S-Parameter Characterization of Nonuniform Microstrip Lines via Perturbative Technique

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Abstract—**This paper presents a frequency-domain perturbative technique for the solution of nonuniform transmission-lines (NUTLs), resorting to a preliminary S-parameter characterization. According to this method, the NUTL S-parameter matrix is obtained column-by-column, by solution of NUTL sub-problems involving different terminal networks. The procedure results to be particularly suitable in the case of differential lines with fully or partially repetitive geometry, since it allows good prediction accuracy and reduced computational burden. As explicative examples, the technique is here applied to high-speed microstrip line configurations for common-mode suppression.**

Index Terms—**Common-Mode Suppression, Non-Uniform Transmission Lines, Perturbative Technique, S-parameter Matrix.**

I. INTRODUCTION

High-speed interconnects often require to be modelled as non-uniform transmission lines (NUTLs) due to either desired or undesired geometrical and/or material non-uniformity. Fast and accurate assessment of interconnect performance is of utmost importance for signal/power integrity (SI/PI). Although full-wave simulation represents a common, yet time-consuming, solution to accurately evaluate the performance of high-speed interconnects, approaches based on transmission-line (TL) theory may represent cost-effective alternatives as long as the assumption of transverse electromagnetic wave propagation is satisfied.

The traditional TL-based solution method foresees to split the NUTL into short sections with constant cross-section, and cascade the relevant chain-parameter matrices to predict voltages/currents at the line ends [1]. Prediction accuracy of such a technique, often referred to as Uniform Cascaded Section (UCS) method, strongly depends on the number of sections in which the NUTL is subdivided. Consequently, the computational burden may significantly increase for NUTLs exhibiting strong non-uniformity.

In order to mitigate this limitation, the perturbative technique (PT) in [2], [3] was recently introduced. According to this technique, line non-uniformity is regarded as a perturbation around an average, uniform TL, and the original NUTL equations, involving place-dependent per-unit-length (p.u.l.) matrices, are suitably recast as the equations of a uniform TL driven by equivalent distributed sources, accounting for the line non-uniformity. Evaluation of the voltages/currents at the line terminals is managed iteratively by updating the involved distributed sources. Several application examples, [3], [4], proved the enhanced computational effectiveness of this technique with respect to the UCS method. Moreover, such a perturbative approach was exploited to provide physical insight into the mechanism of mode conversion occurring in non-uniform differential lines, [4], [5].

Despite the above-mentioned advantages, the PT in [3] results to be less flexible than the UCS method whenever the terminal conditions at the NUTL ends change. Indeed, since the PT iteratively evaluates voltages/currents at the line terminals for a specific set of loads, the solution must be repeated from scratch for every new set of terminal constraints.

To overcome such a limitation, in this paper a reformulation of the original PT in [2], [3] is presented, which resorts to a preliminary representation of the NUTL under analysis in terms of a S-parameter matrix. The proposed approach results to be particularly effective for analysing fully or partially-repetitive differential-line structures, which are often used in advanced trace-routing schemes for high-speed data transmission, e.g., [6]–[9]. As an illustrative example, in this paper such a novel approach is used to evaluate the performance of a differential microstrip line structure for common-mode (CM) suppression, [8], [9]. To this end, elementary line sections with different chirped geometry are composed in various ways in order to optimize CM reduction in a specified frequency interval. Comparison versus full-wave simulation [10] is used to assess prediction accuracy of the proposed TL-based technique.

II. BASIC PRINCIPLES OF THE PROPOSED METHOD

The solution approach presented in this paper makes use of a preliminary $2n$-port representation of the NUTL under analysis in terms of S-parameters. Namely, the (n+1) NUTL under analysis is characterized at the output ports by a $2n$-sized S-parameter matrix, whose entries are evaluated column-by-column by applying $2n$ times the PT in [3] in combination with standard sets of loads. The obtained S-parameter matrix can be easily cascaded with other lumped/distributed networks and/or used in combination with different terminal conditions. The additional computation burden arising from the need for solving the line $2n$ times can be efficiently mitigated by parallel-computing implementation.

