, for describing resistive load at the wire ends and its connection to perfectly conducting ground, are verified. Magnitude of induced current at the one end of loaded wire conductor in the frequency domain, obtained by applying the proposed models and miniNEC simulator, is shown in Figs. 15 and 16, respectively. As it can be seen, both models give good results in comparison with miniNEC results and can be used for resonant frequency prediction of loaded wire conductor. However, it should be noticed that the first model gives better results at lower frequencies, while the second model better describes the modelled connection at higher frequencies.

Also, verification of two proposed models is done for the example of the two-wire line with same dimensions, terminated at both ends with R_1 = R_2 = 100 Ohm.

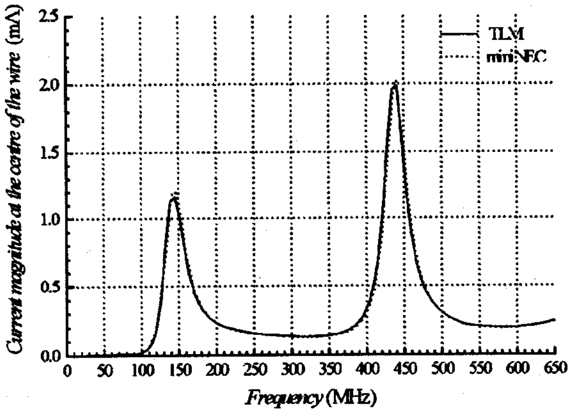


Fig. 12. Magnitude of the induced current at the centre of the unloaded wire conductor, obtained by using: TLM wire node (solid line) and miniNEC simulator (dotted line)

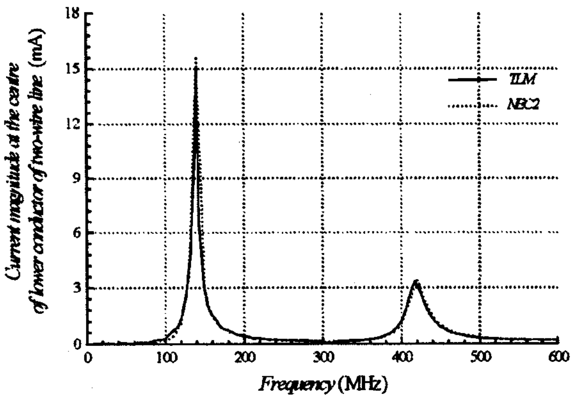


Fig.14. Magnitude of the induced current in two-wire line shorted at both ends, obtained by: TLM (solid line) and NEC2 simulator (dotted line)

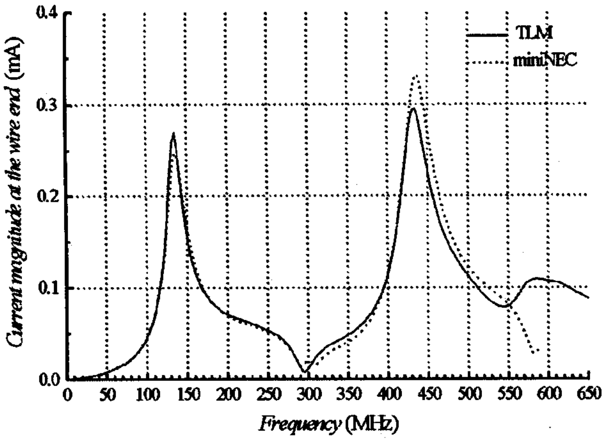


Fig. 15. Magnitude of the induced current at the wire end, obtained by using the first model (Fig. 8a)

Magnitude of induced current at the one end of loaded two-wire line in the frequency domain, obtained by applying the proposed models and NEC2 simulator, is shown in Figs. 17 and 18, respectively. As it can be seen, both models could be used for resonant frequency prediction of loaded two-wire line. However, comparison with NEC2 results shows that second model better describes resistive load at the ends of two-wire line, having in mind that it does not use metal boundaries (short lines) to describe resistive load connection.

