

# The “Equivalent Cable Bundle Method”: an Efficient Multiconductor Reduction Technique to Model Automotive Cable Networks

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## 1. Introduction

In automotive electromagnetic (EM) compatibility (EMC), the cable bundle network study is of great importance. Indeed, a cable network links all the electronic equipment interfaces included the critical ones and consequently can be assimilated both to a reception antenna and to an emission antenna at the same time. On the one end, as far as immunity problem is concerned, where an EM perturbation illuminates the car, the cable network acts as a receiving antenna able to induce and propagate interference currents until the electronic equipment interfaces and potentially induce dysfunction or in the worst case destruction of the equipment. At low frequency, the interference signal propagating on the cable network is generally considered as more significant than the direct coupling between the incident field and the equipment. On the other end, as far as emission problem is concerned, the EM field emitted by the cable network may disturb itself the electronic equipments by direct coupling.

To avoid these problems, automotive manufacturers have to perform normative tests before selling vehicles. These tests are applied on electronic equipments outside and inside the car first to verify that the equipments are not disturbed by an EM perturbation of given magnitude and second to ensure that the EM emission of each equipment does not exceed a limit value at a given distance. Obviously, these tests are not exhaustive and fully representative of real conditions. For example, in immunity tests, two polarizations (vertical and horizontal polarizations) of the EM perturbation are generally tested in free space conditions. In reality, the EM perturbation due for example to a mobile phone outside the car could happen from any direction of space and be reflected by all the scattering objects located in the close environment of the vehicle (ground, other vehicles, buildings,...).

Consequently, the contribution of EM modelling is a great tool for automotive manufacturers in order to proceed to numerical normative, additional and also parametric tests at early stages of the car development on numerical models and for a reasonable cost. Moreover, numerical modelling will reduce the number of prototypes built during the

development of a vehicle which is actually a strong trend in the automotive industry due to the cost of prototypes.

A 2-step approach is generally used (Paletta et al., 2002) for immunity problem. First, electric fields tangent to the cable bundle paths are computed with a 3-dimensional (3D) computer code solving Maxwell's equations such as Finite Difference Time Domain (FDTD) (Taflove & Hagness, 2005) or method of moments (MoM) (Harrington, 1993). Second, a multiconductor transmission line (MTL) (Paul, 2008) technique assuming transverse EM (TEM) mode propagation is used to calculate currents and voltages induced at the input of the electronic equipment devices by the excitation fields calculated in the previous steps (Agrawal et al., 1980). Unfortunately, this method presents two important drawbacks. Indeed, the MTL formalism is frequency limited by the appearance of transverse electric (TE) or magnetic (TM) modes and due to the fact that the EM emission of cables are not taken into account. Moreover, the huge complexity of a real automotive cable network seems to be unreasonable to model considering the required computer resources. Thus, the use of 3D computer codes at high frequency should be a suitable solution to overcome the limits of the MTL formalism but with a large increase of computation times required.

Consequently, this chapter presents the so-called « equivalent cable bundle method » (Andrieu et al., 2008), derived from previous work (Poudroux et al., 1995) developed to model a "reduced" cable bundle containing a limited number of conductors called "equivalent conductors" instead of the initial cable bundle. The huge reduction of the cable network complexity highly reduces the computer resources required to model a real automotive cable network. As an example, Fig. 1 presents the cross-section geometry of an initial cable bundle containing 10 conductors and the corresponding reduced cable bundle containing 3 equivalent conductors.

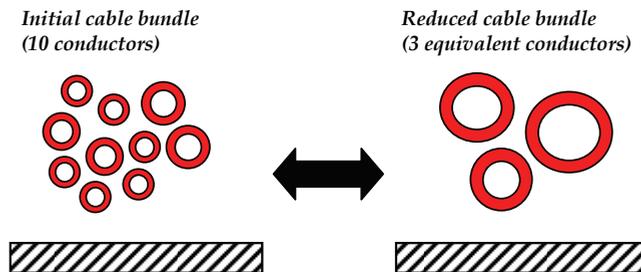


Fig. 1. Principle of the « equivalent cable bundle method »: definition of reduced cable bundle containing a limited number of equivalent conductors

Each equivalent conductor of the reduced cable bundle represents the effect of a group of conductors of the initial cable bundle.

The objective of the method is to be able to calculate the common mode current (algebraic sum of the currents in all the conductors of a cable bundle) induced at the extremities of the reduced cable bundle. The method does not compute the current on each conductor of the cable. For EM immunity problems, the common mode current nevertheless remains the most significant and robust observable.

The method can be used for a large frequency range which constitutes an important advantage provided that the simulation method is able to take into account the cross-coupling between conductors.

After an exhaustive presentation of the method for immunity problems (Andrieu et al., 2008) as well as an application to a concrete example, the adjustments required on the method for emission problems (Andrieu et al., 2009) are detailed with an other example. Finally, the results of a measurement campaign performed on a simplified half scale car body structure are presented in order to show the capability of the method when applied on representative automotive cases.

## 2. The “Equivalent Cable Bundle Method” for immunity problems

The determination of the electric and geometric characteristics of a reduced cable bundle for an immunity problem (Andrieu et al., 2008) requires a four step procedure detailed in this section. It is important to make precise that the method is applied on a point-to-point cable link. To model a cable bundle network as a real automotive one, the procedure has to be repeated on each path of conductors of the network.

### 2.1 Constitution of group of conductors

The aim of the first step of the method is to sort out all the conductors of the initial cable bundle in different groups according to the termination loads connected at their ends. Indeed, each termination load, linking the end of a wire conductor to the ground reference, is compared to the common mode characteristic impedance  $Z_{mc}$  of a whole cable bundle section, themselves sorted out in one of the four groups defined in Table 1.

	Group 1	Group 2	Group 3	Group 4
Common mode load at end 1	$R_{1i} < R_{mc}$	$R_{1i} < R_{mc}$	$R_{1i} > R_{mc}$	$R_{1i} > R_{mc}$
Common mode load at end 2	$R_{2i} < R_{mc}$	$R_{2i} > R_{mc}$	$R_{2i} < R_{mc}$	$R_{2i} > R_{mc}$

Table 1. Definition of the method used to sort each conductor in one of the four groups of conductors

All the impedance loads  $R_{ij}$  are considered in this work as resistances, therefore with no variation with the frequency; it is compared to the real part of  $Z_{mc}$  called  $R_{mc}$ . The index  $i$  corresponds to the label of the extremity (1 or 2) and the label  $j$  is the number of the conductor.

The determination of  $Z_{mc}$  requires the use of the modal theory in order to obtain the characteristics of all the modes propagating along the cable. The diagonalization of the product of the per-unit-length matrices of the MTL theory provides the modal basis. For example, the diagonalization of the product  $[L].[C]^{-1}$  of a cable bundle of  $N$  conductors gives the  $[Z_c^2]$  matrix containing the square of the characteristic impedances ( $Z_1, Z_2, \dots, Z_N$ ) of all the modes:

$$[Z_c^2] = [T_x]^{-1} \cdot [L] \cdot [C]^{-1} \cdot [T_x] = [T_y]^{-1} \cdot [C]^{-1} \cdot [L] \cdot [T_y] = \begin{bmatrix} Z_1^2 & 0 & \dots & 0 \\ 0 & Z_2^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & Z_N^2 \end{bmatrix} \quad (1)$$

$$[\Gamma^2] = [T_v]^{-1} \cdot [L] \cdot [C] \cdot [T_v] = [T_i]^{-1} \cdot [C] \cdot [L] \cdot [T_i] = \begin{bmatrix} 1/v_1^2 & 0 & \dots & 0 \\ 0 & 1/v_2^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1/v_N^2 \end{bmatrix} \quad (2)$$

In the same way, the square of modal propagation matrix  $[\Gamma^2]$  containing the propagation velocity  $v$  of all the modes is obtained with the diagonalization of the  $[L] \cdot [C]$  product.

$[T_x]$ ,  $[T_y]$ ,  $[T_v]$ ,  $[T_i]$  are the eigenvector matrices allowing to link real and modal basis.

