Network and Circuit Models in Electromagnetic Field Computation

Peter Russer, Life Fellow IEEE
Technische Universität München, School of Computation, Information and Technology

***Abstract*—Hybridization schemes for the systematic, general and efficient evaluation of electromagnetic fields are discussed. The computational space is subdivided in various subregions where different analytical and numerical methods are employed. These methods may also be combined in the frame of the same subregion. The application of such methods to stochastic EM fields and in quantum computing algorithms is also outlined.**

I. Introduction

Many applications in modern electronics rely on electromagnetic (EM) field computations in complex structures. The availability of steadily increasing computing facilities has not lessened the need for efficient methods of EM field computation, since in the design of modern electronic components operating at microwave frequencies success relies on efficient techniques for the modeling of complex EM structures. Since the problems exhibit various geometrical features and scales, frequency ranges, and materials, no single method is best suited for dealing with them. Hybridizing field theoretical, network theoretical, and circuit theoretical methods can increase the efficiency of full-wave analysis of EM structures [1]–[4]. We revisit the development of methods for calculating EM fields through network methods.

II. Network Models of EM Structures

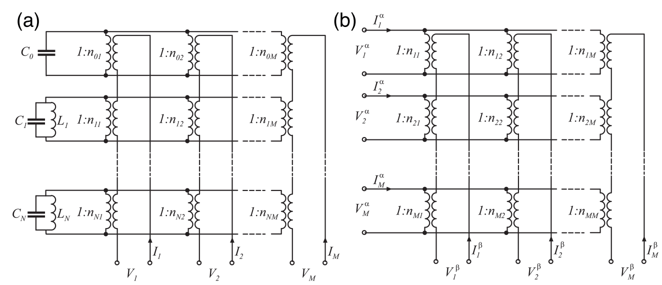

Fig. 1. (a) Foster equivalent circuit, (b) Canonical Connection circuit.

In network theory lumped element circuits are separated into the circuit elements and the connection circuit containing only connections and ideal transformers. This methodology can also be applied to EM structures. The segmentation of the problem in subdomains establishes substructures which define the pertinent circuit elements and boundary surfaces across which the substructures are connected [1]–[10]. Lossless subdomain structures can be represented by canonical Foster equivalent circuits as shown in Fig. 1 (a). The canonical connection circuit shown in Fig. 1 (b) represents the coupling of the substructures. Lossy EM structures can be modeled by adding resistors to the Foster equivalent circuits [11] or by using Brune equivalent circuits [12]. Radiation modes can be described by canonical Cauer networks (Fig. 2) [10], [13], [14]. Analytic methods, e.g. Green's function or numerical methods in connection with system identification techniques [15] allow the synthesis of lumped element models [16]–[19].

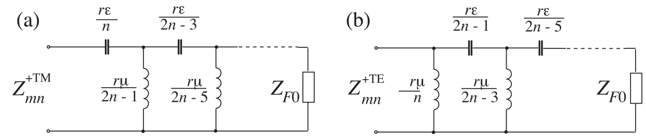

Fig. 2. Equivalent circuits of (a) TM_{mn} and (b) TE_{mn} spherical waves.

III. The Transmission Line Matrix (TLM) Method

EM wave propagation is modeled in the TLM method by wave pulses propagating in a Cartesian mesh and being scattered in the mesh nodes [20]–[23]. The EM field is described by the 12n–dimensional state vector $|a\rangle_k$, where n is the number of nodes and k is the discrete time index. The TLM scheme [24], [25] is given by

$$|a\rangle_{k+1} = \mathbf{\Gamma} \boldsymbol{S} |a\rangle_k, \tag{1}$$

where the matrix $\boldsymbol{S}$ describes the scattering of the wave pulses in the TLM nodes and the connection matrix $\mathbf{\Gamma}$ describes the propagation of the wave pulses to the neighboring node. The TLM scheme has been derived from Maxwell's equations by method of moments [25] or ab initio from symmetry and conservation laws [22]. The TLM method is optimally suited to model broadband and transient EM phenomena.

Microwave circuits containing distributed as well as lumped, and also nonlinear subcircuits can be modeled by simulation with models generated by system identification applied to the results of TLM simulation [8], [16]–[19], [26]. Combining the TLM method with integral equation methods and applying discrete Green's functions yields tools for the modeling of complex EM structures separated by large distances [27]–[30].

