Broad-band Characterization of Wire Interconnects Using a Surface Integral Formulation with a Surface Effective Impedance

A. Maffucci[1], G. Rubinacci[2], S. Ventre[1], F. Villone[1], and W. Zamboni[1]

[1] Ass. EURATOM/ENEA/CREATE, DAEIMI
Università degli Studi di Cassino, I-03043 Cassino (FR), Italy
{maffucci, ventre, villone, zamboni}@unicas.it

[2] Ass. EURATOM/ENEA/CREATE, DIEL
Università degli Studi di Napoli "Federico II", I-80125 Napoli, Italy
rubinacci@unina.it

Abstract **–** A surface integral formulation is used for a broad-band characterization of wire interconnects. A suitable definition of effective impedance accounts for the penetration of currents and charges inside lossy conductors. The results are successfully compared to a volumetric integral approach.

Keywords**:** Surface integral equation, effective surface impedance, and interconnects.

I. INTRODUCTION

The high-frequency operating conditions in digital high-speed circuits require an accurate electromagnetic modeling of all the physical components of the overall system, such as interconnects, packages, discontinuities, and devices. Effects related to the three-dimensional (3D) nature and finite size of the interconnects, are less and less negligible as frequency goes up. For this reason several efforts are made in literature to propose efficient full-wave simulators able to model adequately the high-frequency behavior of such structures. Efficient full-wave models may be obtained starting from integral formulations of the electromagnetic problem: a typical example is the popular EFIE (Electric Field Integral Equation) approach [1]. All the integral approaches benefit from the possibility to reduce the mesh to the conducting regions only and to impose rigorously the boundary conditions at infinity. When dealing with high-conductivity materials or when characterizing high-frequency behavior we can assume that the sources lie only on the conductor surfaces. In this case it is useful to introduce a surface integral formulation.

The most common way of discretizing a surface integral formulation is based on the use of the so-called RGW basis functions [2]. This approach suffers from the so-called low-frequency breakdown problem [1], *i.e.*, an ill-conditioning of the problem at frequencies low enough to make the conductors size small as compared to the wavelength. To overcome this problem, a loop-star or loop-tree decompositions are commonly used [3], able to decouple the solenoidal component of the current density from the non-solenoidal one. This cannot be automatically done for multiconnected domain or in the presence of electrodes. This point has been stressed since the very early applications [4], and has received considerable attention in the last years [5-6]. The Authors have recently proposed a surface integral formulation able to deal with arbitrary topologies thanks to a null-pinv decomposition of the basis functions that can be seen as a generalization of the loop-star and loop-tree decompositions [7-11].

This paper deals with the inclusion in such a formulation of a suitable surface impedance for broad-band characterization of lossy interconnects. A correct evaluation of the broad-band behaviour of ohmic conductors is essential to accurately predict the overall performances of high-speed digital circuits. When testing the signal integrity, for example, the signalling system is forced by a random sequence of bits and the quality is checked by observing the corresponding "eye-diagram". This requires a time-domain analysis performed by representing the interconnects through equivalent circuits, often extracted from a frequency domain characterization (*e.g.*, in terms of S parameters). The equivalent circuits have to be able to reproduce accurately fast transients as well as the DC response, hence the frequency characterization should be accurate for a wide range, from DC to microwave.

The surface approach for perfect conductors is fully consistent at any frequency. On the contrary, when dealing with ohmic conductors the electrical charges and currents do not necessarily lie on the conductor surfaces. This hypothesis is a good approximation when the skin effect is strong (high frequency and or high conductivity). In this case a suitable surface impedance can often be used [12]. On the contrary, the definition of such an impedance should be changed to account for the penetration of sources at low frequency [13-14]. In this work we derive a consistent definition of the surface impedance, able to describe correctly both the low and high frequency behaviour, by solving analytically the axial diffusion problem in ohmic conductors of circular cross section.

The paper is organized as follows. In Section II the surface integral formulation is briefly reviewed and in Section III the theory for the equivalent surface impedance is described for cylindrical conductors. Section IV presents some results with particular reference to Unshielded Twisted Pairs (UTPs). This demonstrates the potentiality of the approach in broad-band modelling of conducting structures of arbitrary topology. Finally, Section V draws the conclusions.

II. MATHEMATICAL AND NUMERICAL FORMULATION

This section briefly illustrates the features of the 3D surface integral formulation used in this paper, and the related code SURFCODE. A more detailed derivation can be found in [9].

We solve Maxwell's equations in the frequency domain, assuming that some good conductors are present in the free space. The formulation can be extended to stratified dielectric media, as illustrated in [11]. Let Σ be the external surface of the conductors (see Fig. 1); we assume that $\partial\Sigma$ is made of N_E linear equipotential electrodes l_j, through which the current can flow.