The authors make precise that the transmission lines are considered in the method as lossless. In order to consider lossy ones, the following impedance  $[Z]$  and admittance  $[Y]$  matrices (containing respectively the resistance  $[R]$  and the conductance  $[G]$  matrices) should be used:

$$[Z] = [R] + j\omega[L] \quad (3)$$

$$[Y] = [G] + j\omega[C] \quad (4)$$

$Z_{mc}$  is determined from the common mode characteristic impedance of each conductor  $z_i$  of a cable which is determined thanks to the analysis of the eigenvector matrices  $[T_x]$  or  $[T_y]$ . For example, a  $[T_x]$  matrix of a 3-conductors cable bundle is presented in equation (5):

$$[T_x] = \begin{bmatrix} 0.57 & 0.81 & -0.1 \\ 0.56 & -0.48 & -0.67 \\ 0.6 & -0.32 & 0.74 \end{bmatrix} \quad (5)$$

Each column of the matrix contains an eigenvector associated to a propagation mode. The eigenvector associated to the common mode can be distinguished from the others. Indeed, all its terms have the same sign and all the coefficients of the eigenvector have close values. Consequently, in the example of equation (5), the eigenvector linked to the common mode is contained in the first column.

The last step to determine  $Z_{mc}$  consists in finding the characteristic impedance of the  $[Z_c^2]$  modal matrix linked to the common mode.

In equation (6), where  $[T_x]$  has been replaced by its value, the characteristic impedance  $z_i$  linked to the common mode eigenvector is  $Z_1$ . Indeed,  $Z_1$  depends of the term of the first column of  $[T_x]$  matrix, the eigenvector of the common mode.

$$[Z_C^2] = [T_x]^{-1} \cdot [L] \cdot [C]^{-1} \cdot \begin{bmatrix} 0.57 & 0.81 & -0.1 \\ 0.56 & -0.48 & -0.67 \\ 0.6 & -0.32 & 0.74 \end{bmatrix} = \begin{bmatrix} Z_1^2 & 0 & 0 \\ 0 & Z_2^2 & 0 \\ 0 & 0 & Z_3^2 \end{bmatrix} \quad (6)$$

$z_i$  also corresponds to the ratio of the common mode voltage  $V_{mc}$  and current  $I_{mc}$  in the modal basis as it is presented in Fig. 2.

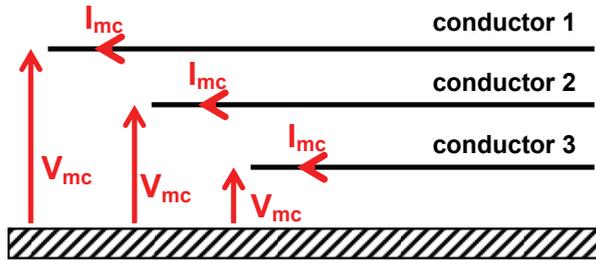


Fig. 2. Representation of the common mode currents and voltages in the modal basis for a 3-conductor cable bundle

$z_i$  being determined, it is easy to determine  $Z_{mc}$ . The common mode voltage  $V_{mc}$  is assumed to be identical on all the conductors of the cable bundle and  $Z_{mc}$  equals the common mode impedance of the cable bundle when all the conductors are short-circuited as it is shown in Fig. 3.

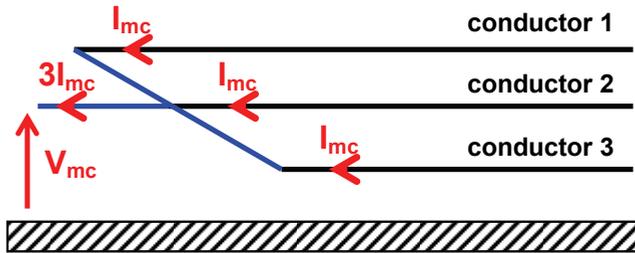


Fig. 3. Physical representation of the common mode characteristic impedance of a cable bundle

On the example in Fig. 3,  $Z_{mc}$  can be written:

$$Z_{mc} = \frac{V_{mc}}{3I_{mc}} = \frac{z_i}{3} \tag{7}$$

In the general case of a N-conductor cable bundle, equation (8) provides  $Z_{mc}$  from  $z_i$ :

$$Z_{mc} = \frac{z_i}{N} \tag{8}$$

Each group of conductors made in this step corresponds to one equivalent conductor of the reduced cable bundle. Thus, each multiconductor cable bundle can be modelled by a reduced cable bundle containing between one to four equivalent conductors according to the terminal load configurations at the end of all the conductors of the initial cable bundle. From a physical point of view, this operation consists in grouping together conductors having a similar distribution of current which is strongly dependent of terminal loads.

**2.2 Determination of the per-unit-length matrices of the reduced cable bundle**

Group current and group voltage: The second step of the method consists in determining the inductance [ $L_{reduced}$ ] and capacitance [ $C_{reduced}$ ] matrices of the reduced cable bundle by

making a simple assumption which considers a short-circuit between all the conductors of a group. This assumption first allows defining a group current  $I_{EC}$  and a group voltage  $V_{EC}$  for each group of conductors. As an example, the group current and the group voltage of a group containing  $N$  conductors can be written:

$$I_{EC} = I_1 + I_2 + \dots + I_N \tag{9}$$

$$V_{EC} = V_1 = V_2 = \dots = V_N \tag{10}$$

From this point, in order to clearly present the demonstration allowing to obtain the inductance matrix of a reduced cable bundle containing 4 equivalent conductors from an initial cable bundle containing  $N$  conductors, the authors prefer to change the index of the conductors belonging to the same group. Thus:

- the  $N_1$  conductors of the first group have the index 1 to  $\alpha$  ;
- the  $N_2$  conductors of the second group have the index  $\alpha+1$  to  $\beta$  ;
- the  $N_3$  conductors of the third group have the index  $\beta+1$  to  $\gamma$  ;
- the  $N_4$  conductors of the fourth group have the index  $\gamma+1$  to  $N$ .

Determination of the inductance matrix of the reduced cable bundle: In the MTL formalism, the inductance matrix links the currents and the voltages on each conductor on an infinitesimal segment of length  $dz$ :

$$\frac{\partial}{\partial z} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = -j \cdot \omega \cdot \begin{bmatrix} L_{11} & L_{12} & \dots & L_{1N} \\ L_{21} & L_{22} & \dots & L_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ L_{N1} & L_{N2} & \dots & L_{NN} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} \tag{11}$$

The determination of the  $[L_{\text{reduced}}]$  matrix requires two additional assumptions. To present and clearly justify these new assumptions, the currents flowing along all the  $N$  conductors of a cable bundle are decomposed in Fig.4 in common mode currents  $I_{ci}$  and differential current  $I_{dij}$ .

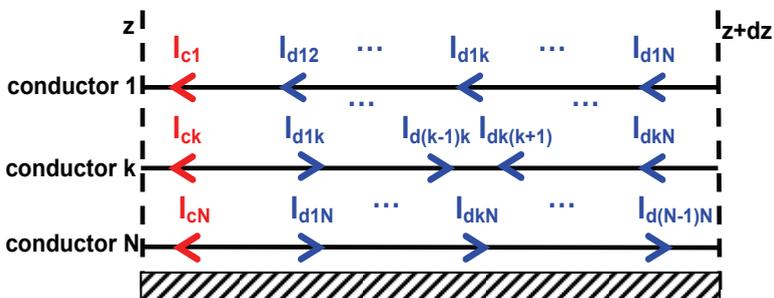


Fig. 4. Decomposition of the common and differential mode currents on a cable bundle containing  $N$  conductors

Thus, the currents  $I_1$ ,  $I_k$  and  $I_N$  on conductors 1,  $k$  and  $N$  can be expressed according to the decomposition in common and differential mode currents:

$$I_1 = I_{c1} + \sum_{i=2}^N I_{d1i} \tag{12}$$

$$I_k = I_{ck} - \sum_{i=1}^{k-1} I_{dik} + \sum_{i=k+1}^N I_{dki} \tag{13}$$

$$I_N = I_{cN} - \sum_{i=1}^{N-1} I_{diN} \tag{14}$$

In eq. (11), currents  $I_i$  can be replaced by general expressions reported in equations (12), (13), (14). When developing the system, the  $k^{\text{th}}$  line of the system can be written in this form:

$$\frac{\partial V_k}{\partial x} = -j \cdot \omega \left[ \sum_{i=1}^N (L_{ki} \cdot I_{ci}) + \sum_{i=1}^{N-1} \sum_{j=i+1}^N (I_{dij} \cdot (L_{ki} - L_{kj})) \right] \tag{15}$$

