

Simple transmission line model suitable for the electromagnetic pulse coupling analysis of twisted-wire pairs above ground

Jeahoon Cho, Hyeongdong Kim, and Kyung-Young Jung^{a)}

*Department of Electronics and Communications Engineering, Hanyang University,
222 Wangsimni-ro, Seongdong-gu, Seoul 133–791, Korea*

a) kyjung3@hanyang.ac.kr

Abstract: A simple transmission line (TL) model is developed for analyzing the electromagnetic pulse (EMP) coupling of a twisted-wire pair (TWP)-TL above a ground plane, illuminated by an external plane wave. To accurately take into account the geometry of the TWP-TL, the TWP-TL is modelled as a cascade of a uniform segment with a different height from the ground plane. Numerical examples are used to illustrate the validity of the proposed TL model for the EMP coupling analysis of TWP-TL.

Keywords: transmission line model, chain matrix, twisted-wire pair

Classification: Electromagnetic theory

References

- [1] W. A. Radasky, C. E. Baum and M. W. Wik: IEEE Trans. Electromagn. Compat. **46** (2004) 314. DOI:10.1109/TEMPC.2004.831899
- [2] C. D. Taylor, R. S. Satterwhite and W. Harrison, Jr.: IEEE Trans. Electromagn. Compat. **13** (1965) 987. DOI:10.1109/TAP.1965.1138574
- [3] C. P. Paul and J. W. Mcknight: IEEE Trans. Electromagn. Compat. **21** (1979) 92. DOI:10.1109/TEMPC.1979.303751
- [4] C. P. Paul and J. W. Mcknight: IEEE Trans. Electromagn. Compat. **21** (1979) 105. DOI:10.1109/TEMPC.1979.303752
- [5] Y. Kami and R. Sato: IEEE Trans. Electromagn. Compat. **27** (1985) 177. DOI:10.1109/TEMPC.1985.304288
- [6] C. D. Taylor and J. P. Castillo: IEEE Trans. Electromagn. Compat. **22** (1980) 16. DOI:10.1109/TEMPC.1980.303816
- [7] R. B. Armenta and C. D. Sarris: IEEE Trans. Electromagn. Compat. **49** (2007) 698. DOI:10.1109/TEMPC.2007.902177
- [8] S. A. Pignari and G. Spadacini: IEEE Trans. Electromagn. Compat. **53** (2011) 508. DOI:10.1109/TEMPC.2010.2061855
- [9] F. M. Tesche: IEEE Trans. Electromagn. Compat. **34** (1992) 93. DOI:10.1109/15.135621
- [10] C. R. Paul: *Introduction to Electromagnetic Compatibility* (John Wiley & Sons, Hoboken, 2006) 2nd ed. 559.

- [11] S. A. Pignari and D. Bellan: ISEMC 3 (2004) 974. DOI:10.1109/ISEMC.2004.1349958
- [12] FEKO Suite 7.0, EM Software & Systems, <http://www.feko.info>

1 Introduction

In high-power electromagnetic (HPEM) environments, it is of great importance to analyze electromagnetic pulse (EMP) coupling responses induced on a transmission line (TL) to determine appropriate protection guidelines for connected electronic subsystems [1]. In order to predict these coupling effects, a general procedure is to *i*) determine the distributed sources (generated by inductive or capacitive coupling) induced on a TL [2], *ii*) develop an equivalent TL model [3, 4, 5, 6, 7, 8], and then *iii*) carry out the coupling analysis for each model. Especially, it is critical to develop an equivalent TL model to accurately represent the structural characteristics of the TL.

A twisted-wire pair (TWP) transmission line is widely used in many applications such as data and power transmission. Basically, the TWP-TL is more suitable than a single-wire pair (SWP) TL because the former can cancel out the EMP coupling from external EM field [3, 4]. Among previous TL models for the TWP-TL, a rectangular loop model [3, 4, 5] and a bifilar helix model [6, 7, 8] were employed. However, the former may lead to inaccurate results because it is too much simplified. The latter is based on a closed form approach and good for analyzing the typical TWP-TL structures. However, it is not straightforward to analyze complicated structures such as non-periodic structures, since it involves the complexity of mathematical expressions.

