Progress In Electromagnetics Research, Vol. 141, 135–148, 2013

APPLICATION OF THE "EQUIVALENT CABLE BUNDLE METHOD" FOR MODELING CROSSTALK OF COMPLEX CABLE BUNDLES WITHIN UNIFORM STRUCTURE WITH ARBITRARY CROSS-SECTION

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Abstract—In this paper, the equivalent cable bundle method (ECBM), an efficient simplified modeling method of the complex cable bundles, is modified for crosstalk prediction of complex cable bundles within uniform structure with arbitrary cross section. The foremost attributes of the modified method are a) the cable bundle within uniform structure with arbitrary cross section can be mapped to equivalent cable bundle above an infinite perfect electric conductor ground plane during the equivalence procedure, b) the culprit and victim conductors are divided into two groups separately during the grouping process, denoted as the culprit group and victim one, which do not participate in the equivalence procedure compared with the original ECBM for crosstalk problem, c) an effective eight-phase procedure is established to define the electrical and geometrical characteristics of the reduced cable bundle model. Numerical simulations performed on a selected cable bundle surrounded by a rectangular cavity illustrate the efficiency and the advantages of the method. This method is considered as a key step for the ECBM to find wide applications in real systems.

Received 23 May 2013, Accepted 6 July 2013, Scheduled 12 July 2013

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1. INTRODUCTION

The "Equivalent Cable Bundle Method" which is based on the main assumption that the common-mode response is more critical than the differential-mode response appears as a relevant solution for the modeling of real cable bundles when the multiconductor transmission lines technology (MTLT) is not applicable and full-wave modelings of the whole cable bundles are not possible for computation burden reasons. It was first developed for calculating the common-mode current induced at the extremity of simplified point-to-point cable structures excited by various incident electromagnetic (EM) fields [1], and also has been successfully extended for emissions [2, 3] and crosstalk [4] problems of complex cable bundles over a large frequency range with some reasonable modifications. Moreover, it was modified in [5] for modeling EM field coupling to the twisted-pair cables based on the assumption that the differential signal lines play a leading role in the equivalence procedure. In [6], it was adopted to predict the crosstalk of a cable bundle within a cylindrical cavity which is considered as the ground return. Then it was further studied and applied for predicting electromagnetic compatibility issues of complex cable bundle terminated in arbitrary loads [7] or in the vicinity of a 60 degree corner [8] and also adapted to model the crosstalk of multicoaxial cable bundles [9].

As mentioned above, the ECBM allows one to highly reduce the computation complexity for the cable network either in MTLT or full-wave calculations. Up to now, the establishment of the reduced cable bundle cross-section geometry only can be implemented either above an infinite PEC ground plane [2–5], inside a cylindrical cavity [6] or in the vicinity of a 60 degree corner [8] through the analytical formulas. However, no analytical formulas are available for direct reconstruction of the reduced cable bundle cross-section geometry model within arbitrary complex structures as Fig. 1(a), which makes the original ECBM unusable in general cases. So, in order to make the ECBM fit for this case, a modified ECBM is proposed for crosstalk prediction of complex cable bundle within any uniform structures with arbitrary cross section by a general mapping to equivalent conductors above an infinite PEC ground plane as shown in Fig. 1(b). Actually, this mapping is based on the fact that crosstalk modeling of cable bundles can be fully determined by the multiconductor transmission lines equation (the per-unit-length (p.u.l.) parameters) and the boundary condition (the termination loads at both ends). The p.u.l. parameters of the complete cable bundle in uniform structures with arbitrary cross section can be easily obtained through numerical method, such as finite