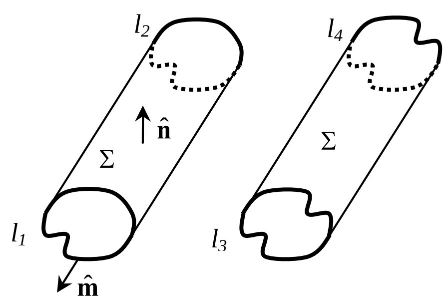


Fig. 1. Reference geometry.

Assuming that the current density lies on the surface Σ, we must satisfy the condition,

$$\mathbf{E}\times\hat{\mathbf{n}}\big|_{\Sigma} = \zeta_S\,\mathbf{J}_s\times\hat{\mathbf{n}}\big|_{\Sigma} \tag{1}$$

where $\mathbf{E}$ is the electric field, $\hat{\mathbf{n}}$ is the unit vector normal to Σ, ζ_S is the surface impedance of the conducting body, and $\mathbf{J}_s$ is the surface current density. The above assumption is rigorously satisfied in case of perfect conductors ($\zeta_S \to \infty$) at any frequency. It can be considered as a good approximation at sufficiently high frequencies due to the skin effect. At very low frequencies as well as in intermediate range condition. Equation (1) may still be imposed, provided that a suitable definition of the surface impedance is adopted.

Introducing the magnetic vector potential $\mathbf{A}$ and the scalar electric potential φ, we express $\mathbf{E}$ as follows,

$$\mathbf{E} = -i\omega\mathbf{A} - \nabla\varphi\,. \tag{2}$$

Using equation (2), we impose equation (1) in weak form using the weighted residual approach and the surface divergence theorem,

$$\begin{aligned} &i\omega\iint_{\Sigma}\mathbf{A}\cdot\mathbf{p}\,dS + \iint_{\Sigma}\zeta_M\,\mathbf{J}_s\cdot\mathbf{p}\,dS + \\ &+\iint_{\Sigma}\varphi\nabla_s\cdot\mathbf{p}\,dS = -\sum_{j=1}^{N_E}\varphi_j\int_{l_j}\mathbf{p}\cdot\hat{\mathbf{m}}\,dl = 0 \quad \forall\mathbf{p} \end{aligned} \tag{3}$$

where $\mathbf{p}$ is a vector weighting function tangent to Σ, $\hat{\mathbf{m}}$ is the normal to $\partial\Sigma$ over Σ (exiting from Σ), and the operator $\nabla_s=\nabla-\hat{\mathbf{n}}\,\partial/\partial n$. Using Lorenz gauge, the potentials are related to the surface current density $\mathbf{J}_s$ and the surface charge density σ through the Green function G as follows,

$$\begin{aligned} \mathbf{A}(\mathbf{r}) &= \frac{\mu_0}{4\pi}\iint_{\Sigma}G\left(|\mathbf{r}-\mathbf{r}'|\right)\mathbf{J}_s(\mathbf{r}')dS', \\ \varphi(\mathbf{r}) &= \frac{1}{4\pi\varepsilon_0}\iint_{\Sigma}G\left(|\mathbf{r}-\mathbf{r}'|\right)\sigma(\mathbf{r}')dS'. \end{aligned} \tag{4}$$

The sources must further satisfy the charge conservation law,

$$\nabla_s\cdot\mathbf{J}_s\big|_{\Sigma} = -\,i\omega\sigma\big|_{\Sigma}\,. \tag{5}$$

To solve the problem numerically, we give a triangular finite elements discretization of Σ, with e edges, n nodes, and t triangles. We expand the surface current density $\mathbf{J}_s$ in terms of div-conforming basis functions $\mathbf{w}_k$, having a continuous normal component all over the mesh [9]. The resulting degrees of freedom (DoF) I_k are the currents flowing across the edges. The surface charge density σ is expanded in terms of piecewise constant functions q_m, so that the resulting DoF Q_m are the charges in the triangles. It can be easily seen that

$$\begin{bmatrix}\nabla_s\cdot\mathbf{w}_1\\ \vdots\\ \nabla_s\cdot\mathbf{w}_e\end{bmatrix} = \underline{\underline{D}}^T\begin{bmatrix}q_1\\ \vdots\\ q_t\end{bmatrix}, \tag{6}$$

where $\underline{\underline{D}}$ is a suitable sparse matrix, which can be seen as the discrete divergence. Using equation (6), equation (5) becomes,

$$\underline{\underline{D}}\,\underline{I} = -i\omega\,\underline{Q}\,, \tag{7}$$

where $\underline{I}$ and $\underline{Q}$ are the vectors of the DoF I_k and Q_m. Assuming that Σ is an open surface, the rank of $\underline{\underline{D}}$ is full, hence we can automatically satisfy equation (7) by writing,