In this work, we propose a simple TL model suitable for the EMP coupling analysis of the TWP-TL above ground. To take into account the non-uniformity of the TWP-TL, it is modelled as a cascade of a uniform segment with a different height from the ground plane. To validate the proposed EMP coupling analysis method, a TWP-TL with periodic or non-periodic structures is analyzed.

2 Proposed TL model for TWP-TL

In this work, we employ a Taylor's source model [2] for distributed sources. Because the TWP-TL is located above ground, we consider not only the incident field but also the reflected field for EM excitation fields in the source model. We apply the equivalent ground model [9] and multi-conductor transmission line (MTL) analysis [10] to take into account the effect of the ground. Also, we apply the riser effects to account for field-to-wire coupling onto the terminal networks [11]. A TWP-TL is composed by two wires twisted together, as shown in Fig. 1. Two loads (Z_{input}, Z_{output}) are connected by the TWP-TL and these two loads are also connected to ground by four impedances (Z_1, Z_2, Z_3, Z_4). Note that the coordinate system used in this work is illustrated in the left figure in Fig. 1. Next, each TWP is modelled by two half-TWPs and then each half-TWP is modelled as a set of N different uniform segments, in order to accurately represent structural

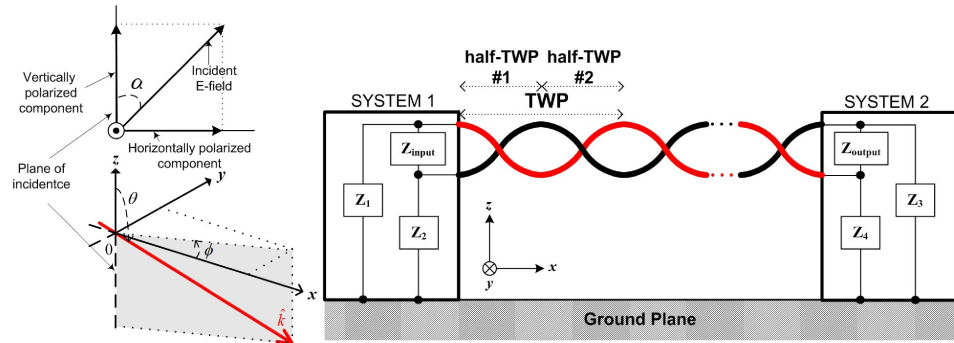


Fig. 1. Configuration of TWP-TL above a ground plane.

characteristics of the TWP-TL. As a proof of concept, we consider five ($N = 5$) different uniform segments in this work as shown Fig. 2, but more segments (e.g., $N = 7, 9, etc.$) can be simply extended to enhance the accuracy. Fig. 3 shows the cross-section of uniform segments for the half-TWP #1, i.e., two vertical (V)-segments, one horizontal (H)-segment, and two diagonal (D)-segments. The similar model can be applied for the half-TWP #2 by considering the opposite polarity.

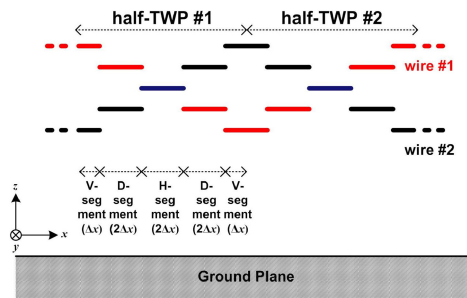


Fig. 2. Equivalent TL model for a single TWP.