IV. Stochastic EM Fields

To describe noisy EM fields we use the auto- and cross correlation spectra of the field components [31], [32]. Autocorrelation spectra are assigned to each field component at a point in space. Cross-correlation spectra exist between different field components at a point in space and between field components at different points in space. The stochastic electric field is described by the correlation dyadic

$$\underline{\underline{\Gamma}}_E(\boldsymbol{x}_a, \boldsymbol{x}_b, \omega) = \lim_{T\to\infty} \frac{1}{2T} \left\langle\!\left\langle \boldsymbol{E}_T(\boldsymbol{x}_a, \omega) \boldsymbol{E}_T^{\dagger}(\boldsymbol{x}_b, \omega) \right\rangle\!\right\rangle, \tag{2}$$

where $\boldsymbol{E}_T(\boldsymbol{x}_a, \omega)$ is the electric field amplitude spectrum time-windowed in the interval $[-T, T]$ and bracket $\langle\!\langle \cdot \rangle\!\rangle$ denotes the forming of an ensemble average [31]. The correlation dyadic of electric field component originating from noise sources described by the correlation dyadic $\underline{\underline{\Gamma}}_J(\boldsymbol{x}'_a, \boldsymbol{x}'_b, \omega)$ is

$$\underline{\underline{\Gamma}}_E(\boldsymbol{x}_a, \boldsymbol{x}_b) = \iint \boldsymbol{G}(\boldsymbol{x}_a - \boldsymbol{x}'_a) \underline{\underline{\Gamma}}_J(\boldsymbol{x}'_a, \boldsymbol{x}'_b) \boldsymbol{G}^\dagger(\boldsymbol{x}_b - \boldsymbol{x}'_b) d^3x'_a d^3x'_b.$$

The Correlation Transmission Line Matrix (CTLM) method allows the time-domain computation of the auto- and cross correlation functions (ACFs and CCFs) of stationary stochastic EM fields. These ACFs and CCFs are computed from the Johns matrices, i.e. the discrete time TLM Green's functions and are directly related to the EMI power spectra [33].

V. Quantum Computing of EM Fields

Quantum computing (QC) is based on the expression of the computer program by the Hamiltonian of a quantum system [34]. The Hilbert space formulation of the TLM method [24], [25] allows to interpret the the product of the TLM scattering and time evolution operators as the Hamiltonian of a quantum computing system [35]. Due to the quantum parallelism of QC a large number of EM structures is simulated simultaneously. Using QC the design problem can be formulated as follows: Given the initial condition and the desired final field distribution, find the EM structures that cause this transformation. The problems to be solved for the implementation of a QTLM simulator are discussed in [36].

Acknowledgement

This article is dedicated to the memory of Leopold Felsen and in particular to our friendship and fruitful collaboration.

References

[1] L. B. Felsen, M. Mongiardo, and P. Russer, "Electromagnetic field representations and computations in complex structures I: Complexity architecture and generalized network formulation," IJNM, vol. 15, pp. 93–107, 2002.

[2] ——, "Electromagnetic field representations and computations in complex structures II: Alternative Green's functions," IJNM, vol. 15, pp. 109–125, 2002.

[3] P. Russer, M. Mongiardo, and L. B. Felsen, "Electromagnetic field representations and computations in complex structures III: Network representations of the connection and subdomain circuits," IJNM, vol. 15, pp. 127–145, 2002.

[4] L. B. Felsen, M. Mongiardo, and P. Russer, Electromagnetic Field Computation by Network Methods. Berlin: Springer, Mar. 2009.

[5] L. B. Felsen, M. Mongiardo, P. Russer, G. Conti, and C. Tomassoni, "Waveguide component analysis by a generalized network approach," Proc. 27th Europ. Microw. Conf., Jerusalem, pp. 949–954, Sep. 1997.

[6] M. Mongiardo, P. Russer, M. Dionigi, and L. B. Felsen, "Waveguide step discontinuities revisited by the generalized network formulation," in 1998 IMS Digest, Baltimore, ML, USA, 1998, pp. 917–920.

[7] M. Mongiardo, P. Russer, C. Tomassoni, and L. B. Felsen, "Analysis of N-furcation in elliptical waveguides via the generalized network formulation," IEEE Trans. MTT, vol. 47, no. 12, pp. 2473–2478, 1999.

[8] P. Russer and A. C. Cangellaris, "Network–oriented modeling, complexity reduction and system identification techniques for electromagnetic systems," in Proc. 4th Int. Workshop on Computational Electromagnetics in the Time–Domain, Nottingham, Sep. 2001, pp. 105–122.

[9] C. Tomassoni, M. M. V. Crino, L. Felsen, A. Omar, and P. Russer, "Electromagnetic field computati with the generalized network formulation (GNF)," in Electromagnetics in a Complex World, ser. Springer Proceedings in Physics. Springer, 2004, pp. 123–134.

[10] P. Russer, Electromagnetics, Microwave Circuit and Antenna Design for Communications Engineering, 2nd ed. Boston: Artech House, 2006.

[11] T. Mangold and P. Russer, "Modeling of multichip module interconnections by the TLM method and system identification," Proc. 27th Europ. Microw. Conf., Jerusalem, pp. 538–543, Sep. 1997.

[12] F. Mukhtar and P. Russer, "Brune's algorithm for lumped element equivalent circuit synthesis of linear lossy multiports," AEÜ, vol. 76, pp. 175–187, Jun. 2016.

[13] P. Lorenz, J. V. Vital, B. Biscontini, and P. Russer, "TLM-G–a grid-enabled time-domain transmission-line-matrix system for the analysis of complex electromagnetic structures," IEEE Trans. MTT, vol. 53, no. 11, pp. 3631–3637, 2005.