The proposed method results to be particularly beneficial in terms of computational time for the solution of differential microstrips exhibiting repetitive geometry. Namely, the whole line can be preliminary subdivided into k repetitive cells, and the proposed approach is applied for the characterization of an elemental line-cell only, by solution of $2n = 4$ sub-problems. The 4-port representation of the whole line is afterwards obtained by cascading the T-parameter matrices associated with all the line sections.

The proposed solution algorithm encompasses the following steps:

1) Subdivide the whole line into k non-repetitive elemental line sections;
2) For the elemental section, apply a non-ideal voltage source with open-end voltage $\hat{V}_S = 2\sqrt{Z_c}$ and internal resistance Z_c (for differential microstrips Z_c= 50 Ω is a common choice) at the left port of wire no. 1 and connect a load Z_c to the other ports;
3) Evaluate by the PT the voltages and currents at the four ports of the elemental line section under analysis, and convert them into forward and backward waves to evaluate the first column of the S-parameter matrix;
4) Connect the non-ideal source to the left port of wire no. 2, and repeat the above step to evaluate the second column of the S-parameter matrix;
5) Repeat the above steps, by connecting the non-ideal source to the right port of wire no. 1 and wire no. 2 to evaluate the third and fourth column, respectively, of the S-parameters matrix;
6) Convert the obtained S-parameter matrix into T-parameters notation;
7) Evaluate the T-parameter matrix of the whole line, by rising the T-parameter matrix obtained for the elemental line section to the k-th power.

III. ANALYSIS OF DIFFERENTIAL MICROSTRIPS FOR CM SUPPRESSION

In this Section, the proposed solution procedure is applied to investigate the performance of the differential microstrip lines for CM suppression introduced in [8], [9]. The line configuration is shown in the first panel of Fig. 1(a). The original design (labelled as $P1$ in Fig. 1) comprises four elemental cells repeated three times each. Geometrical characteristics and parameters of each cell are selected according to those in [9]. In this realization, each cell was designed to provide maximum CM-rejection at the center frequencies of 4 GHz, 4.5 GHz, 6 GHz, 7 GHz, respectively, so that the overall bandwidth of the obtained CM-suppression filter results to be broadened, [9].

In addition to such a realization, other possible configurations were investigated, characterized by (a) different numbers of repeated cells (see differential microstrips labelled as $P2$ and $P3$ in Fig. 1(a)); and (b) different ordering of cells (see differential microstrips labelled as $P4$ and $P5$ in Fig. 1(b)). For these structures, predictions of the mixed-mode S-parameters evaluated by the proposed TL-based approach are compared versus those obtained by full-wave simulations in the plots in Fig. 2 and Fig. 3. The comparison reveals a satisfactory agreement, with only slight discrepancies at high frequency in the modal reflection coefficients (theoretically null). Moreover, with respect to the full-wave approach, requiring a new simulation for each microstrip realization, analysis of all the above structures by the proposed TL-based technique only involves *a posteriori* processing of the T-parameter matrices of the elemental cells (already available). This results in a significant reduction of computational time, and allows fast and pretty accurate evaluation of the performance of different microstrip configurations.

For instance, comparison of the different patterns in Fig. 1 suggests the following conclusions. First, the plots in Fig. 2(c) show that increasing the number of cells enhances CM-rejection performance. The result is consistent with increasing the microstrip length in eq.(7) of [9]. Second, keeping constant the cell number yet changing cell ordering, see Fig. 1(b), shows that the best scheme is the one in [9], where all cells with the same length are collected. Conversely, mixing cells with different lengths as in $P4$, $P5$ should be avoided, since this worsens CM-suppression performance, due to the increased number of CM-impedance transitions and consequent reflections.

IV. CONCLUSION

In this paper, a reformulation of the perturbation technique in [3] is presented, which resorts to a preliminary characterization of the NUTL under analysis in terms of S-parameters. Such a technique is particularly attractive for the analysis of differential interconnects exhibiting repetitive geometries, since it allows accurate line solution with reduced computational burden. Prediction accuracy of the proposed TL-based approach is assessed by application examples involving different realizations of a chirped differential microstrip line for CM suppression.