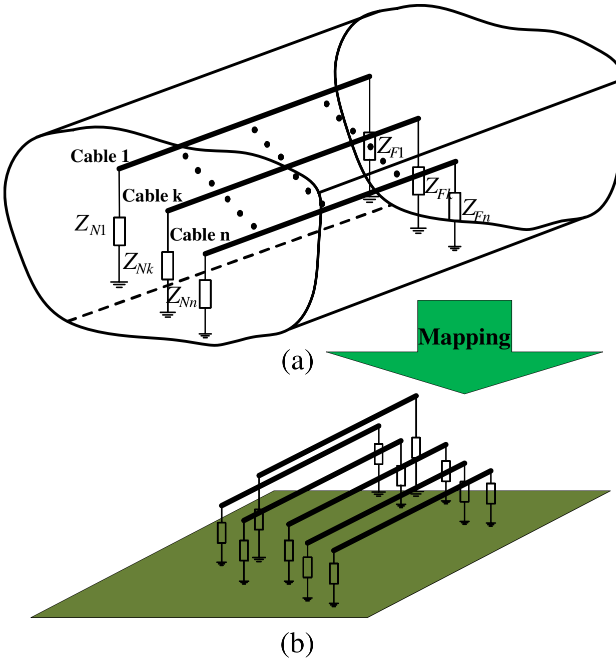

Figure 1. (a) Illustration of n-conductor transmission lines in a uniform structure with arbitrary cross section, (b) the equivalent cable bundle containing the culprit and victim conductors above an infinite perfect electric conductor (PEC) ground plane.

element method (FEM) [10] or method of moments (MoM) [11]. Then the reduced cable bundle model can be reconstructed through the mapping by a modified eight-step procedure to define the electrical and geometrical characteristics.

The organization of this paper is as follows. In Section 2, a modified equivalence procedure is presented. In Section 3, simulation examples are given to validate the proposed method, and some comments are presented in the final section.

2. PRESENTATION OF THE PROPOSED METHOD FOR MODELING CROSSTALK OF COMPLEX CABLE BUNDLES WITHIN UNIFORM STRUCTURE WITH ARBITRARY CROSS-SECTION

The ECBM for modeling crosstalk requires a five-step procedure detailed in [4], and a brief procedure is summarized as follows:

Step I: Classification of the conductors in four or less than four groups by comparing the magnitude of the termination loads to the common-mode characteristic impedance Z_{mc} except the culprit and victim conductors.

Step II: Calculation of the p.u.l. inductance and capacitance parameter matrices of the reduced cable bundle according to the equivalence procedure of the ECBM.

Step III: Building of the cross-section geometry of the reduced cable bundle model by matching $[L_{reduced}]$ and $[C_{reduced}]$ in Step II.

Step IV: Calculation of the equivalent termination loads located at both ends of each equivalent conductor.

Step V: Prediction of the electromagnetic (EM) crosstalk of the cable bundle model through the multiconductor transmission lines network (MTLN) method.

In this section, compared with previous papers [1–9], the differences and also the challenging points of the proposed method are the grouping of conductors and the building of the cross-section geometry of the reduced cable bundle model, which are detailed in the following paragraph. As far as the EM crosstalk is concerned, the approximate assumptions including a) all conductors are PEC and the surrounded medium is lossless, b) only transverse electromagnetic (TEM) mode is considered.

- First, in this paper, we need to classify the conductors of the complete cable bundle. It is important to note that in the grouping process, the culprit and victim conductors are divided into two groups separately, denoted as the culprit group and victim one. Then all the remaining conductors in the complete cable bundle are sorted into four groups (may be less than four) by comparing the magnitude of the termination loads to the common-mode characteristic impedance Z_{mc} [1–4].
- Second, the complete cable bundle model and its surrounding structure should be modeled and then all the p.u.l. inductance and capacitance matrices of the complete cable bundle under this circumstance can be extracted by the numerical simulation with 2-D FEM [10].
- Third, the reduced p.u.l. inductance and capacitance matrices $[L_{reduced}]$ and $[C_{reduced}]$ of the reduced cable bundle in any uniform structures with arbitrary cross section can be calculated through the original ECBM [3], in which the reduced inductance equals the average of all inductances and the reduced capacitance equals the sum of all capacitances of all cables belong to the same group.

- Fourth, the p.u.l. inductance and capacitance matrices $[L']$ and $[C']$ of the reduced cable bundle above an infinite PEC ground plane can be obtained through mapping process with reasonable assumption that $[L'] = [L_{reduced}]$ and $[C'] = [C_{reduced}]$.
- Fifth, the cross-section geometry of the reduced cable bundle model above an infinite PEC ground plane can be established according to the following eight-phase procedure,

1) Phase 1: Calculate the equivalent height $h_{c(v)}$ of the culprit (victim) conductor above an infinite PEC ground plane according to (1) as follows [12, 13]

$$h_{c(v)} = \frac{r_{c(v)}}{2} \cdot \exp\left(\frac{2\pi L_{c(v)}}{\mu_0}\right), \tag{1}$$

in which, $r_{c(v)}$ and $L_{c(v)}$ represent the radius and self inductance of the original culprit (victim) conductor in the complete cable bundle respectively.