Consequently the per-unit-length voltage  $\frac{\partial V_k}{\partial x}$  on a infinitesimal segment of length  $dx$  equals the sum of a term depending of the common mode currents  $I_{ci}$  and a term depending of differential mode currents  $I_{dij}$  between conductor  $k$  and all the other conductors. The assumption made in the method consists in considering that the second term can be neglected compared to the first term depending on the common mode currents. Indeed, in an EM immunity problem, the common mode current induced on a multiconductor cable bundle may be considered as larger than differential currents. This assumption can be generalized with the following equation:

$$L_{ki} \cdot I_{ci} \gg \sum_{i=1}^{N-1} \sum_{j=i+1}^N (I_{dij} \cdot (L_{ki} - L_{kj})) \tag{16}$$

The following matrix system linking the voltages on each conductor  $V_i$  to the common mode current on each conductor  $I_{ci}$  can then be written:

$$\frac{\partial}{\partial z} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = -j \cdot \omega \cdot \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1N} \\ L_{21} & L_{22} & \cdots & L_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ L_{N1} & L_{N2} & \cdots & L_{NN} \end{bmatrix} \cdot \begin{bmatrix} I_{c1} \\ I_{c2} \\ \vdots \\ I_{cN} \end{bmatrix} \tag{17}$$

The second assumption consists in considering that the common mode current on all the conductors of a group is identical on each conductor. This assumption can be written in this form for a group of  $N$  conductors:

$$I_{ck} = \frac{I_{EC}}{N} \tag{18}$$

where  $I_{EC}$  is the group current and  $I_{ck}$  is the common mode current on a conductor of index  $k$  in the group. This second assumption allows writing the matrix system in this form:

$$\begin{aligned}
 \frac{\partial V_1}{\partial x} &= -j.\omega. \left[ \frac{\sum_{j=1}^{\alpha} L_{1j}}{N_1}.I_{EC1} + \frac{\sum_{j=\alpha+1}^{\beta} L_{1j}}{N_2}.I_{EC2} + \frac{\sum_{j=\beta+1}^{\gamma} L_{1j}}{N_3}.I_{EC3} + \frac{\sum_{j=\gamma+1}^N L_{1j}}{N_4}.I_{EC4} \right] \\
 &\vdots \\
 \frac{\partial V_k}{\partial x} &= -j.\omega. \left[ \frac{\sum_{j=1}^{\alpha} L_{kj}}{N_1}.I_{EC1} + \frac{\sum_{j=\alpha+1}^{\beta} L_{kj}}{N_2}.I_{EC2} + \frac{\sum_{j=\beta+1}^{\gamma} L_{kj}}{N_3}.I_{EC3} + \frac{\sum_{j=\gamma+1}^N L_{kj}}{N_4}.I_{EC4} \right] \\
 &\vdots \\
 \frac{\partial V_\delta}{\partial x} &= -j.\omega. \left[ \frac{\sum_{j=1}^{\alpha} L_{Nj}}{N_1}.I_{EC1} + \frac{\sum_{j=\alpha+1}^{\beta} L_{Nj}}{N_2}.I_{EC2} + \frac{\sum_{j=\beta+1}^{\gamma} L_{Nj}}{N_3}.I_{EC3} + \frac{\sum_{j=\gamma+1}^N L_{Nj}}{N_4}.I_{EC4} \right]
 \end{aligned} \tag{19}$$

where  $I_{EC1}$ ,  $I_{EC2}$ ,  $I_{EC3}$  and  $I_{EC4}$  are the group current of all the equivalent conductors. It is reminded that the voltages on each conductor belonging to a same group are considered as equal. Consequently, the  $N*N$  matrix system of equation (19) can be reduced to a simplified  $4*4$  matrix system relating the group currents and the groups voltages on the four groups of conductors as follows:

$$\begin{aligned}
 \frac{\partial V_{EC1}}{\partial x} &= -j.\omega. \left[ \frac{\sum_{i=1}^{\alpha} \sum_{j=1}^{\alpha} L_{ij}}{N_1^2}.I_{EC1} + \frac{\sum_{i=1}^{\alpha} \sum_{j=\alpha+1}^{\beta} L_{ij}}{N_1.N_2}.I_{EC2} + \frac{\sum_{i=1}^{\alpha} \sum_{j=\beta+1}^{\gamma} L_{ij}}{N_1.N_3}.I_{EC3} + \frac{\sum_{i=1}^{\alpha} \sum_{j=\gamma+1}^N L_{ij}}{N_1.N_4}.I_{EC4} \right] \\
 \frac{\partial V_{EC2}}{\partial x} &= -j.\omega. \left[ \frac{\sum_{i=\alpha+1}^{\beta} \sum_{j=1}^{\alpha} L_{ij}}{N_1.N_2}.I_{EC1} + \frac{\sum_{i=\alpha+1}^{\beta} \sum_{j=\alpha+1}^{\beta} L_{ij}}{N_2^2}.I_{EC2} + \frac{\sum_{i=\alpha+1}^{\beta} \sum_{j=\beta+1}^{\gamma} L_{ij}}{N_2.N_3}.I_{EC3} + \frac{\sum_{i=\alpha+1}^{\beta} \sum_{j=\gamma+1}^N L_{ij}}{N_2.N_4}.I_{EC4} \right] \\
 \frac{\partial V_{EC3}}{\partial x} &= -j.\omega. \left[ \frac{\sum_{i=\beta+1}^{\gamma} \sum_{j=1}^{\alpha} L_{ij}}{N_1.N_3}.I_{EC1} + \frac{\sum_{i=\beta+1}^{\gamma} \sum_{j=\alpha+1}^{\beta} L_{ij}}{N_2.N_3}.I_{EC2} + \frac{\sum_{i=\beta+1}^{\gamma} \sum_{j=\beta+1}^{\gamma} L_{ij}}{N_3^2}.I_{EC3} + \frac{\sum_{i=\beta+1}^{\gamma} \sum_{j=\gamma+1}^N L_{ij}}{N_3.N_4}.I_{EC4} \right] \\
 \frac{\partial V_{EC4}}{\partial x} &= -j.\omega. \left[ \frac{\sum_{i=\gamma+1}^N \sum_{j=1}^{\alpha} L_{ij}}{N_1.N_4}.I_{EC1} + \frac{\sum_{i=\gamma+1}^N \sum_{j=\alpha+1}^{\beta} L_{ij}}{N_2.N_4}.I_{EC2} + \frac{\sum_{i=\gamma+1}^N \sum_{j=\beta+1}^{\gamma} L_{ij}}{N_3.N_4}.I_{EC3} + \frac{\sum_{i=\gamma+1}^N \sum_{j=\gamma+1}^N L_{ij}}{N_4^2}.I_{EC4} \right]
 \end{aligned} \tag{20}$$

where  $V_{EC1}$ ,  $V_{EC2}$ ,  $V_{EC3}$  and  $V_{EC4}$  are the group voltages of the 4 equivalent conductors. Finally, with the assumptions made, a 4\*4 reduced matrix system corresponding to the reduced cable bundle is obtained and the  $[L_{reduced}]$  matrix appears:

$$\frac{\partial}{\partial x} \begin{bmatrix} V_{EC1} \\ V_{EC2} \\ V_{EC3} \\ V_{EC4} \end{bmatrix} = -j \cdot \omega \cdot [L_{reduced}] \cdot \begin{bmatrix} I_{EC1} \\ I_{EC2} \\ I_{EC3} \\ I_{EC4} \end{bmatrix} \quad (21)$$

Each diagonal term of  $[L_{reduced}]$  corresponds to the MTL inductance of an equivalent conductor of the reduced cable bundle with respect to the ground reference. It is equal to the sum of each diagonal and off-diagonal inductance terms of the initial  $[L]$  matrix between all the conductors of the group divided by the square of the number of conductors of the group.

Off-diagonal terms of  $[L_{reduced}]$  represent the mutual inductance between both groups of conductors and equal the sum of the mutual inductances between all the conductors belonging to two different groups divided by the number of conductors of both groups.

As an example, the following 7-conductors cable bundle has been studied.

