

Enhanced MoM Scheme with Incorporation of General N-Port Networks in Application to Automotive EMC Problems

Faik Bogdanov^{#1}, Roman Jobava^{#2}, Stephan Frei^{*3}, Anna Gheonjian[#],
Ekaterina Yavolovskaya[#], Birgit Huneke^{&4}, Christian Lippert^{&5}

[#]EMCoS, 8 Ingorokva str., Tbilisi, 0108, Georgia

¹faik.bogdanov@emcos.com

²roman.jobava@emcos.com

^{*}Universität Dortmund, Friedrich-Wöhler-Weg 4, 44227 Dortmund, Germany

³stephan.frei@uni-dortmund.de

[&]EMC Center, AUDI AG, Ingolstadt, Germany

⁴birgit.huneke@audi.de

⁵christian.lippert@audi.de

Abstract— An enhanced MoM scheme is suggested to effectively handle EM and EMC problems with including general N-port networks. This scheme is based on incorporation of network equations for voltages and currents into the standard MoM scheme. Application of this scheme to handle complicated automotive EMC problems is considered. Potential of integrated MoM-network scheme to solve complicated automotive and other vehicle EMC problems is outlined.

I. INTRODUCTION

The Method of Moments (MoM) [1] is one of the most powerful numerical tools for treating EM and EMC problems on complicated 3-D geometries. Moreover, MoM is rather flexible for further development to incorporate new features allowing modelling realistic geometries in situations of practical interest [2-5]. That is why; MoM is intensively used for treating various complicated problems arisen in antenna and vehicle design. However, permanent complication of EM and EMC models requires further enhancing of the MoM scheme.

Network (circuit) theory [6] is the most commonly used tool for analysing separate elements and modules of electric and electronic systems, such as transmission lines, waveguide junctions, directional couplers, filters, amplifiers, printed circuit boards (PCBs) and so on. Moreover, this theory is often used to interpret or combine full wave analysis results [7]. At once, detailed analysis of two-port, and especially multiport, networks is very often redundant or even impossible in frame of MoM. Therefore, direct incorporation of these circuits in MoM through their network parameters, such as open-circuit impedance parameters (Z-matrices), short-circuit admittance parameters (Y-matrices), scattering parameters (S-matrices) and so on is in very demand.

In this work, an enhanced MoM scheme is suggested to effectively handle EM and EMC problems with including general N-port networks of various types. Further, application of this scheme to handle complicated automotive EMC

problems is considered. Finally, potential applications of this scheme to solve various EM and EMC problems are outlined.

II. STANDARD MoM SCHEME

Consider first a standard MoM scheme applied to the boundary-value problem on the given geometry

$$L(\vec{J}) = \vec{g} \quad (1)$$

where L is a linear integro-differential operator, \vec{g} is a known excitation, and \vec{J} is an unknown current density.

To apply MoM to (1), we perform discretization of geometry to consider the following expansion for the unknown current

$$\vec{J}(\vec{r}') = \sum_n I_n \vec{f}_n(\vec{r}') \quad (2)$$

where $\vec{f}_n(\vec{r}')$ are sub-domain expansion (or basis) functions, and I_n are unknown coefficients to be determined.

Substituting now (2) into (1) and applying testing procedure with testing functions $\vec{w}_1(\vec{r}'), \dots, \vec{w}_m(\vec{r}'), \dots$ defined in the range of L reduces (1) to the set of linear equations written in matrix form as

$$\mathbf{Z}^{MoM} \mathbf{I} = \mathbf{V} \quad (3)$$

where \mathbf{Z}^{MoM} is MoM impedance matrix with elements $Z_{mn}^{MoM} = \langle \vec{w}_m, L\vec{f}_n \rangle$, \mathbf{V} is an excitation matrix vector with elements $V_m = \langle \vec{w}_m, \vec{g} \rangle$, and \mathbf{I} is a vector of unknown coefficients I_n in the current expansion (2).