REFERENCES

[1] C. R. Paul, *Analysis of multiconductor transmission lines*. John Wiley & Sons, 2008.

[2] M. Chernobryvko, D. V. Ginste, and D. De Zutter, “A two-step perturbation technique for nonuniform single and differential lines,” *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 5, pp. 1758–1767, 2013.

[3] P. Manfredi, D. De Zutter, and D. V. Ginste, “Analysis of nonuniform transmission lines with an iterative and adaptive perturbation technique,” *IEEE Trans. Electromagn. Compat.*, vol. 58, no. 3, pp. 859–867, 2016.

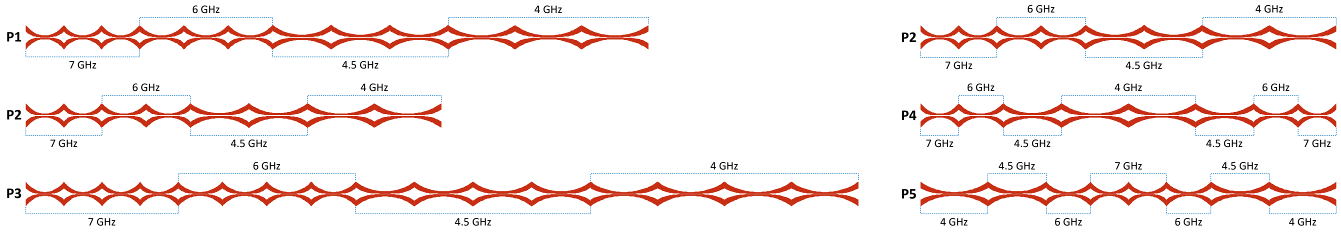
[4] X. Wu, F. Grassi, P. Manfredi, and D. V. Ginste, “Perturbative analysis of differential-to-common mode conversion in asymmetric nonuniform interconnects,” *IEEE Trans. Electromagn. Compat.*, vol. 60, no. 1, pp. 7–15, 2018.

[5] F. Grassi, P. Manfredi, X. Liu, J. Sun, X. Wu, D. V. Ginste, and S. A. Pignari, “Effects of undesired asymmetries and nonuniformities in differential lines,” *IEEE Trans. Electromagn. Compat.*, vol. 59, no. 5, pp. 1613–1624, 2017.

[6] R. K. Kunze, Y. Chu, Z. Yu, S. K. Chhay, M. Lai, and Y. Zhu, “Crosstalk mitigation and impedance management using tabbed lines,” *Intel white paper*, 2015.

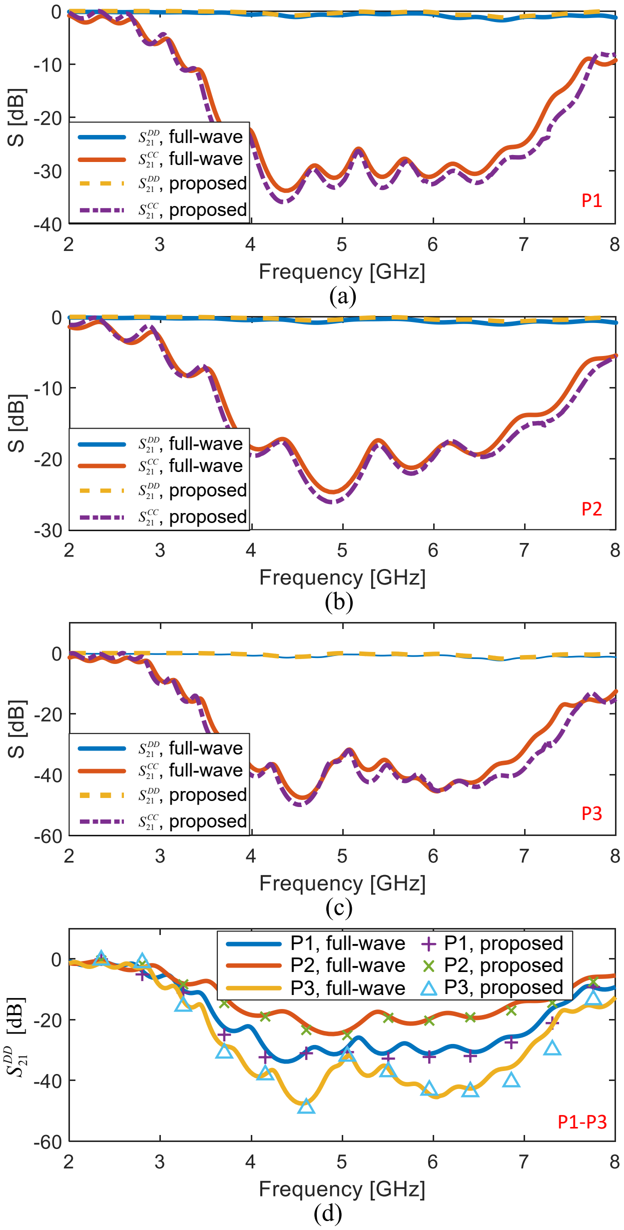
[7] M. Baldwin and V. Di Lello, “New techniques to address layout challenges of high-speed signal routing,” tech. rep., Cadence, PCB West, 2016.