2) Phase 2: Calculate the distance d_{cv} between the culprit and victim conductors according to (2) [12, 13]

$$d_{cv} = \sqrt{\frac{4h_c h_v}{\exp\left(\frac{4\pi L_{cv}}{\mu_0}\right) - 1}}, \tag{2}$$

in which, L_{cv} represents the mutual inductance between the culprit and victim conductors.

3) Phase 3: Estimate the height h_i of each equivalent conductor above an infinite PEC ground plane. h_i equals to the average heights of all the conductors in group i [3].

4) Phase 4: Calculate the radius r_i of each equivalent conductor according to (3) as follows [12, 13]

$$r_i = \frac{2h_i}{\exp\left(\frac{2\pi L'_{ii}}{\mu_0}\right)}, \tag{3}$$

5) Phase 5: Calculate the distance d_{ij} between each two equivalent conductors according to (4) [12, 13]

$$d_{ij} = \sqrt{\frac{4h_i h_j}{\exp\left(\frac{4\pi L'_{ij}}{\mu_0}\right) - 1}}. \tag{4}$$

6) Phase 6: Adjust d_{cv}, r_i, d_{ij} determined by the above procedures using a dichotomic optimization [3] realized with exact electrostatic calculations in the error range.

7) Phase 7: Determine the thickness of all the dielectric coating surrounding each equivalent conductor to avoid overlapping [3].

8) Phase 8: Calculate the relative permittivity ε_r of each conductor dielectric coating according to the $[C_{reduced}]$ matrix using

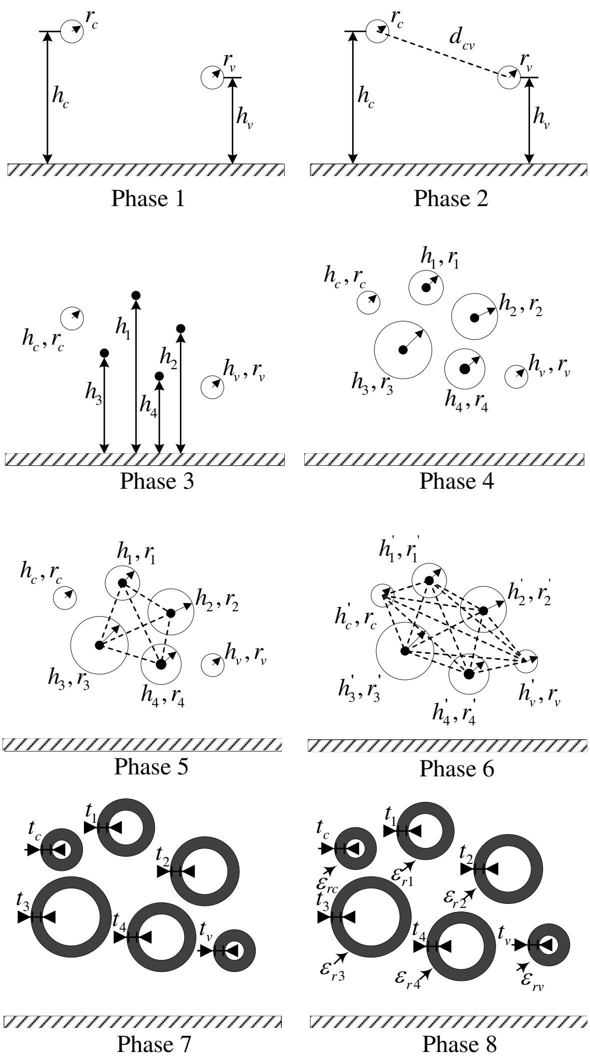

Figure 2. An eight-phase procedure for building the cross-section geometry of a reduced cable bundle model above an infinite PEC ground plane through the proposed method.

an electrostatic calculation [3].

Figure 2 illustrates the eight-phase procedure to build the cross-section geometry of a reduced cable bundle model above an infinite PEC ground plane made of six groups including the culprit and victim groups.