$$\underline{I} = \underline{\underline{K}}\,\underline{I_s} - i\omega\underline{\underline{R}}\,\underline{Q}\,, \tag{8}$$

where $\underline{\underline{K}}$ is a matrix whose columns are a basis for the null space of $\underline{\underline{D}}$, $\underline{\underline{R}}$ is a pseudoinverse matrix of $\underline{\underline{D}}$, and $\underline{I_s}$ are unknowns which give no contribution to the current density divergence (and hence to the charge). We are in fact using the following "null-pinv" basis functions [9],

$$\begin{aligned} \boldsymbol{\alpha}_h &= \sum_{k=1}^{e} K(k,h)\mathbf{w}_k\,, \quad h = 1,\dots,n_x\,, \\ \boldsymbol{\beta}_h &= \sum_{k=1}^{e} R(k,h)\mathbf{w}_k\,, \quad h = 1,\dots,t \end{aligned} \tag{9}$$

where n_x is a number depending on the topology of the solution domain. The null-pinv decomposition of equation (9) is a generalization of the loop-star decomposition [3], hence, it allows avoiding the so-called "low-frequency breakdown". Furthermore, the proposed decomposition also provides the possibility to deal with topologically complex geometries (via holes, bends, and electrodes).

Using equation (9) as weighting functions in equation (2), we have,

$$\begin{aligned} &i\omega\begin{bmatrix} \underline{\underline{L}}_{\alpha\alpha} & \underline{\underline{L}}_{\alpha\beta} \\ \underline{\underline{L}}_{\beta\alpha} & \underline{\underline{L}}_{\beta\beta} \end{bmatrix}\begin{bmatrix} \underline{I_s} \\ -i\omega\underline{Q} \end{bmatrix} + \begin{bmatrix} \underline{\underline{R}}_{\alpha\alpha} & \underline{\underline{R}}_{\alpha\beta} \\ \underline{\underline{R}}_{\beta\alpha} & \underline{\underline{R}}_{\beta\beta} \end{bmatrix}\begin{bmatrix} \underline{I_s} \\ -i\omega\underline{Q} \end{bmatrix} + \\ &-\begin{bmatrix} \underline{\underline{0}} \\ \underline{\underline{S}} \end{bmatrix}\underline{Q} = -\begin{bmatrix} \underline{\underline{F}}_{\alpha} \\ \underline{\underline{F}}_{\beta} \end{bmatrix}\underline{\varphi} = -\underline{\underline{F}}\,\underline{\varphi} \end{aligned} \tag{10}$$

where $\underline{\varphi}$ is a vector containing N_E electrode potentials and the other elements are defined as follows,

$$\begin{aligned} L_{\gamma\delta}(i,j) &= \frac{\mu_0}{4\pi}\iint_\Sigma\iint_\Sigma G(|\mathbf{r}-\mathbf{r}'|)\boldsymbol{\gamma}_j(\mathbf{r}')\cdot\boldsymbol{\delta}_i(\mathbf{r})\,dS'\,dS\,, \\ S(i,j) &= \frac{1}{4\pi\varepsilon_0}\iint_\Sigma\iint_\Sigma G(|\mathbf{r}-\mathbf{r}'|)q_j(\mathbf{r}')q_i(\mathbf{r})\,dS'\,dS\,, \\ R_{\gamma\delta}(i,j) &= \iint_\Sigma \zeta_S\,\boldsymbol{\gamma}_j(\mathbf{r}')\cdot\boldsymbol{\delta}_i(\mathbf{r})\,dS\,, \\ F_\gamma(h,j) &= \int_{l_j}\boldsymbol{\gamma}_h\cdot\hat{\mathbf{m}}\,dl\,. \end{aligned} \tag{11}$$

Equation (10) can be rewritten in a compact form as,

$$\underline{\underline{Z}}\,\underline{T} = -\underline{\underline{F}}\,\underline{\varphi}\,, \tag{12}$$

with a suitable definition of the matrices $\underline{\underline{Z}}$, $\underline{T}$. From this point, simple algebraic manipulations [9] allow the computation of any matrix describing the behavior of the interconnect at its terminals. For instance the admittance matrix $\underline{\underline{Y}}$ is simply given by,

$$\underline{\underline{Y}} = \underline{\underline{F}}^T\,\underline{\underline{Z}}^{-1}\,\underline{\underline{F}}\,. \tag{13}$$