[8] P. Vélez, J. Bonache, and F. Martín, “Differential microstrip lines with common-mode suppression based on electromagnetic band-gaps (EBGs),” *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 40–43, 2015.



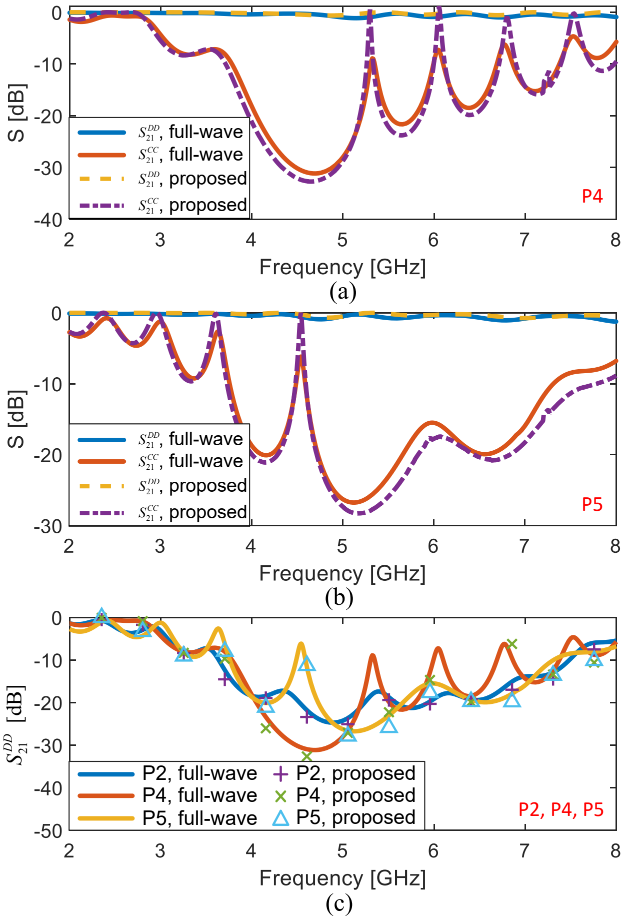
(a) (b)

Fig. 1. Different realizations of the differential microstrip with CM suppression under analysis.



(a) (b) (c) (d)

Fig. 2. Mixed-mode S-parameters for $P1$, $P2$, $P3$.



(a) (b) (c)

Fig. 3. Mixed-mode S-parameters for $P2$, $P4$, $P5$.

[9] P. Vélez, M. Valero, L. Su, J. Naqui, J. Mata-Contreras, J. Bonache, and F. Martín, "Enhancing common-mode suppression in microstrip differential lines by means of chirped and multi-tuned electromagnetic bandgaps," *Microw. Opt. Technol. Lett.*, vol. 58, no. 2, pp. 328–332, 2016.

[10] Keysight Technologies, "ADS Product Documentation." http://edadocs.software.keysight.com/display/ads2017update1/Home/. (Accessed July 15, 2019).