The Sixth and Seventh procedures are same as Step IV and Step V in the ECBM [4] respectively and are omitted here for the sake of brevity.

3. VALIDATIONS OF THE PROPOSED METHOD FOR CROSSTALK PREDICTION THROUGH NUMERICAL SIMULATIONS

For validation of the proposed method, a 14-conductor point-to-point connected cable bundle, 1 m long, set inside a rectangular cavity which is considered as a ground return shown in Fig. 3(a) is investigated, in which all cables are PEC with the radius of 0.5 mm and surrounded by a dielectric coating with the thickness of 1.5 mm and the relative permittivity $\varepsilon_r = 2.5$ and relative permeability $\mu_r = 1.0$. $h_{x1} = h_{x2} = 50$ mm, $h_{y1} = h_{y2} = 40$ mm. The near end of Cable 3 (culprit cable) is excited with a periodic trapezoidal pulse voltage source shown in Fig. 4. Cables 4 and 14 serve as the victim cables. The p.u.l. parameter inductance $[L]$ (in nanohenry/meter) and capacitance $[C]$ (in picofarad/meter) matrices of the complete cable bundle are listed

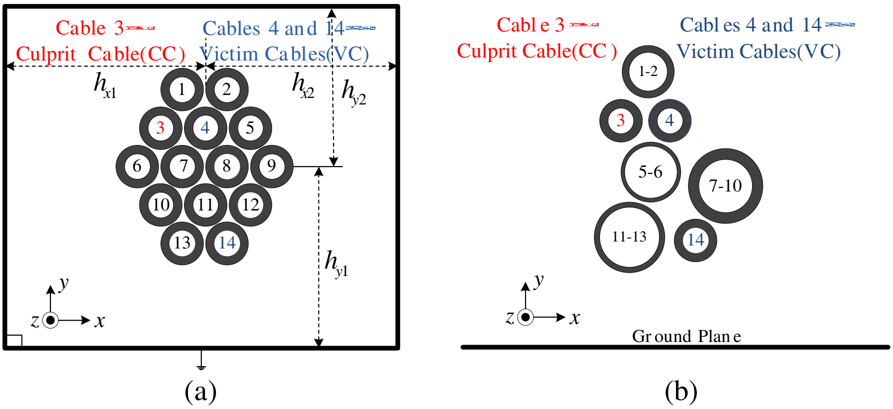

Figure 3. Cross section geometry. (a) Complete cable bundle model within a rectangular cavity. (b) Reduced cable bundle model above an infinite PEC ground plane.

in (5) and (6). All the conductors in the cable bundle are connected to real termination loads described in Table 1.

Meanwhile, the common-mode characteristic impedance Z_{mc} which can be determined by modal analysis [3] equals 126 Ω. According to the grouping process of the proposed method, the conductors of the complete cable bundle can be sorted into seven groups as follows

Group 1: Cables 1 ∼ 2;
Group 2: Cables 3;
Group 3: Cables 4;
Group 4: Cables 5 ∼ 6;
Group 5: Cables 7 ∼ 10;
Group 6: Cables 11 ∼ 13;
Group 7: Cables 14.

$$[L]=$$

$$\begin{bmatrix}
1410 & 537 & 525 & 536 & 385 & 338 & 371 & 339 & 273 & 261 & 262 & 234 & 198 & 189 \\
 & 1410 & 385 & 536 & 525 & 273 & 339 & 371 & 338 & 234 & 262 & 261 & 189 & 198 \\
 & & 1451 & 584 & 364 & 534 & 556 & 409 & 286 & 371 & 346 & 276 & 261 & 234 \\
 & & & 1514 & 584 & 403 & 575 & 575 & 403 & 346 & 387 & 346 & 262 & 262 \\
 & & & & 1451 & 286 & 409 & 556 & 534 & 276 & 346 & 371 & 234 & 261 \\
 & & & & & 1428 & 580 & 375 & 258 & 534 & 403 & 286 & 338 & 273 \\
 & & & & & & 1525 & 616 & 375 & 556 & 575 & 409 & 371 & 339 \\
 & & & & & & & 1525 & 580 & 409 & 575 & 556 & 339 & 371 \\
 & & & & & & & & 1428 & 286 & 403 & 534 & 273 & 338 \\
 & & & & & & & & & 1451 & 584 & 364 & 525 & 385 \\
 & & & & & & & & & & 1514 & 584 & 536 & 536 \\
 & & & & & & & & & & & 1451 & 385 & 525 \\
 & & & & & & & & & & & & 1410 & 537 \\
 & & & & & & & & & & & & & 1410
\end{bmatrix}_{14\times 14}, \tag{5}$$