III. EQUIVALENT SURFACE IMPEDANCE FOR CYLINDRICAL CONDUCTORS OF CIRCULAR CROSS SECTION

Let us consider cylindrically-shaped straight conductors with circular cross section of radius a. In order to derive a possible expression for the surface impedance ζ_S, for each conductor we consider a single straight cylindrical wire with a volumetric current density $\mathbf{J}_{vol}$ directed along the conductor axis. In ohmic conductors of resistivity η the amplitude of the electric field E is related to the volumetric current density J_{vol} through,

$$E = \eta J_{vol} \tag{14}$$

in the whole conductor domain, including its surface Σ. Neglecting the displacement current in the conductor, the amplitude of the magnetic field on Σ is related to the total current I flowing in the wire by,

$$H\big|_\Sigma = \frac{I}{2\pi a}\,. \tag{15}$$

It is possible to prove that the volumetric current density depends on the radial coordinate r as follows [15],

$$J_{vol}(r) = \frac{\sqrt{2}\,I}{i^{5/2}\,2\pi\,a\,\delta}\,\frac{J_0\left(i^{3/2}\sqrt{2}\,r/\delta\right)}{J_1\left(i^{3/2}\sqrt{2}\,a/\delta\right)}, \tag{16}$$

where δ is the penetration depth,

$$\delta = \sqrt{\frac{2\eta}{\omega\mu}}\,, \tag{17}$$

and J_α is the Bessel function of order α. On the surface Σ this volumetric current density is equal to,

$$J_{vol}\big|_\Sigma = \frac{\sqrt{2}\,I}{i^{5/2}\,2\pi\,a\,\delta}\,\frac{J_0\left(i^{3/2}\sqrt{2}\,a/\delta\right)}{J_1\left(i^{3/2}\sqrt{2}\,a/\delta\right)} = T\,I\,, \tag{18}$$

where the quantity T can be approximated as,

$$T = \frac{\sqrt{2}}{i^{5/2}\,2\pi\,a\,\delta}\,\frac{J_0\left(i^{3/2}\sqrt{2}\,\dfrac{a}{\delta}\right)}{J_1\left(i^{3/2}\sqrt{2}\,\dfrac{a}{\delta}\right)} \cong \begin{cases} \dfrac{1}{\pi a^2} & \delta >> a \\ \dfrac{(1+i)}{2\pi a\delta} & \delta << a \end{cases}. \tag{19}$$

Consequently, the relation between the electric and magnetic fields on Σ becomes,

$$E\big|_{\Sigma} = \eta\, J_{vol}\big|_{\Sigma} = \eta\, T\; I = \eta\, T\; 2\pi a\; H\big|_{\Sigma} = \zeta_S\, H\big|_{\Sigma}\,, \qquad (20)$$

where the surface impedance is defined as,

$$\zeta_S = \frac{\sqrt{2}\,\eta}{i^{5/2}\,\delta}\,\frac{J_0\!\left(i^{3/2}\sqrt{2}\,\dfrac{a}{\delta}\right)}{J_1\!\left(i^{3/2}\sqrt{2}\,\dfrac{a}{\delta}\right)} \cong \begin{cases} \eta\,\dfrac{2}{a} & \delta >> a \\ \eta\,\dfrac{(1+i)}{\delta} & \delta << a \end{cases}. \qquad (21)$$

Note that the high frequency limit of equation (21) reduces to the standard Leontovich expression.

In the range of frequency in which δ and a are comparable, instead of the exact expression of equation (21) it is often used the following heuristic *coth* law [14, 16],

$$\zeta_S = \eta\,\frac{(1+i)}{\delta}\coth\!\left(\frac{a}{2}\sqrt{\frac{j\,\omega\,\mu}{\eta}}\right), \qquad (22)$$

that provides the values of equation (21) in the high and low frequency limits, since,

$$\lim_{\omega\to 0}\ \coth\!\left(\frac{a}{2}\sqrt{\frac{i\,\omega\,\mu}{\eta}}\right) = \frac{2}{a}\sqrt{\frac{\eta}{i\,\omega\,\mu}} = \frac{2}{a}\,\frac{\delta}{1+i}\,, \qquad (23)$$

$$\lim_{\omega\to +\infty}\ \coth\!\left(\frac{a}{2}\sqrt{\frac{i\,\omega\,\mu}{\eta}}\right) = 1\,. \qquad (24)$$

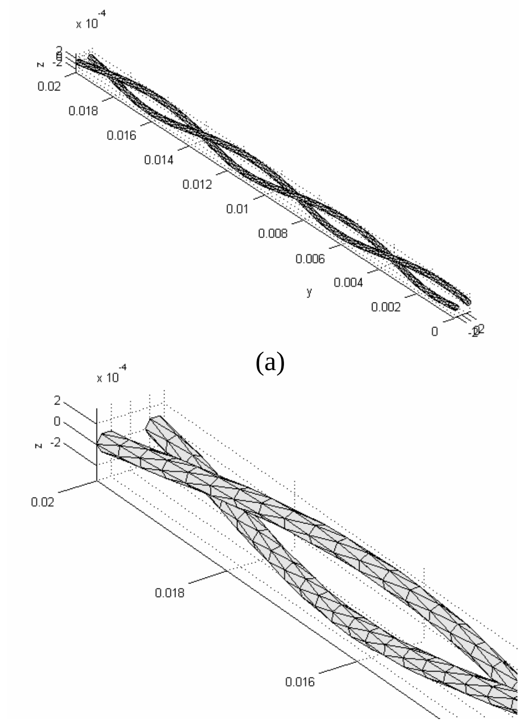
Note that the impedance of equation (21) is spatially homogeneous.