Thus, the standard MoM scheme reduces the initial boundary-value problem (1) to the solution of matrix equations (3), which may be formally found as

$$\mathbf{I} = (\mathbf{Z}^{MoM})^{-1} \mathbf{V} \quad (4)$$

III. NETWORK EQUATIONS

The advanced EM, and especially EMC, models include a variety of electric or electronic equipment (units), detailed modeling of which is either impossible due to unknown internal structure, or unnecessary due to excessive computational intensity. Such the units may be generally represented as N-port networks (Fig. 1) connected to the elements (wire segments), or ports, of the examined model. Network connection to the ports forces the currents i_1, i_2, \dots, i_N through and voltages U_1, U_2, \dots, U_N over the ports $1, 2, \dots, N$ according to the network parameters of the considered network.

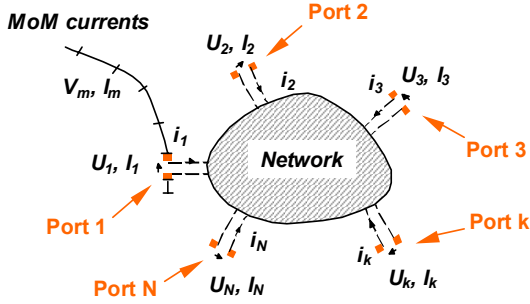


Fig. 1 N-port network

A number of network parameters are used to describe relations between the network voltages U_k and currents i_k [7]. These parameters may be introduced via different forms of network equations, the most important of which may be written in matrix form as

$$\mathbf{U} = \mathbf{Z}^{Net} \mathbf{i} \quad (5)$$

where \mathbf{i} and \mathbf{U} are network port current and voltage vectors, and \mathbf{Z}^{Net} is network Z-matrix with so-called open-circuit impedance parameters of N-port network;

$$\mathbf{i} = \mathbf{Y}^{Net} \mathbf{U} \quad (6)$$

where \mathbf{Y}^{Net} is network Y-matrix with short-circuit admittance parameters of N-port network;

$$\mathbf{a}^- = \mathbf{S}^{Net} \mathbf{a}^+ \quad (7)$$

where \mathbf{S}^{Net} is network S-matrix with scattering parameters of N-port network, $\mathbf{a}^\pm = \frac{1}{2}(\bar{\mathbf{U}} \pm \bar{\mathbf{i}})$ are normalized incident (+) and reflected (-) port voltages, $\bar{\mathbf{U}} = \mathbf{Z}_L^{-1/2} \mathbf{U}$ and $\bar{\mathbf{i}} = \mathbf{Z}_L^{1/2} \mathbf{i}$ are, respectively, normalized network voltage and current vectors, and \mathbf{Z}_L is diagonal matrix of characteristic impedances of transmission lines, connected to each port.

Note that original network matrices are square matrices of N degree and may be equally used to describe behavior of arbitrary network. Therefore, different matrices may be related to each other according to the matrix algebra. So, for

instance, $\mathbf{Z}^{Net} = (\mathbf{Y}^{Net})^{-1}$, $\mathbf{S}^{Net} = (\mathbf{E} - \bar{\mathbf{Y}})(\mathbf{E} + \bar{\mathbf{Y}})^{-1}$, where \mathbf{E} is a unit matrix, and $\bar{\mathbf{Y}} = \mathbf{Z}_L^{1/2} \mathbf{Y}^{Net} \mathbf{Z}_L^{1/2}$.

Our purpose is now to incorporate network equations (5) to (7) into MoM system (3).

IV. ENHANCED MOM SCHEME

To incorporate network equations (5) to (7) into MoM system (3), let first clarify treatment of elements of matrix vectors \mathbf{V} and \mathbf{I} in MoM system (3) and their relation to those for network port voltage and current vectors \mathbf{U} and \mathbf{i} .

Indeed, expansion and testing functions $\bar{f}_n(\bar{r}')$ and $\bar{w}_m(\bar{r}')$ in (2) and (3) may be chosen so that V_m and I_n in MoM system (3) would be interpreted as segment currents and voltages (see Fig. 1). Then, network port currents may be easily related to the segment currents as

$$i_n = -I_n, \quad (8)$$

and segment voltages may be shared between that induced by external sources and by network voltages

$$V_m = V_m^s + U_m \quad (9)$$

In matrix form, (8) and (9) are expressed as

$$\mathbf{i} = -\mathbf{I}, \quad \mathbf{V} = \mathbf{V}^s + \mathbf{U}$$

Note, that forcing voltages are meant over network ports (included in \mathbf{U}). If network is not connected to the segment, forcing voltage is included in external sources: $\mathbf{V} = \mathbf{V}^s$.