$$[C]=$$

$$\begin{bmatrix}
21.7 & -6.5 & -5.2 & -3.7 & -0.8 & -0.9 & -0.3 & -0.1 & -0.2 & -0.2 & -0.0 & -0.1 & -0.1 & -0.1 \\
 & 21.7 & -0.8 & -3.7 & -5.2 & -0.2 & -0.1 & -0.3 & -0.9 & -0.1 & -0.0 & -0.2 & -0.1 & -0.1 \\
 & & 23.2 & -4.7 & -0.3 & -5.2 & -3.6 & -0.4 & -0.1 & -0.6 & -0.1 & -0.0 & -0.2 & -0.1 \\
 & & & 25.6 & -4.7 & -0.6 & -3.4 & -3.4 & -0.6 & -0.1 & -0.2 & -0.1 & -0.0 & -0.0 \\
 & & & & 23.2 & -0.1 & -0.4 & -3.6 & -5.2 & -0.0 & -0.1 & -0.6 & -0.1 & -0.2 \\
 & & & & & 21.8 & -4.8 & -0.2 & -0.1 & -5.2 & -0.6 & -0.1 & -0.9 & -0.2 \\
 & & & & & & 25.6 & -4.5 & -0.2 & -3.6 & -3.4 & -0.4 & -0.3 & -0.1 \\
 & & & & & & & 25.6 & -4.8 & -0.4 & -3.4 & -3.6 & -0.1 & -0.3 \\
 & & & & & & & & 21.8 & -0.1 & -0.6 & -5.2 & -0.2 & -0.9 \\
 & & & & & & & & & 23.2 & -4.7 & -0.3 & -5.2 & -0.8 \\
 & & & & & & & & & & 25.6 & -4.7 & -3.7 & -3.7 \\
 & & & & & & & & & & & 23.2 & -0.8 & -5.2 \\
 & & & & & & & & & & & & 21.7 & -6.5 \\
 & & & & & & & & & & & & & 21.7
\end{bmatrix}_{14\times 14}. \tag{6}$$

According to the calculation procedure of the original ECBM [3], the p.u.l. parameter matrices $[L_{reduced}]$ (in nanohenry/meter) and capacitance $[C_{reduced}]$ (in picofarad/meter) of the reduced cable bundle can be obtained as (7) and (8).

$$[L_{reduced}]=\begin{bmatrix} 974 & 455 & 536 & 380 & 316 & 235 & 194 \\ & 1451 & 584 & 449 & 405 & 294 & 234 \\ & & 1514 & 494 & 475 & 332 & 262 \\ & & & 863 & 440 & 330 & 267 \\ & & & & 723 & 459 & 358 \\ & & & & & 821 & 533 \\ & & & & & & 1410 \end{bmatrix}_{7\times 7}, \tag{7}$$

$$[C_{reduced}]=\begin{bmatrix} 30.4 & -6.0 & -7.4 & -7.2 & -2.4 & -0.5 & -0.2 \\ & 23.2 & -4.7 & -5.4 & -4.7 & -0.4 & -0.1 \\ & & 25.6 & -5.2 & -7.4 & -0.4 & -0.0 \\ & & & 44.9 & -19.5 & -2.3 & -0.4 \\ & & & & 69.0 & -27.3 & -2.2 \\ & & & & & 52.1 & -15.3 \\ & & & & & & 21.7 \end{bmatrix}_{7\times 7}. \tag{8}$$

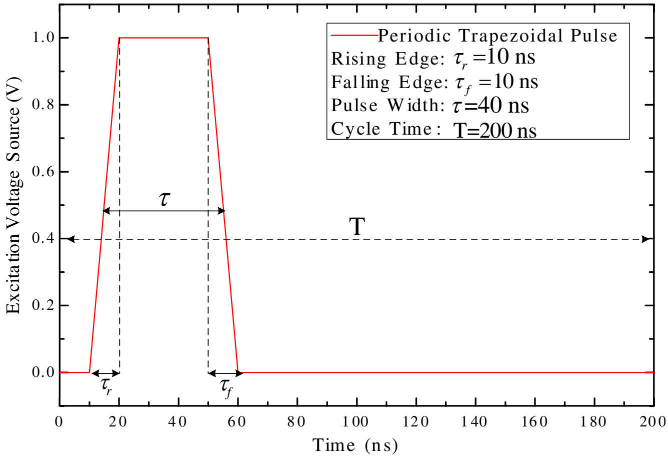

Figure 4. Trapezoidal pulse waveform of the voltage source excited on Cable 3.