IV. NUMERICAL RESULTS

The analyzed test-case is a typical broad-band wire interconnect, namely an unshielded twisted pair (UTP) cable, made of cylindrical copper conductors. Let us assume Cu resistivity $\eta = 1.7\cdot 10^{-8}\ \Omega\,\mathrm{m}$, twist pitch 10 mm, radius a = 0.1 mm, center-to-center distance of 0.5 mm, and a total length equal to 2 twist pitches.

The surface mesh used for the computation is plotted in Fig. 2. The mesh is made of 576 triangular elements, giving up to 876 degrees of freedom (DoFs). We have evaluated the impedance, Z_{in} computed at one end when the other one is short-circuited. This has been done both using the exact formula of equation (21), and the *coth* law of equation (22), so to compare the error introduced by using the latter approximated law.

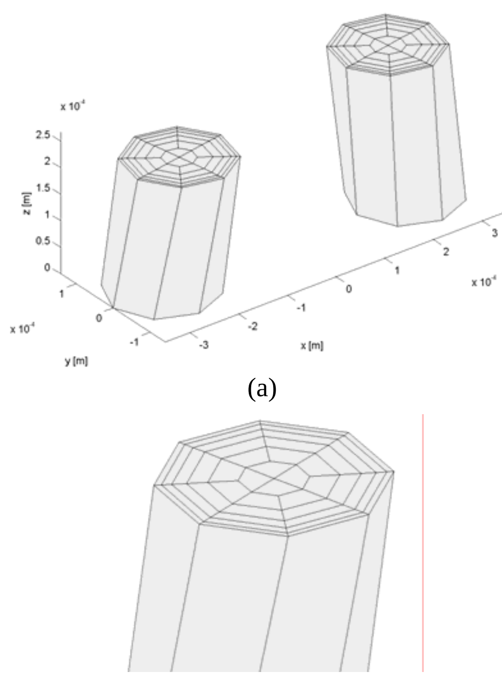
The results are further compared to those obtained by the 3D volumetric code CARIDDI [17-19] in two different discretization conditions. The mesh for the case "CARIDDI 1" (7448 points, 6600 elements, giving rise to 12688 DoFs) is characterized by a fine discretization along the longitudinal and radial directions of the cylinders, as depicted in Fig. 3.



(a)

(b)

Fig. 2. Surface mesh used for the UTP (a); detail (b).



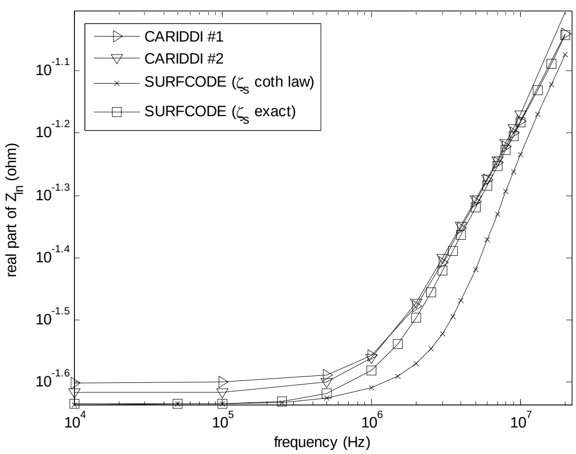
(a)

(b)

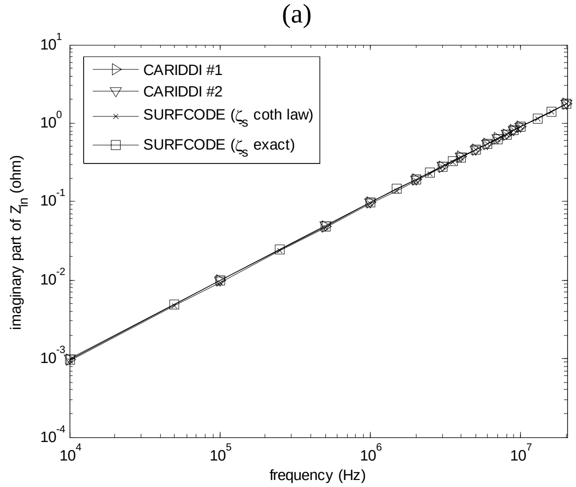
Fig. 3. Volume mesh (a), detail (b) for the case "CARIDDI 1".