Note that the uniform segment can be represented by a 4×4 chain matrix M_{nw} , where n represents the type of segments (V, H, or D) and w (1 or 2) represents the number of wire:

$$M_{n1} = \begin{bmatrix} \cosh(\gamma_{n1} \frac{\Delta x_n}{2}) & 0 & X_{n1} L_{n1g} & X_{n2} L_{nm} \\ 0 & \cosh(\gamma_{n2} \frac{\Delta x_n}{2}) & X_{n1} L_{nm} & X_{n2} L_{n2g} \\ X_{n1}(C_{n1g} + C_{nm}) & -X_{n2} C_{nm} & \cosh(\gamma_{n1} \frac{\Delta x_n}{2}) & 0 \\ -X_{n1} C_{nm} & X_{n2}(C_{n2g} + C_{nm}) & 0 & \cosh(\gamma_{n2} \frac{\Delta x_n}{2}) \end{bmatrix} \quad (1)$$

$$M_{n2} = \begin{bmatrix} \cosh(\gamma_{n2} \frac{\Delta x_n}{2}) & 0 & X_{n2} L_{n2g} & X_{n1} L_{nm} \\ 0 & \cosh(\gamma_{n1} \frac{\Delta x_n}{2}) & X_{n2} L_{nm} & X_{n1} L_{n1g} \\ X_{n2}(C_{n2g} + C_{nm}) & -X_{n1} C_{nm} & \cosh(\gamma_{n2} \frac{\Delta x_n}{2}) & 0 \\ -X_{n2} C_{nm} & X_{n1}(C_{n1g} + C_{nm}) & 0 & \cosh(\gamma_{n1} \frac{\Delta x_n}{2}) \end{bmatrix} \quad (2)$$

where Δx is a unit length, γ is a propagation constant, and X_{nw} is $j\omega[\sinh(\gamma_{nw} \frac{\Delta x_n}{2})]/\gamma_{nw}$. Here, γ is obtained by the total per-unit-length (p.u.l.) impedance and admittance, which can include the losses of the TL and lossy

ground [9]. Parameter L_{1g} , L_{2g} , C_{1g} , and C_{2g} are p.u.l. self-inductance and self-capacitance between each wire and ground, respectively. Note that L_m and C_m are the p.u.l. mutual components between each wire [10]. Fig. 4 shows the final equivalent TL model for each half-TWP with distributed voltage (V_{nw}) and current (I_{nw}) sources. The induced voltages and currents (EMP coupling responses) can be obtained by calculating the multi-cascaded chain matrix.

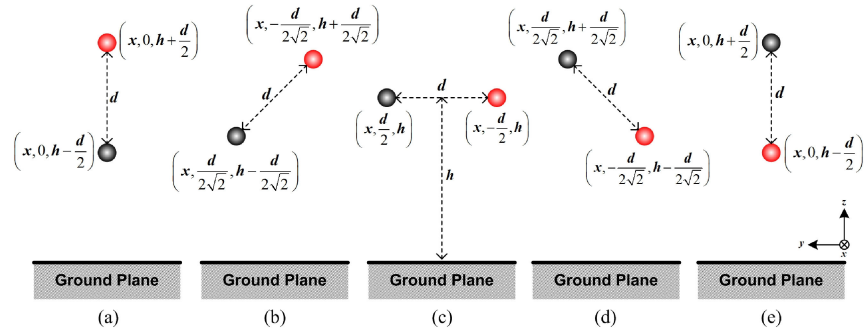


Fig. 3. Cross-section of uniform segments for the half-TWP #1. (a) V-segment. (b) D-segment. (c) H-segment. (d) D-segment. (e) V-segment.