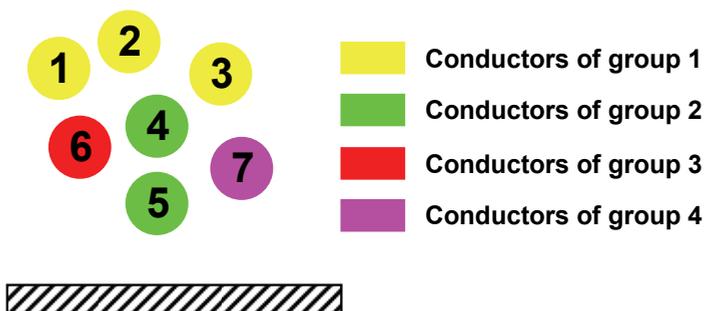


Fig. 5. Example of groups of conductors of a 7-conductor cable bundle

The reduced inductance matrix of the reduced cable bundle containing 4 equivalent conductors equals:

$$[L_{reduced}] = \begin{bmatrix} \frac{L_{11} + L_{22} + L_{33} + 2.L_{12} + 2.L_{13} + 2.L_{23}}{9} & \dots & \dots & \dots \\ \frac{L_{14} + L_{15} + L_{24} + L_{25} + L_{34} + L_{35}}{6} & \frac{L_{44} + L_{55} + 2.L_{45}}{3} & \dots & \dots \\ \frac{L_{16} + L_{26} + L_{36}}{3} & \frac{L_{46} + L_{56}}{2} & L_{66} & \dots \\ \frac{L_{17} + L_{27} + L_{37}}{3} & \frac{L_{47} + L_{57}}{2} & L_{67} & L_{77} \end{bmatrix} \quad (22)$$

Determination of the capacitance matrix of the reduced cable bundle: In the MTL formalism, the the capacitance matrix links the currents and the voltages on each conductor on an infinitesimal segment of length dx:

$$\frac{\partial}{\partial z} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} = -j \cdot \omega \cdot \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1N} \\ C_{21} & C_{22} & \cdots & C_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ C_{N1} & C_{N2} & \cdots & C_{NN} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} \quad (23)$$

The determination of the capacitance matrix depends of the medium surrounding all the conductors and the ground reference of the cable bundle.

In a homogeneous medium (generally air), all the modes have the same propagation velocity  $v$  depending of the light velocity in the vacuum ( $C=3.10^8\text{m.s}^{-1}$ ) and the relative dielectric permittivity  $\epsilon_r$  of the medium:

$$v = \frac{C}{\sqrt{\epsilon_r}} \quad (24)$$

The capacitance matrix of the reduced cable bundle  $[C_{\text{reduced}}]$  is then directly obtained with this simple formula:

$$[C_{\text{reduced}}] = \frac{1}{v^2} \cdot [L_{\text{reduced}}]^{-1} \quad (25)$$

In a inhomogeneous medium where all the conductors are surrounded by a non uniform dielectric medium as for example various insulating dielectric coatings, equation (25) cannot be used to derive the  $[C_{\text{reduced}}]$  matrix.

Replacing voltages  $V_i$  on each conductor by the group voltage  $V_{CEi}$  of each group of index  $i$  and developing the matrix system, equation (23) can be written:

$$\begin{aligned} \frac{\partial I_1}{\partial x} &= j \cdot \omega \cdot \left[ \sum_{j=1}^{\alpha} C_{1j} \cdot V_{EC1} + \sum_{j=\alpha+1}^{\beta} C_{1j} \cdot V_{EC2} + \sum_{j=\beta+1}^{\gamma} C_{1j} \cdot V_{EC3} + \sum_{j=\gamma+1}^N C_{1j} \cdot V_{EC4} \right] \\ &\vdots \\ \frac{\partial I_k}{\partial x} &= j \cdot \omega \cdot \left[ \sum_{j=1}^{\alpha} C_{kj} \cdot V_{EC1} + \sum_{j=\alpha+1}^{\beta} C_{kj} \cdot V_{EC2} + \sum_{j=\beta+1}^{\gamma} C_{kj} \cdot V_{EC3} + \sum_{j=\gamma+1}^N C_{kj} \cdot V_{EC4} \right] \\ &\vdots \\ \frac{\partial I_\delta}{\partial x} &= j \cdot \omega \cdot \left[ \sum_{j=1}^{\alpha} C_{Nj} \cdot V_{EC1} + \sum_{j=\alpha+1}^{\beta} C_{Nj} \cdot V_{EC2} + \sum_{j=\beta+1}^{\gamma} C_{Nj} \cdot V_{EC3} + \sum_{j=\gamma+1}^N C_{Nj} \cdot V_{EC4} \right] \end{aligned} \quad (26)$$

Then, the common mode current of each group of conductors can be calculated by adding all the lines corresponding to the current  $I_i$  if  $i$  is a conductor of the group. Thus, a  $4 \times 4$  matrix system is obtained from the  $N \times N$  matrix system linked to the initial cable bundle.

This reduced matrix system, a  $4 \times 4$  matrix system the  $[C_{\text{reduced}}]$  matrix having a dimension equal to the number of groups of conductors made in the first step of the method.

Applying the simple assumptions described in this section, the reduced matrix system of the MTL obtained has a dimension equal to the number of groups of conductors made in the first step of the procedure.

$$\begin{aligned}
 \frac{\partial I_{EC1}}{\partial x} &= j.\omega. \left[ \sum_{i=1}^{\alpha} \sum_{j=1}^{\alpha} C_{ij}.V_{EC1} + \sum_{i=1}^{\alpha} \sum_{j=\alpha+1}^{\beta} C_{ij}.V_{EC2} + \sum_{i=1}^{\alpha} \sum_{j=\beta+1}^{\gamma} C_{ij}.V_{EC3} + \sum_{i=1}^{\alpha} \sum_{j=\gamma+1}^N C_{ij}.V_{EC4} \right] \\
 \frac{\partial I_{EC2}}{\partial x} &= j.\omega. \left[ \sum_{i=\alpha+1}^{\beta} \sum_{j=1}^{\alpha} C_{ij}.V_{EC1} + \sum_{i=\alpha+1}^{\beta} \sum_{j=\alpha+1}^{\beta} C_{ij}.V_{EC2} + \sum_{i=\alpha+1}^{\beta} \sum_{j=\beta+1}^{\gamma} C_{ij}.V_{EC3} + \sum_{i=\alpha+1}^{\beta} \sum_{j=\gamma+1}^N C_{ij}.V_{EC4} \right] \\
 \frac{\partial I_{EC3}}{\partial x} &= j.\omega. \left[ \sum_{i=\beta+1}^{\gamma} \sum_{j=1}^{\alpha} C_{ij}.V_{EC1} + \sum_{i=\beta+1}^{\gamma} \sum_{j=\alpha+1}^{\beta} C_{ij}.V_{EC2} + \sum_{i=\beta+1}^{\gamma} \sum_{j=\beta+1}^{\gamma} C_{ij}.V_{EC3} + \sum_{i=\beta+1}^{\gamma} \sum_{j=\gamma+1}^N C_{ij}.V_{EC4} \right] \\
 \frac{\partial I_{EC4}}{\partial x} &= j.\omega. \left[ \sum_{i=\gamma+1}^N \sum_{j=1}^{\alpha} C_{ij}.V_{EC1} + \sum_{i=\gamma+1}^N \sum_{j=\alpha+1}^{\beta} C_{ij}.V_{EC2} + \sum_{i=\gamma+1}^N \sum_{j=\beta+1}^{\gamma} C_{ij}.V_{EC3} + \sum_{i=\gamma+1}^N \sum_{j=\gamma+1}^N C_{ij}.V_{EC4} \right]
 \end{aligned} \tag{27}$$

Equation(28) presents the reduced matrix system obtained in a condensed form.

$$\frac{\partial}{\partial x} \begin{bmatrix} I_{EC1} \\ I_{EC2} \\ I_{EC3} \\ I_{EC4} \end{bmatrix} = j.\omega. [C_{reduced}] \cdot \begin{bmatrix} V_{EC1} \\ V_{EC2} \\ V_{EC3} \\ V_{EC4} \end{bmatrix} \tag{28}$$

The  $[C_{reduced}]$  capacitance matrix corresponding to the cable bundle presented in Fig. 5 can be written:

$$[C_{reduced}] = \begin{bmatrix} C_{11} + C_{22} + C_{33} + 2.C_{12} + 2.C_{13} + 2.C_{23} & \dots & \dots & \dots \\ C_{14} + C_{15} + C_{24} + C_{25} + C_{34} + C_{35} & C_{44} + C_{55} + 2.C_{45} & \dots & \dots \\ C_{16} + C_{26} + C_{36} & C_{46} + C_{56} & C_{66} & \dots \\ C_{17} + C_{27} + C_{37} & C_{47} + C_{57} & C_{67} & C_{77} \end{bmatrix} \tag{29}$$

Diagonal terms of the reduced capacitance matrix  $[C_{reduced}]$  equal the sum of the physical capacitances between each conductor of the group and the ground reference minus all the physical capacitances between two conductors belonging to the group. As an example, the  $C_{22\_reduced}$  term of the Fig.5  $[C_{reduced}]$  matrix can be expressed in this following form according to the physical capacitances:

$$C_{22\_reduced} = \sum_{i=1}^N C_{4i}^p + \sum_{i=1}^N C_{5i}^p - 2.C_{45}^p \tag{30}$$

Off-diagonal terms of the  $[C_{reduced}]$  matrix represents either the mutual capacitances between two equivalent conductors or between both corresponding groups of conductors.