Conversely, in case “CARIDDI 2” the mesh is characterized by a fine discretization in the poloidal direction of each cylinder (3796 points, 3200 elements, giving rise to 6128 DoFs).

Figure 4 shows the comparison between the surface and volume approaches in a transition region. The results agree satisfactorily, being the displacement between the related curves within 8%. For $f < 40$ kHz, we have a ratio $\delta/a > 3$, hence, the conductors can be considered as fully penetrated. As clearly shown, the low frequency behaviour of the resistance is correctly modelled. Indeed, the real part of the impedance approximates the DC resistance of the wire. For $f > 10$MHz we have $\delta/a < 0.2$ and the solution CARIDDI 2 suffers for a lack of precision, due to the discretization along the conductor radius, too coarse to describe the skin effect. This may also explain the (even small) mismatch of the results at higher frequencies. Note that the solution obtained by using the *coth* law approximates the exact one within a 20% error.



(a)

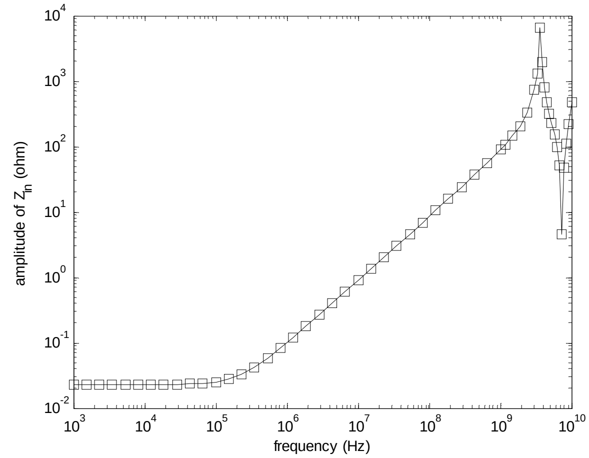


(b)

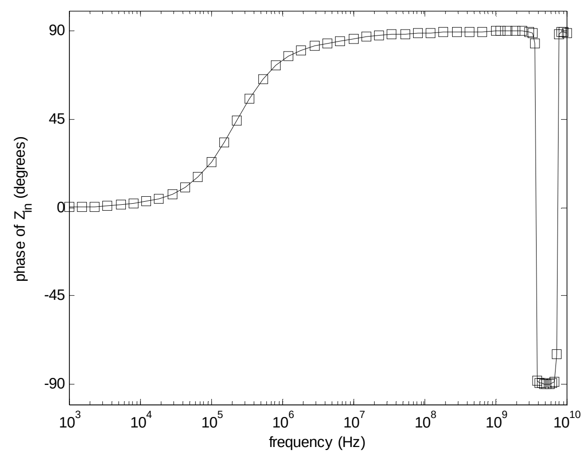
Fig. 4. Input impedance of a UTP in a transition region. Real (a) and imaginary (b) parts.

Figure 5 shows the broad-band frequency behaviour of the input impedance computed by our code. The considered range deeply enters the asymptotic regions $\delta/a >> 1$ and $\delta/a << 1$.

Finally, in Fig. 6 it is plotted the current density pattern computed at 20 MHz, highlighting a non-uniform distribution due to proximity effect.



(a)



(b)

Fig. 5. Input impedance of a UTP in broad interval of frequency. Real (a) and imaginary (b) parts.

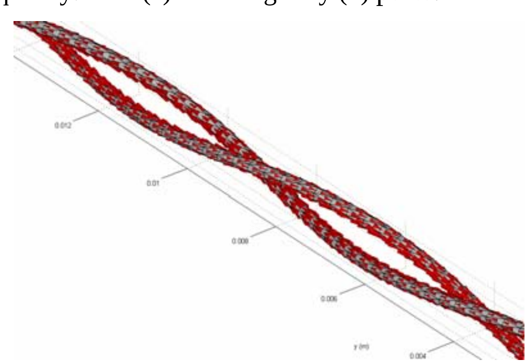


Fig. 6. Current density pattern at 20 MHz.

V. CONCLUSIONS AND PERSPECTIVES

In this paper a surface integral formulation is used to obtain a broad-band characterization of 3D wire interconnects. The use of null-pinv basis functions in the numerical model allows an automatic treatment of arbitrarily complex geometries, while retaining all the benefits of a decomposition that does not suffer from low-frequency breakdown problems. The presence of lossy conductors is correctly taken into account at any frequency by introducing suitable surface effective impedance, obtained by solving the diffusion problem.

The test case (characterization of a UTP cable) shows the consistency of the approach with volumetric techniques in the low frequency region, and the inaccuracy of the approximated *coth* law is often used to describe lossy conductors.