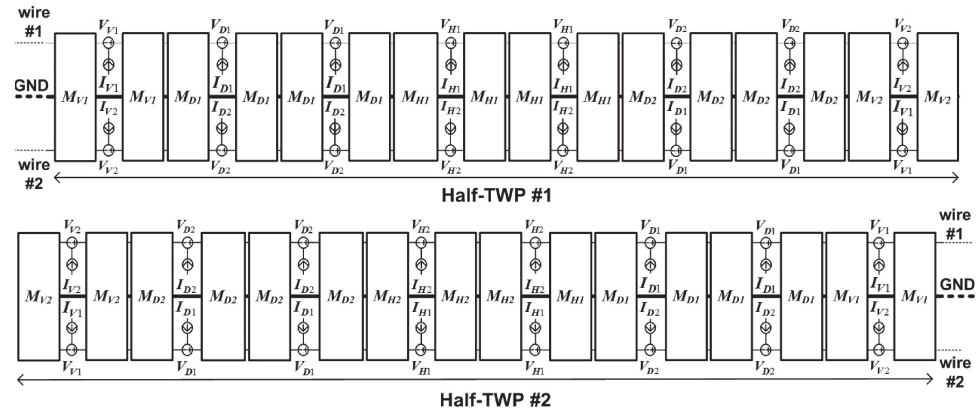


Fig. 4. Proposed multi-cascaded chain matrix model for half-TWP.

3 Numerical examples

In order to validate the accuracy of the proposed TL model, we consider the TWP-TL used in [8]. The TWP-TL is characterized by 40 TWPs (the overall line length of 2 m) with the wire separation (d) of 4 mm, height (h) of 5 cm, and the wire radii (r) of 0.5 mm. The TWP-TL is terminated by the floating termination condition (Z_1, Z_2, Z_3, Z_4) are open, with $Z_{input} = Z_{output} = 100 \Omega$ for an incident plane wave with constant magnitude (1 V/m), $\theta = 135^\circ$, $\phi = 135^\circ$, and $\alpha = -135^\circ$ (see Fig. 1).

Fig. 5 shows the induced current response at Z_{input} in the floating termination versus frequency. The solid line and the dashed line indicate the proposed TL model and the rectangular loop model respectively, and Pignari's data [8] are

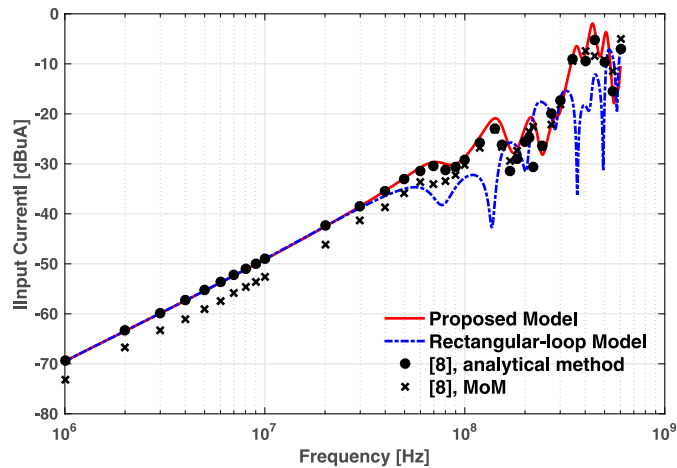


Fig. 5. Induced current response for the TWP-TL above ground.

indicated by symbols. As shown in Fig. 5, the coupling response by using the proposed TL model is in good agreement with the Pignari’s analytical data, but the results of the rectangular loop model are quite different from the Pignari’s data for the high frequencies (>100 MHz). In low-frequency range, however, there is a discrepancy between TL models (proposed and Pignari’s analytical model) and the method of moment (MoM) data, which is mainly occurred due to approximations derived from the lumped-parameter model of field-to-wire coupling onto the terminations, as mentioned in [8]. Note that the computational efficiency (memory requirement and calculation time) of TL models is better than that of the full-wave method such as MoM.