To incorporate now network equations (5) to (7) to MoM system (3), let classify all network ports into free ports (those with operated voltages) and forcing ports (with forcing voltage). The reason is that forcing voltage U_m appears on the right column of MoM system (3) in ordinary way, and including network has no effect on MoM solution except for extra powers to supply the network currents.

Besides, let generalize network equations on the case of crossed connection of network ports. This may be taken into account, if replace arbitrary network matrix \mathbf{M}^{Net} by the cross matrix $\hat{\mathbf{M}}^{Net}$ with elements $\hat{M}_{ij}^{Net} = n_{ij} M_{ij}^{Net}$, where n_{ij} are connection matrix elements: $n_{ij} = 1$ for direct connection of ports i and j , and $n_{ij} = -1$ for crossed connection.

If N-port network has only free ports (without forcing voltages), introducing (9) into the MoM system (3) with accounting of (5) and (8) results in the following integrated MoM-network system

$$(\mathbf{Z}^{MoM} + \hat{\mathbf{Z}}^{Net}) \mathbf{I} = \mathbf{V}^s \quad (10)$$

Thus, network with only free ports is that way included into the MoM solution.

Consider now extension of MoM-network solution (10) to the case of N-port network with mixed free and forcing ports. Let N' and N'' are the numbers of free and forcing ports,

such as $N' + N'' = N$. Then, network equations (6) for free ports may be written as

$$\mathbf{i} = \hat{\mathbf{Y}}'^{Net} \mathbf{U}' + \hat{\mathbf{Y}}''^{Net} \mathbf{U}'' \quad (11)$$

where $\hat{\mathbf{Y}}'^{Net}$ and \mathbf{U}' are reduced network matrix and voltage vector including only free port elements, \mathbf{U}'' is network forcing voltage, and $\hat{\mathbf{Y}}''^{Net}$ is mixed network matrix with row index for free port, and column index for forcing port. Remind, that hat over matrix symbol means generalized network matrix accounting cross connections of ports.

Inversion of (11) gives the following matrix equation for network voltages in free ports:

$$(\hat{\mathbf{Y}}'^{Net})^{-1} \mathbf{i} = \mathbf{U}' + (\hat{\mathbf{Y}}'^{Net})^{-1} \hat{\mathbf{Y}}''^{Net} \mathbf{U}'' \quad (12)$$

or

$$\mathbf{U}' = \hat{\mathbf{Z}}'^{Net} \mathbf{i} + \mathbf{V}^{add} \quad (13)$$

where $\hat{\mathbf{Z}}'^{Net} = (\hat{\mathbf{Y}}'^{Net})^{-1}$ is reduced Z-matrix of N-port network (only for free ports), and $\mathbf{V}^{add} = -\hat{\mathbf{Z}}'^{Net} \hat{\mathbf{Y}}''^{Net} \mathbf{U}''$ is additional voltage on free network ports induced due to the connection to forcing ports. They may be interpreted as voltage drop at network free port impedance elements due to the currents induced by connection to forcing ports.

Introducing now (13) into MoM system (3) with accounting for the free port relations $\mathbf{i} = -\mathbf{I}$, $\mathbf{V} = \mathbf{V}^s + \mathbf{U}'$ results in the following general integrated MoM-network system

$$(\mathbf{Z}^{MoM} + \hat{\mathbf{Z}}'^{Net}) \mathbf{I} = \mathbf{V}^s + \mathbf{V}^{add} \quad (14)$$

Thus, in general MoM-network system, the total impedance matrix is a superposition of MoM matrix and reduced network matrix for free ports, and voltage column is composed of MoM voltages and impressed network voltages induced by the connection to the forcing ports.

V. VALIDATION OF ENHANCED MOM SCHEME

The suggested scheme was validated to estimate characteristics of EMC model consisting of a 2-port linear amplifier, fed by a voltage generator with 50-Ω internal resistance, a transmission line formed of a 1 m single wire over PEC ground, and an unmatched termination load (Fig. 2). In enhanced MoM scheme simulations, a signal source, transmission line and a load termination were considered as MoM part, while amplifier as a network part of the model.