In this example, the  $C_{12\_reduced}$  term corresponds to the mutual capacitances between equivalent conductors 1 and 2. The value of  $C_{12\_reduced}$  can be expressed with respect to the physical capacitances existing between the various conductors of group 1 and group 2 in the initial cable bundle.

$$C_{12\_reduced}^p = C_{14}^p + C_{15}^p + C_{24}^p + C_{25}^p + C_{34}^p + C_{35}^p \tag{31}$$

Thus, the physical capacitances existing between two equivalent conductors equals the sum of all the physical capacitances existing between 2 conductors belonging to these two different groups.

### 2.3 Procedure used to obtain the cross-section geometry of a reduced cable bundle

The aim of the third step of the method is to create the cross-section geometry of the reduced cable bundle. This operation is not mandatory and is only required in case of a 3D modeling. Indeed, for a MTL simulation, the reduced inductance and capacitance matrices obtained in the previous step are sufficient and can be directly introduced in the MTL models.

The procedure developed in this method requires 6 phases detailed in the following. It makes the assumption that the ground reference is a plane.

In the first phase, the height  $h_i$  of each equivalent conductor with respect to the ground reference is chosen by the user to be coherent with the geometry of the initial cable bundle. For example, the height of an equivalent conductor can be the mean of the height of all the conductors belonging to the corresponding group.

In the second phase, the radius  $r_i$  of each equivalent conductor is calculated with the well-known approximated analytical formula giving the inductance  $L_{ii}$  of a wire upon a ground plane.

$$r_i = \frac{2h_i}{e^{\mu_0} \frac{4\pi L_{ii}}{2\pi}} \quad (32)$$

where  $h_i$  and  $r_i$  are respectively the height of the conductor over the ground reference and its radius.

In the third phase, distances  $d_{ij}$  between equivalent conductors of index  $i$  and  $j$  are calculated with the analytical formula giving the mutual inductances  $L_{ij}$  between two conductors above a ground plane:

$$d_{ij} = \sqrt{\frac{4h_i h_j}{\frac{4\pi L_{ij}}{e^{\mu_0}} - 1}} \quad (33)$$

where  $h_i$  and  $h_j$  are the height of equivalent conductors  $i$  and  $j$  with respect to the ground reference.

After the first three phases, a first cross-section of the reduced cable bundle is obtained; the geometry is only an approached one. Indeed, the analytical formulas used are approximated. The use of an electrostatic code allows to obtain a cross-section geometry which perfectly matches the inductance and capacitance matrix of the reduced cable bundle obtained in the previous step could help but would not give a fully optimized solution. Indeed, this process is necessarily iterative and may not give a unique solution.

By using an electrostatic code, the objective is to optimized the radius and the distances between all the equivalent conductors to get a good convergence with the  $[L_{\text{reduced}}]$  matrix.

In the case where all the conductors of the initial cable bundle are not surrounded by a dielectric coating (not a realistic situation for electrical wiring in systems), the building of the cross-section geometry is completed. Otherwise, two additional phases are required.

In the fifth phase, the thickness of all the dielectric coating  $\epsilon_r$  surrounding each equivalent conductor is fixed to avoid overlapping.

In the sixth and last phase, on optimization is made on the relative permittivity of the dielectric coating surrounding all the equivalent conductors. The objective of the optimization process is to calculate  $\epsilon_r$  in order to comply the  $C_{ii}$  terms surrounding all the equivalent conductors in order to respect the  $C_{ii}$  term of the  $[C_{\text{reduced}}]$  matrix obtained at step 2. This process is also an

iterative process which requires the use of an electrostatic two dimensional (2D) code solving Laplace's equation.

The six-phase procedure used to determine the cross-section geometry of the reduced cable bundle is illustrated in Fig. 6 for a 3 equivalent conductor:

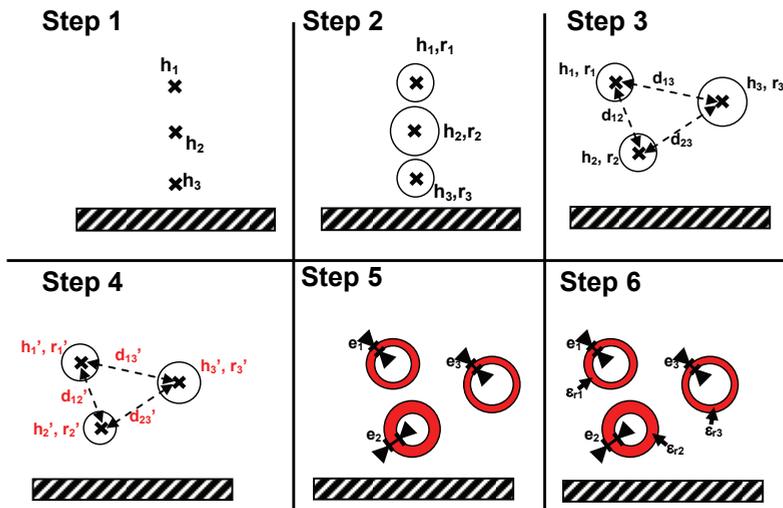


Fig. 6. Illustration on 3 equivalent conductors of the 6-phases procedure used to build the cross-section geometry of a reduced cable bundle

### 2.4 Equivalent termination loads of the reduced cable bundle

In the fourth and last step of the procedure, the objective is to determine the equivalent termination loads to be connected at each end of the equivalent conductors of the reduced cable bundle. Two kinds of loads have to be distinguished: termination loads connecting the end of a conductor to the ground reference which are called common-mode loads and termination loads connecting the ends of two conductors called differential loads.

*Common-mode loads:* Conductors of the same group are considered as short-circuited together as it is shown on the left of Fig. 7.

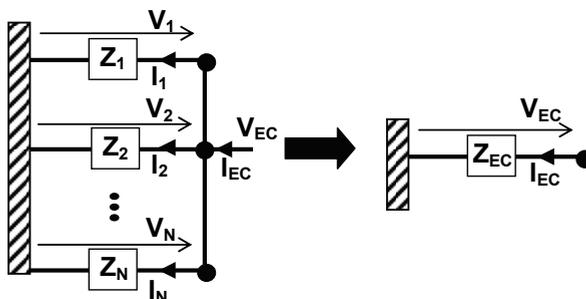


Fig. 7. Terminal impedance network of a group of conductors and equivalent load at the end of the corresponding equivalent conductor

Consequently, the group current  $I_{EC}$  can be expressed with respect to this straightforward equation according to the group voltage  $V_{EC}$ :

$$I_{EC} = I_1 + I_2 + \dots + I_N = V_{EC} \cdot \left( \frac{1}{Z_1} + \frac{1}{Z_2} + \dots + \frac{1}{Z_N} \right) \tag{34}$$

Thus, the termination load  $Z_{EC}$  at one end of an equivalent conductor equals all the termination loads of all the conductors of the corresponding group at the same end set in parallel.

$$Z_{EC} = \frac{1}{\left( \frac{1}{Z_1} + \frac{1}{Z_2} + \dots + \frac{1}{Z_N} \right)} = Z_1 // Z_2 // \dots // Z_N \tag{35}$$

*Differential loads:* Two kind of differential loads have to be considered depending if the load connects two conductors belonging to the same group or not.