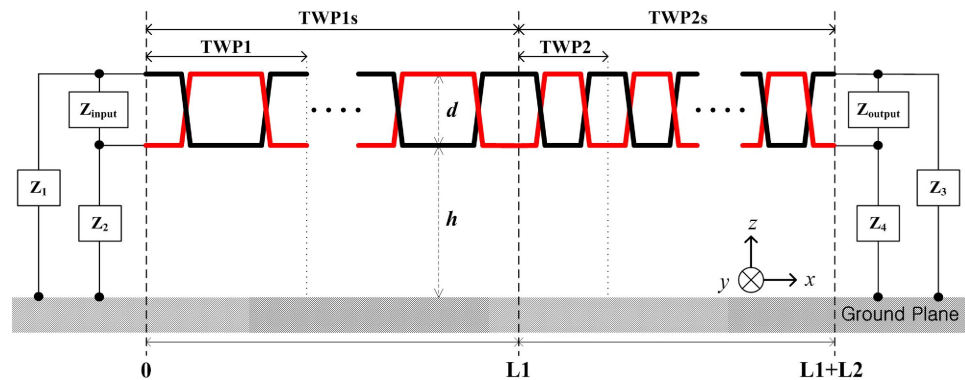


Fig. 6. Non-periodic TWP-TL above ground.

Next, we consider a non-periodic TWP-TL under an uniform plane wave excitation with constant magnitude (1 V/m), as shown in Fig. 6. It is assumed that the incident field is $\alpha = 0^\circ$ polarized with the wave incidence angle $\theta = 150^\circ$, $\phi = 0^\circ$ (see Fig. 1). The whole TWP-TL is composed of two TWP-TL subsections to represent the non-periodic structure. Each subsection is composed of 40 TWPs for $L1$ (line length of 1.6 m), 20 TWPs for $L2$ (line length of 1.6 m) with the wire radii of 0.5 mm , $d = 4 \text{ mm}$, and $h = 5 \text{ cm}$. We assume that the TWP-TL is terminated by the same impedance load ($Z_{input} = Z_{output} = 100 \Omega$) with a floating termination where Z_1 , Z_2 , Z_3 , and Z_4 are open.

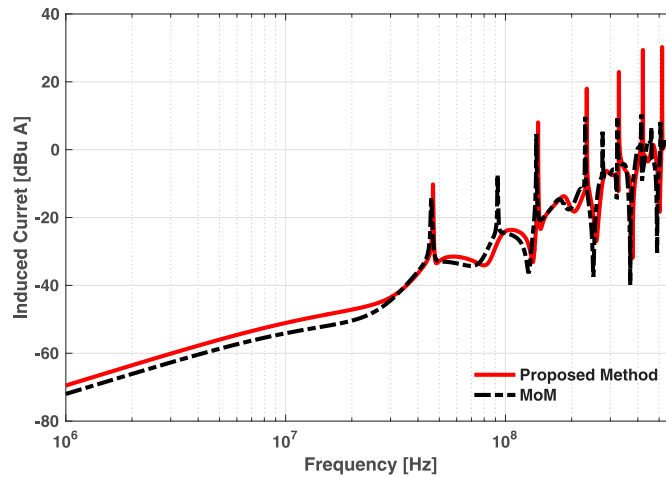


Fig. 7. Induced current response for the non-periodic TWP-TL above ground.

Fig. 7 shows the induced current response at Z_{input} of the non-periodic TWP-TL with the floating termination conditions. The solid lines indicate the induced current calculated by the proposed TL method and the dash lines indicate the MoM result of the commercial software FEKO [12]. As shown in Fig. 7, the coupling response calculated via the proposed model is in good agreement with the FEKO solution. It is worth noting that more segments (higher N) would be needed, when the wire separation is increased. As shown in the numerical example, the non-periodic TWP-TL structure can be easily modelled by our proposed TL approach by properly considering the unit length of the chain matrix for each section (TWP1s and TWP2s) but the previous analytical method is not straightforward to analyze the non-periodic TWP-TL structure.

4 Conclusion

A simple equivalent TL model has been proposed to analyze the EMP coupling of the TWP-TL above a ground plane, illuminated by an external plane wave. Take accurately and simply into account a helix structure, the TWP-TL is modelled as a cascade of several uniform segments with a different height from the ground plane. We have validated the proposed TL model for the TWP-TL from numerical experiments.

Acknowledgments

This work was supported by the research fund of Hanyang University (HY-2012-G).