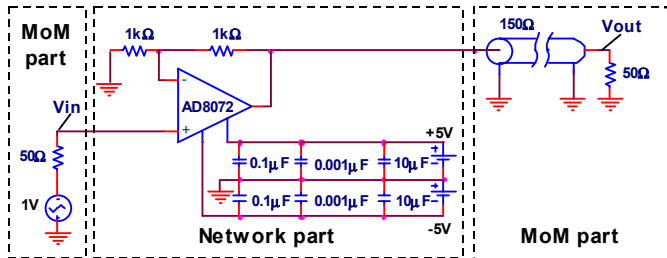


Fig. 2 EMC model including amplifier network and transmission line

Fig. 3 presents the transfer function

$$TF_V = V_{out} / V_{in} \quad (15)$$

between the voltages V_{out} at the transmission line output, and V_{in} at the amplifier input calculated by the suggested enhanced MoM scheme (solid line) and PSPICE (markers).

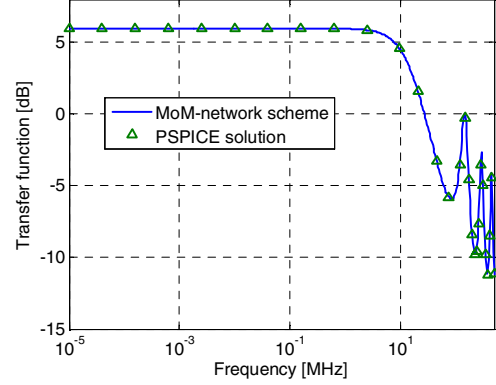


Fig. 3 Comparison of transfer functions calculated by enhanced MoM scheme and PSPICE

Comparison of the obtained results with those calculated by PSPICE demonstrates a perfect agreement between them in a frequency range up to 500 MHz including a high frequency oscillation range due to mismatch at the transmission line end.

The results above validate the enhanced MoM scheme with incorporation of networks to calculate integrated EM and EMC models with including networks.

VI. APPLICATION OF ENHANCED MOM SCHEME

Further, the suggested scheme was applied to solve automotive EMC problem to model characteristics of the given amplifier connected to glass antenna pattern located in the car rear window (Fig. 4).

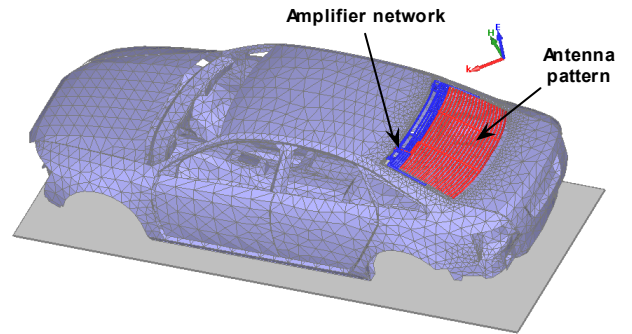


Fig. 4 EMC model of car geometry with amplifier network

The MoM model for EMC simulations was represented by the car bodyshell modelled by 12,900 triangles, and antenna pattern modelled by 80 triangles and 1,200 segments representing metallic traces on glass substrate. EMC model of the problem also includes 2-port RF Micro Devices amplifier

RF2314 described by S-parameters shown in Fig. 5. The amplifier connected to the glass antenna output is terminated by 50- Ω load resistance. We were interested in transfer function between amplifier output voltage and that received by antenna when exposed to vertically polarized plane wave.

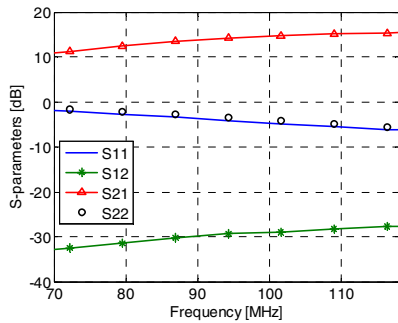


Fig. 5 Scattering parameters of amplifier network

Fig. 6 gives schematic view of amplifier network with frequency dependent series voltage source $V_s(f)$ and impedance $Z_s(f)$ at input terminals, and steady frequency load impedance $Z_L=50\Omega$ at output terminals. Voltage source V_s represents a signal received by antenna without amplifier, and $Z_s(f)$ is antenna input impedance.