The case of differential loads connecting two conductors belonging to the same group is illustrated in Fig. 8 on a group of 3 conductors having three differential loads  $Z_{12}$ ,  $Z_{13}$  and  $Z_{23}$ .

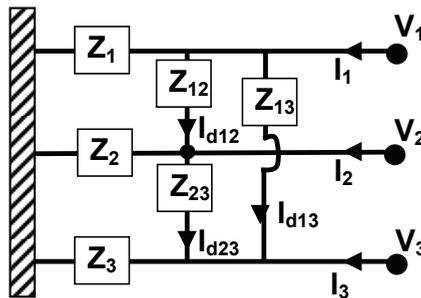


Fig. 8. Terminal impedance network of a 3-conductor group having 3 differential loads:  $Z_{12}$ ,  $Z_{13}$  and  $Z_{23}$

The admittance matrix of this termination load network is:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} = \begin{bmatrix} \frac{1}{Z_1} + \frac{1}{Z_{12}} + \frac{1}{Z_{13}} & -\frac{1}{Z_{12}} & -\frac{1}{Z_{13}} \\ -\frac{1}{Z_{12}} & \frac{1}{Z_2} + \frac{1}{Z_{12}} + \frac{1}{Z_{13}} & -\frac{1}{Z_{23}} \\ -\frac{1}{Z_{13}} & -\frac{1}{Z_{23}} & \frac{1}{Z_3} + \frac{1}{Z_{12}} + \frac{1}{Z_{13}} \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{36}$$

For this group of conductors, the hypothesis of the method is applied:

$$I_{EC} = I_1 + I_2 + I_3 \tag{37}$$

$$V_{EC} = V_1 = V_2 = V_3 \tag{38}$$

Consequently, the  $I_{EC}$  group current can be expressed in this simple form:

$$I_{cm} = I_1 + I_2 + I_3 = \frac{V_1}{Z_1} + \frac{V_2}{Z_2} + \frac{V_3}{Z_3} \tag{39}$$

Equation(39) clearly shows that the group current does not depend of differential loads connecting two conductors of the same group hypothesis. Consequently, in the method, this type of differential loads is neglected.

The case of differential loads connecting two conductors belonging to two different groups (conductors 1 and 2 in group 1, conductors 3 and 4 in group 2) is illustrated in Fig. 9 with the loads  $Z_{13}$  and  $Z_{24}$ .

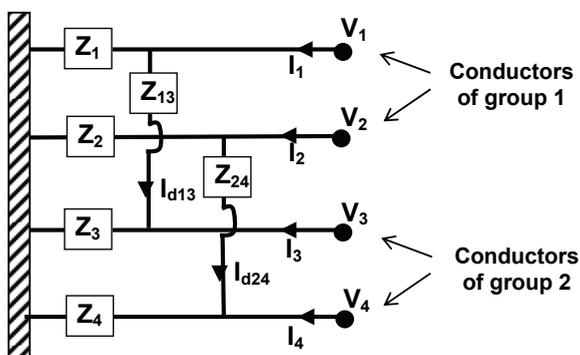


Fig. 9. Terminal impedance network of two groups of 2 conductors having 2 differential loads :  $Z_{13}$  and  $Z_{24}$

The admittance matrix of this terminal load network can be written:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} \frac{1}{Z_1} + \frac{1}{Z_{13}} & 0 & -\frac{1}{Z_{13}} & 0 \\ 0 & \frac{1}{Z_2} + \frac{1}{Z_{24}} & 0 & -\frac{1}{Z_{24}} \\ -\frac{1}{Z_{13}} & 0 & \frac{1}{Z_3} + \frac{1}{Z_{13}} & 0 \\ 0 & -\frac{1}{Z_{24}} & 0 & \frac{1}{Z_4} + \frac{1}{Z_{24}} \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} \tag{40}$$

For this example, the hypothesis of the method are the following ones :

$$I_{EC1} = I_1 + I_2 \tag{41}$$

$$I_{EC2} = I_3 + I_4 \tag{42}$$

$$V_{EC1} = V_1 = V_2 \tag{43}$$

$$V_{EC2} = V_3 = V_4 \tag{44}$$

Thanks to the admittance matrix of the terminal load network and the hypothesis of the method, group currents  $I_{EC1}$  and  $I_{EC2}$  can be written:

$$I_{EC1} = I_1 + I_2 = \frac{V_1}{Z_1} + \frac{V_2}{Z_2} + (V_{EC1} - V_{EC2}) \cdot \left( \frac{1}{Z_{13}} + \frac{1}{Z_{24}} \right) \tag{45}$$

$$I_{EC2} = I_3 + I_4 = \frac{V_3}{Z_3} + \frac{V_4}{Z_4} + (V_{EC2} - V_{EC1}) \cdot \left( \frac{1}{Z_{13}} + \frac{1}{Z_{24}} \right) \tag{46}$$

Both equations lead to the conclusion that the common mode current of a group of conductors depends of the common mode loads ( $Z_1, Z_2, Z_3$  and  $Z_4$  in this example) and of the differential loads connected to conductors belonging to the other groups ( $Z_{13}$  and  $Z_{24}$  in this example).

Thus, the group current  $I_{EC1}$  depends of the differential voltage between the first and the second group of conductors ( $V_{CE1} - V_{CE2}$ ) multiplied by the differential loads placed between the conductors belonging to different groups  $Z_{13}$  and  $Z_{24}$  set in parallel.

Thus, the terminal load network to be placed in this example at the end of both equivalent conductors is presented in Fig. 10.

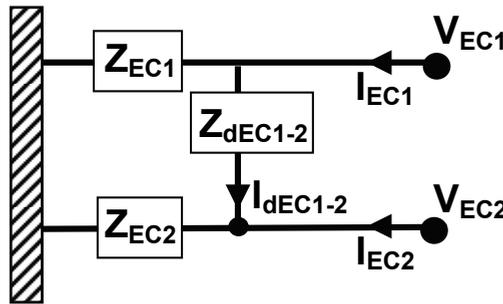


Fig. 10. Terminal load network at the extremity of both equivalent conductors

The terminal load values of this network have the following expressions:

$$Z_{EC1} = \frac{1}{Z_1} + \frac{1}{Z_2} = Z_1 // Z_2 \tag{47}$$

$$Z_{EC2} = \frac{1}{Z_3} + \frac{1}{Z_4} = Z_3 // Z_4 \tag{48}$$

$$Z_{dEC1-2} = \frac{1}{Z_{13}} + \frac{1}{Z_{24}} = Z_{13} // Z_{24} \tag{49}$$

In the general case, the equivalent terminal loads between two equivalent conductors equal all the differential loads connecting conductors of the two groups in parallel.

Consequently, the method is able to take into account all the types of terminal load networks made of resistive loads.

### 2.5 Example of application

To present a concrete example of use of the method in immunity, a 4-conductor cable bundle of 1m length and located at a distance of 2 cm from a perfect electric ground has been studied.

The following table presents the terminal loads of all the conductors having a 1 mm radius at both extremities:

	Conductor 1	Conductor 2	Conductor 3	Conductor 4
End 1	24 Ω	10 Ω	59 Ω	63 Ω
End 2	50 Ω	22 Ω	38 Ω	16 Ω

Table 2. – Values of the common mode loads connected at the ends of each conductor of the cable bundle

Considering the terminal load values and the common mode characteristic impedance of the initial cable bundle ( $Z_{mc} = 161 \Omega$ ), the reduced cable bundle only requires one equivalent conductor connected at both ends by loads of respective values 5.7 and 6.5 Ω.

Fig. 11. presents the cross-section geometry of the initial cable bundle and of the corresponding reduced cable bundle containing one equivalent conductor.