Table 1. Termination loads of the complete and reduced cable bundle (unit: Ω).

Conductor	1	2	3	4	5	6	7
Near End	90	80	50	50	60	90	1.3k
Far End	30	50	50	100	1.2k	1.5k	1.2k
Conductor	8	9	10	11	12	13	14
Near End	1k	1.8k	1.5k	1.3k	1.5k	1.4k	50
Far End	900	800	2k	40	60	90	100

Table 2. Termination loads of the reduced cable bundle (unit: Ω) and some parameters of the 7-reduced cable bundle model (unit: mm).

Conductor	$1 \sim 2$	3	4	$5 \sim 6$	$7 \sim 10$	$11 \sim 13$	14
Near End	42.4	50	50	36.0	334.2	464.9	50
Far End	18.8	50	100	666.7	270.7	18.9	100
Conductor Radius	1.4	0.5	0.5	1.8	2.0	2.3	0.5
Insulator Thickness	0.3	1.5	1.5	0.1	0.2	0.6	1.5

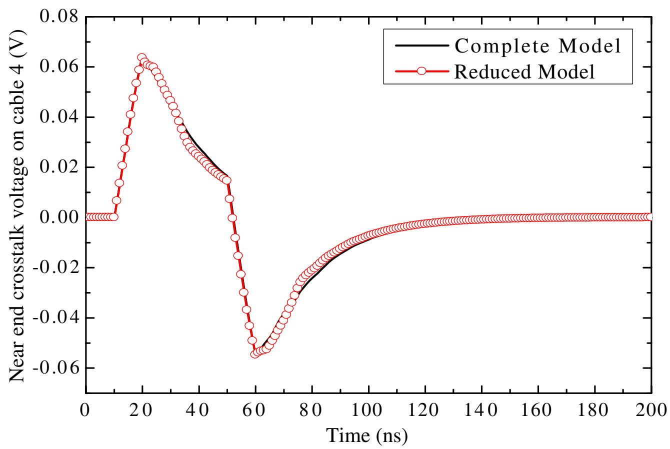

Figure 5. Comparison of the near end crosstalk voltage in the time domain on Cable 4 between the complete and reduced cable bundle models.

After applying the eight-phase procedure described in Section 2, we can obtain the cross-section geometry of the reduced cable bundle model composed of seven equivalent conductors above an infinite PEC ground plane shown in Fig. 3(b). Indeed, as it has been described in Section 2, the strict application of the first five phases of the equivalence procedure might lead to some non-matching results between the cross-section geometry of the reduced cable bundle in Fig. 3(b) and the p.u.l. reduced matrices calculated by the ECBM shown as (7) and (8). Consequently, a second-order optimization result with a mean difference of 0.8% and 10.4% respectively for the $[L_{reduced}]$ and $[C_{reduced}]$ matrices is obtained in this paper [14]. The equivalent termination loads connected to each end of all equivalent conductors and some parameters of the reduced cable bundle are presented in Table 2.

The near and far end crosstalk voltages on Cable 4 and Cable 14 can be obtained by applying the MTLN to the complete and reduced

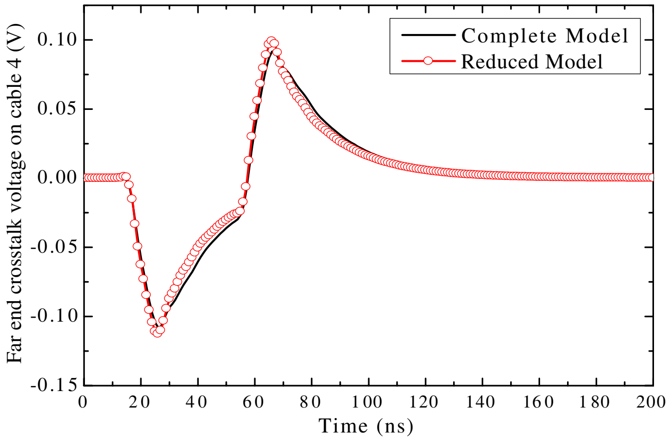

Figure 6. Comparison of the far end crosstalk voltage in the time domain on Cable 4 between the complete and reduced cable bundle models.