CONCLUSIONS

In this paper, two current integrated TLM solutions of couple modelling between electromagnetic field and wire structures are presented. For the appropriate example, the advantage of TLM wire node in relation to the first integrated wire solutions is shown. The key feature of the presented wire node is its ability to model very fine wires on the otherwise coarse mesh, making it adequate for the large modelling space encountered in the EMC problems. With some recent developments (integrated multi-conductor TLM model), TLM method can now be used to model very complicated wire structures, without generating excessive demand for computing resources.

For the first time, two TLM models, for describing connection of a resistive load at the wire ends to perfectly conducting ground are proposed and verified in this paper. The results obtained with these models are found to be in very good agreement with the Method of Moments model. However, it should be pointed out that the second model, based on using bent-wire segments, more naturally describes wire ends and their resistive loads (having in mind the flow of induced wire current) and because of that it gives better results (especially for the case of loaded two-wire line). In this paper, we have assumed that only resistive loads (i.e. no capacitors or inductors) are used for the termination. A further generalisation of proposed models is possible for termination in the form of arbitrary lumped circuits.

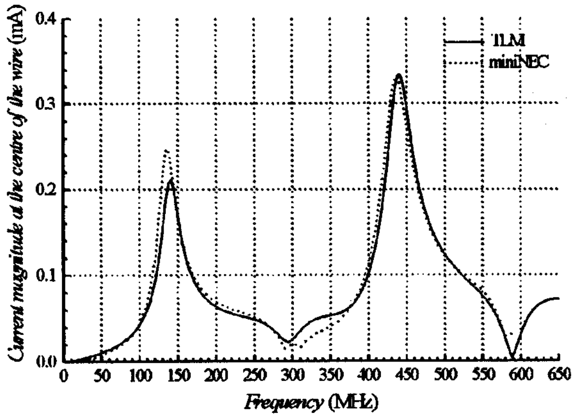


Fig. 16. Magnitude of the induced current at the wire end, obtained by using the second model (Fig. 8b)

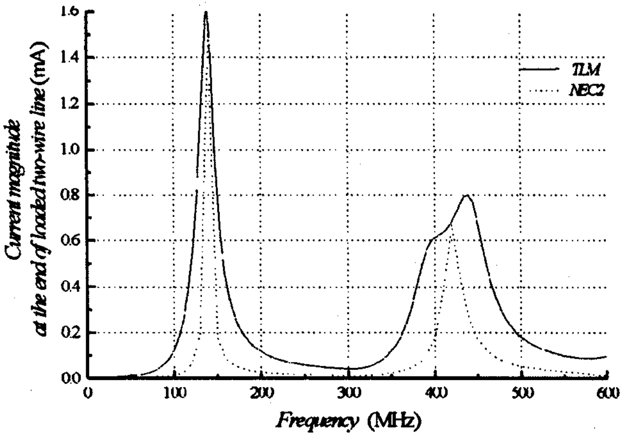


Fig. 17. Magnitude of the induced current at the end of loaded two-wire line, obtained by using the first proposed model (Fig.9a)

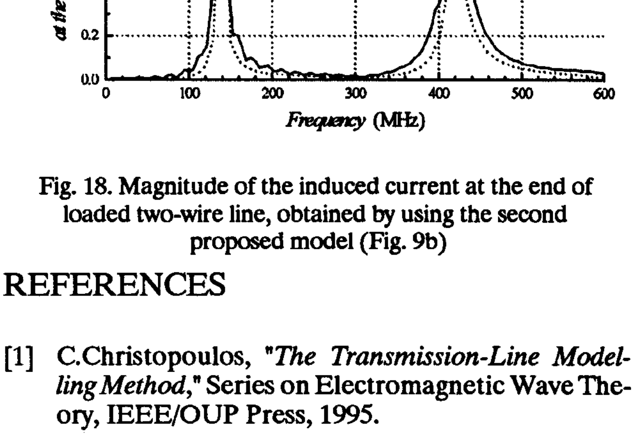


Fig. 18. Magnitude of the induced current at the end of loaded two-wire line, obtained by using the second proposed model (Fig. 9b)

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