In principle, the definition of an effective impedance presented here could be extended to the case of more complicated geometries. This could be achieved by solving numerically the internal diffusion equation inside the region occupied by the conductors, *e.g.*, with a differential code.

VI. ACKNOWLEDGEMENTS

This work was supported in part by by Consorzio CREATE and by the Italian Ministry of Research under a Program for the development of Research of National Interest (PRIN Grant #2004093025).

REFERENCES

[1] J. S. Zhao and W. C. Chew, “Integral equation solution of Maxwell’s equations from zero frequency to microwave frequency,” *IEEE Trans. Antennas Propag.*, vol. 48, pp. 1635–1645, 2000.

[2] S. M. Rao, D. R. Wilton, and A. W. Glisson, “Electromagnetic scattering by surface of arbitrary shape,” *IEEE Trans. Antennas Propag.*, vol. AP-30, pp. 409–418, 1982.

[3] G. Vecchi, “Loop-star decomposition of basis functions in the discretization of EFIE,” *IEEE Trans. Antennas Propag.*, vol. 47, pp. 339–346, 1999.

[4] D. R. Wilton, “Topological considerations in surface patch and volume cell modeling of electromagnetic scatterers,” in *Proc. URSI Int. Symp. Electromagn. Theory*, pp. 65–68, Santiago de Compostela, Spain, Aug. 1983.

[5] V. I. Okhmatovski, “An efficient algorithm for generation of loop-tree basis in 2.5D interconnect models,” *Proc. of 14th EPEP Meeting*, pp. 297-300, Oct. 2005.

[6] S. Chakrabortry, D. Gope, G. Ouyang, and V. Jandhyala, “A three-stage preconditioner for geometries with multiple holes and handles in integral equation based electromagnetic simulation of integrated packages,” *Proc. of 14th EPEP Meeting*, pp. 199-202, Oct. 2005.

[7] D. Belfiore, G. Miano, F. Villone, and W. Zamboni, “A surface integral formulation for Maxwell’s equations,” *Proc. 11th IGTE Symp. Conf.*, pp. 62–67, Graz, Austria, Sep. 2004.

[8] A. Chiariello, A. Maffucci, G. Miano, F. Villone, and W. Zamboni, “Analysis of interconnects in huge frequency ranges with a 3-D superficial integral formulation,” *Proc. of 9th IEEE Workshop on Signal Propagation on Interconnects (SPI)*, pp. 89-92, Garmish, Germany, 10-13 May 2005.

[9] G. Miano and F. Villone, “A surface integral formulation of Maxwell equations for topologically complex conducting domains,” *IEEE Trans. Antennas Propag.*, vol. 53, pp. 4001-4014, 2005.

[10] S. Caniggia, A. Maffucci, F. Maradei, F. Villone, and W. Zamboni “Time-domain analysis of the performances of unshielded twisted pairs in high-speed circuits,” *Proc. of EMC-Europe 2006,* pp.550-555, Barcelona, Spain, 4-8 Sept. 2006.

[11] A. G. Chiariello, A. Maffucci, G. Miano, F. Villone, and W. Zamboni, “Full-wave numerical analysis of single-layered substrate planar interconnects,” *Proc. of IEEE Workshop on Signal Propagation on Interconnects*, pp. 57-60, Berlin, Germany, 9-12 May 2006.

[12] Y. Wang, D. Gope, V. Jandhyala, and C. J. R. Shi, “Generalized Kirchhoff’s current and voltage law formulation for coupled circuit-electromagnetic simulation with surface integral equations,” *IEEE Trans. Microwave Theory Tech.*, vol. 52, pp. 1673–1682, 2004.

[13] A. Rong, A. C. Cangellaris, and L. Dong, “Comprehensive broad-band electromagnetic modeling of on-chip interconnects with a surface discretization-based generalized PEEC model,” *IEEE Trans. Advanced Packaging*, vol. 28, no. 3, pp. 434 - 444, Aug. 2005.

[14] D. De Zutter and L. Knockaert, “Skin effect modeling based on a differential surface admittance operator,” *IEEE Trans. Microwave Theory Tech.*, vol. 53, no. 8, pp. 2526 - 2538, 2005.

[15] F. Barozzi and F. Gasparini, “Fondamenti di elettrotecnica. Elettromagnetismo,” Ed.*UTET*, Torino Italy, 1989.

[16] A. G. Chiariello, A. Maffucci, G. Miano, F. Villone, and W. Zamboni, “Broad-Band characterization of conductors with arbitrary topology using a surface integral formulation,” *Proc. of 15th EPEP Meeting*, pp. 131-134, Scottsdale (USA), 23-25 Oct. 2006.