[14] U. Siart, B. Biscontini, P. Lorenz, and P. Russer, "Ultra-wide-band antenna design," RadioTecC, Berlin, 2005.

[15] L. Ljung, System Identification. Theory for the User. Upper Saddle River, NJ: Prentice Hall PTR, 1999.

[16] M. Righi, C. Eswarappa, W. Hoefer, and P. Russer, "An alternative way of computing S–parameters via impulsive TLM analysis without using absorbing boundary conditions," 1995 IMS Digest, Orlando, FL, USA, pp. 1203–1206, May 1995.

[17] N. Fichtner, U. Siart, Y. Kuznetsov, A. Baev, and P. Russer, "TLM Modeling and system identification of optimized antenna structures," in Kleinheubacher Tagung, Miltenberg, Germany, Sep. 2007.

[18] P. Russer, "Overview over network methods applied to electromagnetic field computation," in ICEAA 2009, Torino, Italy, Sept. 2009.

[19] J. A. Russer, Y. Kuznetsov, and P. Russer, "Discrete-time network and state equation methods applied to computational electromagnetics," Mikrotalasna Revija (Microwave Review), pp. 2–14, July 2010.

[20] W. Hoefer, "The transmission line matrix method-theory and applications," IEEE Trans. MTT, vol. 33, no. 10, pp. 882–893, Oct. 1985.

[21] P. Russer, "The transmission line matrix method," in New Trends and Concepts im Microwave Theory and Technics, H. Baudrand, Ed. Trivandrum, India: Research Signpost, 2003, pp. 41–82.

[22] P. Russer and U. Siart, Time-Domain Methods in Electrodynamics. Berlin, Heidelberg, Germany: Springer Berlin, 2008.

[23] P. Russer and J. A. Russer, "Some remarks on the transmission line matrix (TLM) method and its application to transient EM fields and to EMC problems," in Computational Electromagnetics, I. Ahmed and Z. D. Chen, Eds. Heidelberg: Springer, Aug. 2014, pp. 29–56.

[24] P. Russer and M. Krumpholz, "The Hilbert Space Formulation of the TLM Method," IJNM, vol. 6, no. 1, pp. 29–45, Feb. 1993.

[25] M. Krumpholz and P. Russer, "A field theoretical derivation of TLM," IEEE Trans. MTT, vol. 42, no. 9, pp. 1660–1668, 1994.

[26] P. Russer, P. P. M. So, and W. J. R. Hoefer, "Modeling of nonlinear active regions in TLM [distributed circuits]," IEEE Microwave and Guided-Wave Letters, vol. 1, no. 1, pp. 10–13, 1991.

[27] M. Krumpholz and P. Russer, "Discrete time–domain Green's functions for three–dimensional tlm modelling of the radiating boundary conditions," in Proc. 9th Ann. Rev. Progr. in Appl. Comp. Electromagnetics ACES, Monterey, (Monterey, CA), Mar. 1993, pp. 458–466.

[28] M. I. Sobhy, E.-S. A. Bakkar, M. W. R. Ng, E. A. Hosny, B. Isele, and P. Russer, "Modelling of microwave circuits by system identification methods," in 25h Europ. Microw. Conf., Bologna, 1995, pp. 1173–1176.

[29] L. Pierantoni, S. Lindenmeier, and P. Russer, "Efficient analysis of microstrip radiation by the TLM integral equation (TLMIE) method," in 1998 IMS Digest, Baltimore, ML, USA, 1998, pp. 1267–1270.

[30] F. Alimenti, F. Tiezzi, R. Sorrentino, S. Lindenmeier, L. Pierantoni, and P. Russer, "Accurate analysis and modeling of slot coupled patch antennas by the TLM–IE and the FDTD methods," Proc. 28th European Microwave Conference, Amsterdam, vol. 1, pp. 30–35, 1998.

[31] J. A. Russer and P. Russer, "Modeling of noisy EM field propagation using correlation information," IEEE Trans. MTT, vol. 63, no. 1, pp. 76–89, Jan. 2015.

[32] J. A. Russer, M. Haider, and P. Russer, "Time-domain modeling of noisy electromagnetic field propagation," IEEE Transactions on Microwave Theory and Techniques, vol. 66, no. 12, pp. 5415–5428, Dec. 2018.

[33] J. A. Russer, A. Cangellaris, and P. Russer, "Correlation transmission line matrix (CTLM) modeling of stochastic electromagnetic fields," in 2016 IEEE MTT-S IMS Digest, May Boston, CA, USA, May 2016.

[34] M. A. Nielsen and I. L. Chuang, Quantum Computation and Quantum Information. Cambridge University Press, Oct. 2000.

[35] S. Sinha and P. Russer, "Quantum computing algorithm for electromagnetic field simulation," QUIP, vol. 9, no. 3, pp. 385–404, 2009.

[36] J. A. Russer, M. Haider, C. Jirauschek, and P. Russer, "On the possibility of quantum simulation of electromagnetic structures," in 2018 IEEE MTT-S IMS Digest, June, Boston, CA, USA, Boston, Jun. 2019.