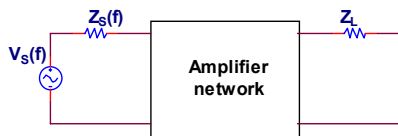


Fig. 6 Schematic view of amplifier network

The complete EMC problem may be analysed using system simulation approach. At the first stage of this approach, a conventional MoM scheme is applied to the system without amplifier. As a result, voltage received by the antenna, and antenna input impedance are calculated. At the second stage, network parameters of amplifier are determined either from measurements or calculations. At last stage, scattering parameters of amplifier are combined with results obtained by MoM to construct the system shown in Fig. 6. Analysis of this system can be performed either using circuit simulation tools or scattering parameter flow-graphs and non-touching loop rule [8].

Fig. 7 shows comparison of transfer functions calculated by the suggested enhanced MoM-network scheme with that obtained using system simulation approach. A little difference between these results is because the MoM-network scheme gives a complete solution of the problem while the system simulation approach does not consider the reverse influence of amplifier to the voltage received by antenna.

The results above illustrate advantage of the suggested scheme to effectively solve complicate automotive EMC problems. This scheme can be also applied for analysing other EM/EMC problems including MoM and network parts, such

as emission from automotive harness systems to RF antennas, radiation from PCBs, etc. Moreover, a number of different networks integrated in the same MoM geometry may be efficiently analysed using the Partition MoM scheme [5].

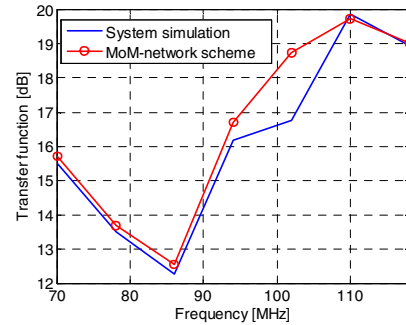


Fig. 7 Transfer function between amplifier output voltage and voltage received by antenna obtained by different approaches

Both these schemes are included in a MoM-based code “TriD” [9] being a part of package “EMC Studio” [10].

VII. CONCLUSIONS

An enhanced MoM scheme is suggested to effectively handle EM and EMC models with including general N-port networks. This scheme is based on incorporation of network equations for voltages and currents into the standard MoM scheme. Application of this scheme to handle complicated automotive EMC problems has been illustrated.

REFERENCES

- [1] R. F. Harrington, *Field Computation by Moment Methods*, IEEE Press, New York, 1993.
- [2] M. Bückner, “Enhanced numerical integration technique”, in *Proc. IEEE EMC Symposium*, Seattle, Washington, 1999, pp. 328-333.
- [3] F. G. Bogdanov, R. G. Jobava, and S. Frei, “Scheme of improving accuracy of MoM solutions based on analysing boundary conditions performance,” in *Proc. East-West Workshop, ATE-2004*, Warszawa, Poland, 2004, pp. 217-224.
- [4] R. Jobava, F. Bogdanov, A. Gheonjian, and S. Frei, “Application of adaptive scheme for the Method of Moments in EMC automotive problems,” *Proc. 16th Zurich EMC Symposium*, Zurich, Switzerland, 2005, pp. 131-136.
- [5] F. G. Bogdanov, R. G. Jobava, P. Tsereteli, and S. Frei, “A partitioned MoM scheme for treating EMC problems on a series of geometries with a predominant common part,” in *Proc. 16th Zurich EMC Symposium*, Zurich, Switzerland, 2005, pp. 415-418.
- [6] F. M. Tesche, M. V. Ianoz, T. Karisson, *EMC Analysis Methods and Computational Models*, John Wiley & Sons, Inc., New York, 1996.
- [7] R. P. Parrikar and K. C. Gupta, “Multiport network model for CAD of electromagnetically coupled microstrip patch antennas,” *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 475-483, April 1998.
- [8] R. W. Anderson, S-Parameter techniques for faster, more accurate network design, Hewlett-Packard Application Note 95-1, PN 5952-1130, 1997.
- [9] F. G. Bogdanov, R. G. Jobava, P. Tsereteli, “TriD: Tri-Dimensional code for electromagnetic modeling of arbitrary surface and wire configurations. User’s Manual, version 2.90”, EMCoS Tech. Rep. D0041, Tbilisi, 2007.
- [10] *EMC Studio User’s Manual*. v. 3.1a, EMCoS Tech. Rep. S010701, Tbilisi, 2007.