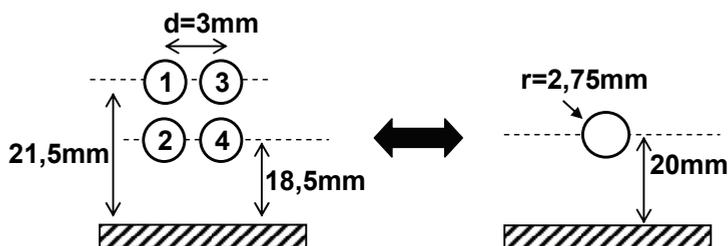


Fig. 11. Cross-section geometry of the initial cable bundle and of the corresponding equivalent conductor

The per-unit-length inductance and capacitance matrices of the initial cable bundle are given in the following (the matrices are symmetric and lower off-diagonal terms have not been written):

$$[L] = \begin{bmatrix} 694.3 & 501.6 & 511.6 & 455.5 \\ & 674.2 & 455.5 & 491.6 \\ & & 694.3 & 501.6 \\ & & & 674.2 \end{bmatrix} nH / m \quad (50)$$

$$[C] = \begin{bmatrix} 45.8 & -19.1 & -19.3 & -2.7 \\ & 46.2 & -2.7 & -18.8 \\ & & 45.8 & -19.1 \\ & & & 46.2 \end{bmatrix} pF / m \quad (51)$$

The per-unit-length inductance and capacitance of the equivalent conductor are respectively  $L=536 \text{ nH/m}$  and  $C=20.8 \text{ pF/m}$ .

Both cable bundles are supposed to be illuminated by a plane wave of 3 V/m amplitude propagating in the direction of the cables. The electric field component is oriented vertically compared to the ground reference.

Fig. 12. presents the comparison between the common mode current (in dBA) induced at the first end of the initial cable bundle and the current on the corresponding equivalent conductor at the same end. The calculations have been performed with the FEKO software using the method of moments (MoM) to solve Maxwell's equations.

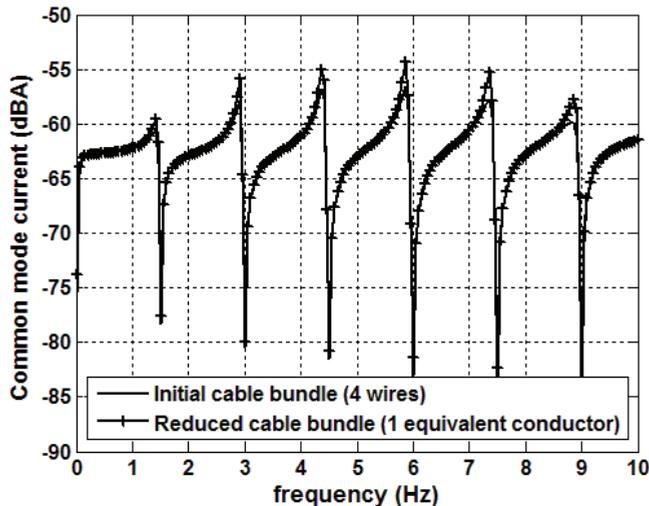


Fig. 12. Comparison of common mode current induced at the first end of both cable bundles (initial and reduced) by a 3V/m plane wave

The excellent agreement between both curves shows the high accuracy of the method. Moreover, the total computation times required to compute the  $[Z]$  impedance matrix in MoM has been divided by a factor higher than 10 for this simple modelling.

### 3. The “Equivalent Cable Bundle Method” for emission problems

#### 3.1 Specificity of the EM emission problem

In EM immunity problems, all the conductors are excited by the same EM incident field whereas in EM emission problems, each conductor of a cable bundle can be excited by sources of different amplitudes and internal impedances in different frequency ranges (or for different time domain spectrums). Consequently, the application of the method requires specific adjustments to be applied for EM emission problems.

In the following sub-section, the procedure required to define the electric and geometric characteristics of a reduced cable bundle for an emission problem (Andrieu et al., 2009) is presented. As in the previous section, the method is described on a point-to-point cable link. To be applied on a tree-like cable network, the procedure has to be repeated on each path of conductors inside the network.

The authors make precise that the whole problem is considered in the frequency domain and the excitation sources are restricted to voltage sources localized at conductor ends.

### 3.2 Presentation of the modified procedure

For EM emission problems, the procedure required to constitute the groups of conductors is decomposed in two phases to take into account the second degree of freedom due to the fact that each conductor of the cable bundle can be excited by its own source.

After a first classification of all the conductors of the initial cable bundle in four groups as it is made for an EM immunity problem, a second phase is made inside the groups according to the magnitude of the voltage source applied on each conductor belonging to the same group. The objective is to avoid that two conductors belonging to the same group are excited by sources having significant amplitude difference. Indeed, this configuration could lead to important differential currents between both conductors of a same group not taken into account by only one equivalent conductor. As it has been explained in section 2, the method assumes that the EM emissions of a cable bundle mainly come from the common mode current. Thus, the differential mode currents are neglected. The ratio of the voltage source magnitude applied on two conductors belonging to the same group must not be higher than a factor 3, 5 or 10 according to the accuracy aimed in the calculation.

Then, the three steps presented in sub-sections 2.2, 2.3 and 2.4 are performed identically. Finally, a fifth additional step is required to determine the equivalent voltage sources used to excite each equivalent conductor. Fig. 13. presents an example of a N-conductor group where each conductor is lumped by a resistance  $Z_i$  and excited by a voltage source  $V_i$ . The equivalent voltage source  $V_{EC}$  and terminal load  $Z_{EC}$  to connect at the end of the corresponding equivalent conductor are also presented in the figure.

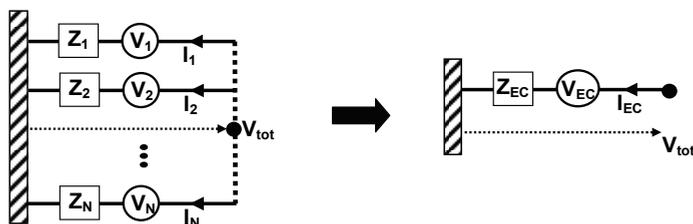


Fig. 13. Equivalent voltage source and impedance of an equivalent conductor corresponding to a 4-conductor group

According to Fig. 13, the current  $I_i$  flowing along conductor  $i$  belonging to the group of 4 conductors and the current  $I_{EC}$  on the corresponding equivalent conductor can be written:

$$I_i = \frac{V_{tot} - V_i}{Z_i} \tag{52}$$

$$I_{EC} = \frac{V_{tot} - V_{EC}}{Z_{EC}} \tag{53}$$

With (52), the common mode current  $I_{EC}$  of the 4-conductor group can be expressed in this simple form:

$$I_{EC} = \frac{V_{tot}}{Z_{EC}} - \left( \frac{V_1}{Z_1} + \frac{V_2}{Z_2} + \dots + \frac{V_N}{Z_N} \right) \tag{54}$$

Thus, the equivalent source voltage  $V_{EC}$  to be inserted on the equivalent conductor model is:

$$V_{EC} = (Z_{EC}) \cdot \left( \frac{V_1}{Z_1} + \frac{V_2}{Z_2} + \dots + \frac{V_N}{Z_N} \right) \quad (55)$$

where  $Z_{EC}$  equals all the termination loads of each group of conductors set in parallel:

$$Z_{EC} = Z_1 // Z_2 // \dots // Z_N \quad (56)$$

### 3.3 Example of application

To present a concrete application of the method for an EM emission problem, the initial cable bundle presented in section 2.5 has been studied. In this case, each conductor of the cable bundle has been excited at the first end by a voltage source respectively equals to 1 V for wire 1, 2 V for wire 2, 3 V for wire 3 and 4 V for wire 4. As for the immunity problem, the reduced cable bundle contains one equivalent conductor according to the terminal load and voltage source configurations.