[17] R. Albanese and G. Rubinacci, “Integral formulation for 3D eddy current computation using edge-elements,” *IEE Proceedings*, vol. 135, Part A, no. 5, pp. 457-462, 1988.

[18] R. Albanese and G. Rubinacci, “Finite element methods for the solution of 3D eddy current problems,” *Advances in Imaging and Electron Physics*, vol. 102, pp. 1-86, Academic Press, 1998.

[19] A. Maffucci, G. Rubinacci, A. Tamburrino, S. Ventre, and F. Villone, “Fast low-frequency impedance extraction using a volumetric three-dimensional integral formulation,” *Proc. of ACES 2007*, pp. 1652-1657, Verona, Italy, 19-23 March 2007.

Antonio Maffucci received in 1996 the Laurea Degree in Electronic Engineering *summa cum laude* and in 2000 the Ph.D. degree in Electrical Engineering from the University of Naples “Federico II”, Italy.
In 1997 he was with the nuclear fusion laboratory JET (Culham, U.K.). From 1998 to 2002 he was with the Department of Electrical Engineering at the University of Naples. From 2002 he is with the Elettrotecnica Group at the Faculty of Engineering of the University of Cassino, Italy, where he is currently an Associate Professor, teaching courses on circuit theory and electromagnetic compatibility.
His research areas include electromagnetic modeling of distributed systems, electromagnetic compatibility, computational electromagnetism, and nanotechnology.
He is author of more than 80 technical papers on international journals, conference proceedings and essays on books. He is also co-author of the book *Transmission lines and lumped circuits* (New York, Academic Press, 2001). He is Associate Editor of the *IEEE Transactions on Advanced Packaging*.

Guglielmo Rubinacci received the Laurea degree (*summa cum laude*) in Electronic Engineering from the University of Naples “Federico II”, Italy, in 1975.
Currently, he is a Full Professor of fundamentals in electrical engineering at the University of Naples “Federico II.” He was the Dean of the Faculty of Engineering of the University of Cassino from 1996 to 2003. As a Fulbright-Hays Fellow he was a Visiting Scientist at MIT in 1980/81. He has been a Researcher at the University of Naples (1982/85), Associate Professor at the Universities of Calabria (1979–84), Salerno (1984/88) and Napoli (1988/90), and Full Professor at the University of Cassino (1990–2004). He is the author/coauthor of more than 100 papers in refereed scientific journals and books and coeditor of two volumes. His research interests are mainly in computational electromagnetics with applications in several fields such as plasma engineering in tokamaks and electromagnetic nondestructive evaluation

Salvatore Ventre received in 1990 the Laurea Degree in Electronic Engineering *summa cum laude* in Electrical Engineering from the University of Naples “Federico II”, Italy. From 1993 is with the Elettrotecnica Group at the Faculty of Engineering of the University of Cassino, Italy, where he is currently a Research Scientist.
His research interests are mainly in computational electromagnetic with application in several fields such as electromagnetic nondestructive evaluation, electromagnetic compatibility, analysis of the time evolution of MHD equilibria, for the identification of the plasma boundary in tokamaks.
He is author/coauthor of more than 30 technical papers on international journals and conference proceedings.

Fabio Villone received the Laurea degree (summa cum laude) in Electronic Engineering in 1994 at the University of Naples Federico II, and the Ph.D. in Industrial Engineering in 1998 at the University of Cassino.
Currently, he is Full Professor at the Faculty of Engineering of the University of Cassino, where he formerly was Research Assistant (1997-2001) and Associate Professor (2001-2007). He teaches "Basic Electrical Engineering".
In 1996 he was visiting scientist at CRPP-Lausanne (Switzerland), and in the last years at JET (Joint European Torus), close to Oxford (UK).
His scientific interests are in the field of computational electromagnetics, with particular reference to fusion plasma modelling and engineering, electromagnetic compatibility and eddy current non destructive testing.
He is co-author of more than 60 papers on international journals and essays on books, and more than 50 contributions to international conferences, among which several invited papers. He was Scientific Coordinator of several experiments carried out at JET, and Principal Investigator of a national research project on fusion plasma modelling and control.

Walter Zamboni received the Laurea degree in Electrical Engineering (*summa cum laude*) in 2001 and the Ph. D. degree in Electrical Engineering in 2004 from the Faculty of Engineering, Università degli Studi di Napoli "Federico II", Italy. In 2003 he has been Stager at CERN, Geneva, Switzerland, and Visiting Scientist at EPFL-CRPP Superconductivity Group, Villigen-PSI, Switzerland. From 2005 he is with the the Faculty of Engineering, Università degli Studi di Cassino, Italy, where he works as a research assistant. From 2006 he teaches Circuits Theory at the Università degli Studi del Sannio, Italy

His scientific interests are in the field of computational electromagnetics, with particular reference to interconnects and applied superconductivity.