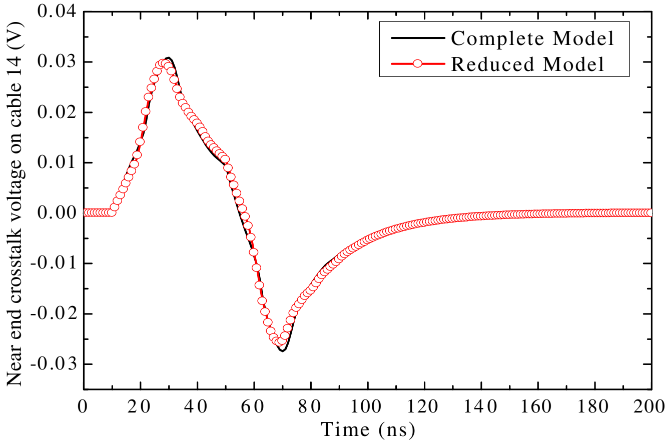

Figure 7. Comparison of the near end crosstalk voltage in the time domain on Cable 14 between the complete and reduced cable bundle models.

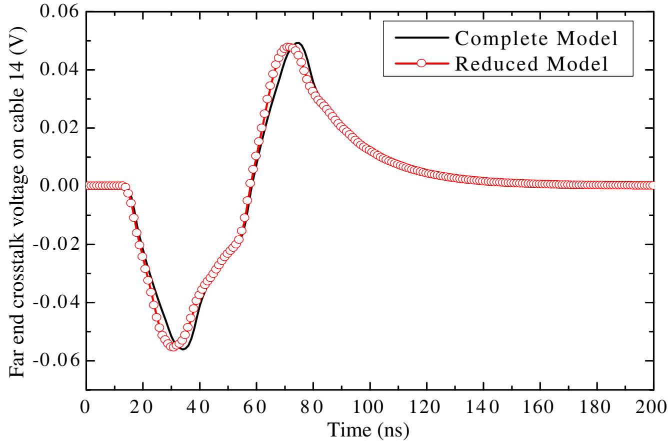

Figure 8. Comparison of the far end crosstalk voltage in the time domain on Cable 14 between the complete and reduced cable bundle models.

cable bundle models and are shown in Figs. 5 $\sim$ 8 respectively. The excellent agreement between the numerical simulation results of the complete and reduced cable bundle models validates the efficiency and the advantages of the proposed method.

4. CONCLUSIONS

This paper details the implementation of the modified ECBM for complex cable bundle within a uniform structure of arbitrary cross-section and an effective eight-phase procedure to define the electrical and geometrical characteristics of the reduced cable bundle model. In this paper, a complete cable bundle model within an infinite PEC rectangular cavity is mapped to a reduced cable bundle model above an infinite PEC ground plane during the implementation process of the ECBM and the culprit and victim conductors are divided into two groups separately during the grouping process. This work is considered as a key step for the ECBM to find wide applications in some real systems in the near future.

The main purpose of the method is to reduce the complexity and computation time, and the total computation time is reduced by a factor of 4.8 (complete model costs 29 seconds, reduced model costs 6 seconds) after equivalence of the complete model by using the method of MTLN theory, which have been performed on a 2.1-GHz processor and a 2.0-GB RAM memory computer. All these results fully demonstrate that this method can significantly reduce the prediction time and memory requirements. We believe that as the cable number in the original cable bundle increases, we can cut down much more computation time and memory.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China for Young Scholars under Grant No. 61102033, the Fundamental Research Funds for the Central Universities under Grant NS2012096, the Foundation of State Key Laboratory of Millimeter Waves, Southeast University, P. R. China under Grant No. K201302 and the Aeronautical Science Foundation of China under grant No. 20128052063.

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