The equivalent voltage source located at the first end of the equivalent conductor and corresponding to this configuration equals 2.04 V as it is demonstrated with the following equation:

$$V_{eq} = 5,73 \cdot \left( \frac{1}{24} + \frac{2}{10} + \frac{3}{59} + \frac{4}{63} \right) = 2,04V \quad (57)$$

The total radiated power by both initial and reduced cable bundles has been calculated by the FEKO 3D MoM software on the half-superior sphere (above the infinite ground plane). The total radiated power is obtained by making the integration of the Poynting vector on numerous points of the half superior sphere after the calculation of the electric and magnetic fields emitted at these points. Fig. 14 presents the comparison of the total radiated power (in dBW) of both cable bundle models:

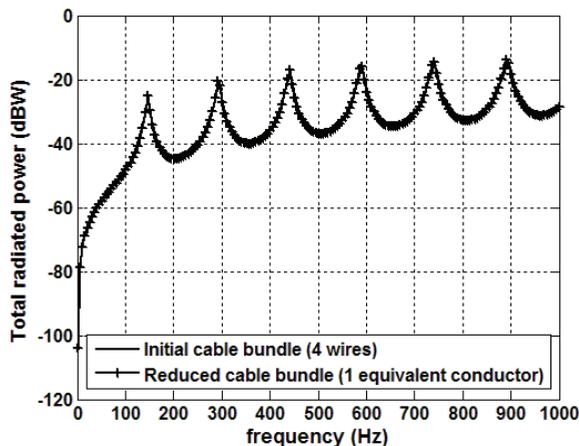


Fig. 14. Comparison of the total radiated power (in dBW) of both cable bundle models when introduced in a 3D MoM simulation

As for the EM immunity problem, the results show on this example the high accuracy of the method for EM emission problem. From the computation time point of view, the use of the reduced cable bundle has been reduced by a factor 14 the time necessary to compute all the terms of the  $[Z]$  impedance matrix with the MoM technique.

#### 4. Example of application on a representative automotive case

This section presents some results of a measurement campaign performed on a realistic automotive structure which is a half scale simplified car model, 180cm long, 80cm large and 70cm high presented in Fig. 15.



Fig. 15. Picture of the simplified car structure

The experiment has been performed in an anechoic chamber to ensure free space conditions. The measurement setup is presented in Fig. 16.

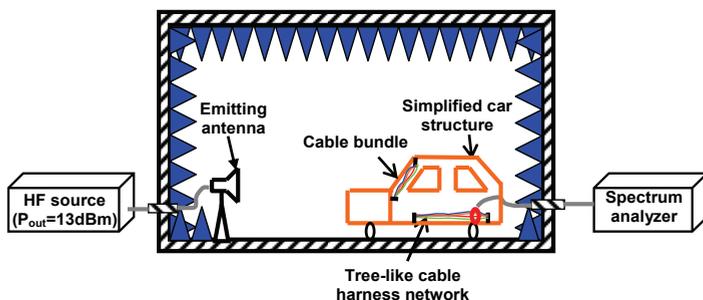


Fig. 16. Schematic description of the measurement setup

An emitting antenna illuminates with a vertical polarized electric field the front of the simplified car structure located approximately at 3m. In order to cover a large frequency range, two types of emitting antennas have been considered: a log periodic antenna up to 1 GHz and a double ridge horn antenna from 1 to 2 GHz. One cable bundle containing 5 conductors of 48 cm length plus one tree-like network having 4 extremities and a total of 16 conductors have been placed in the simplified structure. SMT (Surface Mount Technology) termination loads have been connected to each extremity of all the conductors to a metallic bracket fixed on the walls of the car which are considered as the ground reference. A current probe measured the common mode current induced at the ends of the cables by the EM incident field applied by the antennas.

The corresponding 3D model has been built thanks to the FEKO software. The MoM model of the simplified car structure containing the reduced cable bundle and the reduced tree-like cable network are presented in Fig. 17.

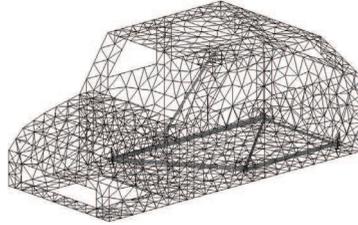


Fig. 17. MoM modelling of the test structure

The first result presented in Fig. 18 corresponds to the comparison of the common mode current at an extremity of the cable measured and calculated in MoM with a reduced cable bundle containing one equivalent conductor. Indeed, all the termination loads connected at both ends of all the conductors are small compared to the common mode characteristic impedance  $Z_{mc}$ .

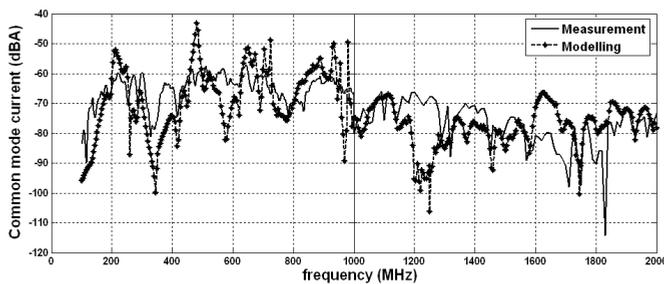


Fig. 18. Comparison of the common mode current measured and calculated at one extremity of the cable bundle

The second result presented in Fig. 19 concerns the comparison of the current measured and calculated at one extremity of the tree-like cable bundle network placed on the floor of the simplified car structure.

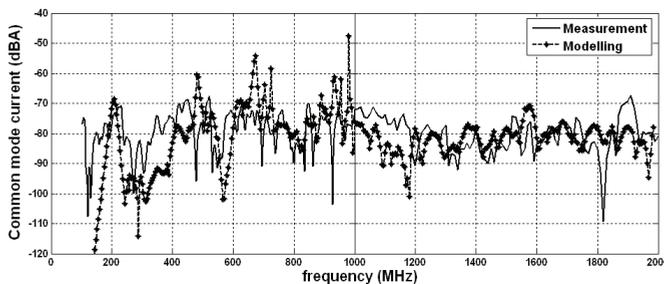


Fig. 19. Comparison of the common mode current measured and calculated at one extremity of the tree-like cable bundle network

Both figures present two very satisfying comparisons between measurements and modelling results on a large frequency range (100 MHz – 2 GHz). The average level is very close and the fundamental resonances of the bundles are quite well reproduced by the calculation. These results are very encouraging due to the fact that the tested structure is very oversized according to the wavelength.

To conclude, thanks to the use of the Fast Multipole Method (FMM) (Engheta et al., 1992), our method provides reasonable computation times compatible with an industrial application. For example, at the frequency of 1 GHz and on a 2.66 GHz processor with a memory of 1.5 Go, only 4 minutes are required to solve the MoM problem which contains more than 15 000 unknowns.

Applying the four-step procedure, our method has decreased the complexity of the reduced cable bundle and network by a 50 % factor.

## 5. Conclusion

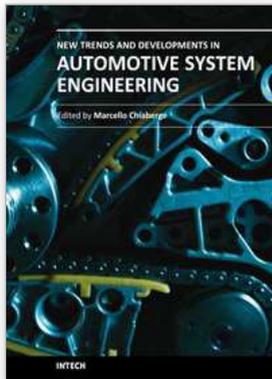
This chapter has presented the so-called "equivalent cable bundle method" allowing to highly reduce the complexity of a real automotive cable bundle network. Consequently, the modelling of the simplified cable bundle network can be made with a strong reduction of involved computation times both for immunity and emission problems for any simulation method able to take into account the couplings between coupled conductors and for a large frequency range.

This work presents a lot of interesting future axis of work. The first one is to compute the current on each conductor of the initial cable bundle after the use of the reduced cable bundle. Another important one is to take into account real passive loads as inductive and capacitive ones to represent with a more important accuracy real loads encountered at the input of automotive electronic equipments.

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## **New Trends and Developments in Automotive System Engineering**

Edited by Prof. Marcello Chiaberge

ISBN 978-953-307-517-4

Hard cover, 664 pages

**Publisher** InTech

**Published online** 08, January, 2011

**Published in print edition** January, 2011

In the last few years the automobile design process is required to become more responsible and responsibly related to environmental needs. Basing the automotive design not only on the appearance, the visual appearance of the vehicle needs to be thought together and deeply integrated with the "power" developed by the engine. The purpose of this book is to try to present the new technologies development scenario, and not to give any indication about the direction that should be given to the research in this complex and multi-disciplinary challenging field.

### **How to reference**

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Guillaume Andrieu, Xavier Bunlon, Lamine Koné, Jean-Philippe Parmantier, Bernard Démoulin and Alain Reineixl (2011). The 'Equivalent Cable Bundle Method': an Efficient Multiconductor Reduction Technique to Model Industrial Cable Networks, *New Trends and Developments in Automotive System Engineering*, Prof. Marcello Chiaberge (Ed.), ISBN: 978-953-307-517-4, InTech, Available from:

<http://www.intechopen.com/books/new-trends-and-developments-in-automotive-system-engineering/the-equivalent-cable-bundle-method-an-efficient-multiconductor-reduction-technique-to-model-industri>

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